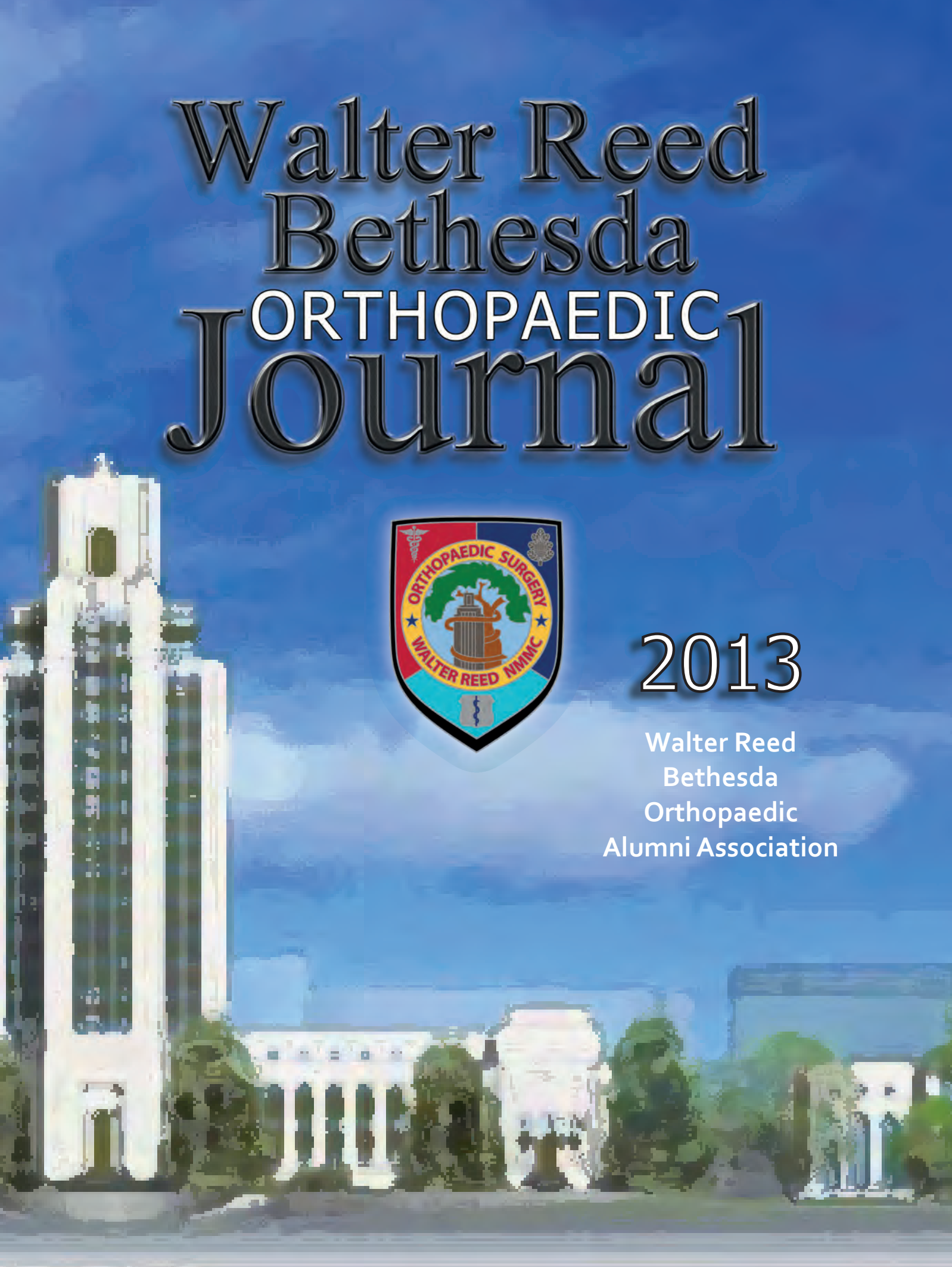
Walter Reed Bethesda ORTHOPAEDIC Journal



2013

Walter Reed
Bethesda
Orthopaedic
Alumni Association

Walter Reed Bethesda
Orthopaedic Journal

Contents 2013

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Walter Reed Bethesda Orthopaedic Alumni Association

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110 West Road, Suite 227
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Dear Members of the Walter Reed Bethesda Orthopedic Alumni Association,

Although long overdue, we now have an Alumni Association. This is a fitting culmination of an overwhelmingly successful merger of the Walter Reed and Bethesda orthopaedic residency training programs. To those who have worked hard to establish this organization, I extend my sincerest thanks. It is truly an honor to serve as your inaugural president.

As a training program, I am convinced that our best work is ahead of us. At this time, with our country still engaged in war, our training program finds itself with the opportunity to reaffirm its mission – a mission that ultimately focuses on developing a military orthopedic surgeon capable of operating in and withstanding the demands of leading a surgical unit in combat. We can now visualize the nature and the complexities of delivering orthopaedic surgical combat care in the 21st century and can therefore work backward from there to the operating rooms, clinics, and labs of Walter Reed National Military Medical Center. We have an understandable context for clearly defining the vision of our training program and the Department of Orthopaedic Surgery. From there, we have an exceptional and unremitting responsibility to export this common vision and leadership through our graduates to all of our military hospitals and medical centers as well as the battlefield, creating a collaborative effort and unity of purpose. This will provide an opportunity to examine and refine our research priorities and processes with a principled and disciplined approach. This is the chance to truly make a difference – to establish an enduring legacy.

I look forward to seeing all of you at what promises to be an exceptional first annual meeting in September.

With gratitude and warmest wishes,

Martin Deafenbaugh, MD
CAPT, MC, USN (ret)
President, Walter Reed Bethesda Orthopaedic Alumni Association

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DEPARTMENT OF ORTHOPAEDICS

Walter Reed National Military Medical Center
Bethesda, MD

Alumni of Walter Reed Bethesda Orthopaedics,

Many thanks for your interest in Walter Reed Bethesda Orthopaedics. Over the past year there have been many changes and events in orthopaedics.

First and foremost, the Department of Orthopaedics was established. This was an evolution that occurred over a number of years from the Army perspective, and back to the norm from the Navy perspective. From the mid 1900s to 2001, the Army had an Orthopaedic Surgery Service, while the Navy was a separate department. In 2001, the Army established a Department of Orthopaedics and Rehabilitation, and when our two facilities integrated in 2011, the model of a Department of Orthopaedics and Rehabilitation was chosen for our present institution. Over the years, the size of the department grew enormously, not only due to the current war, but also through the expansion of rehabilitation services offered. In late 2012, the structure of the department was evaluated by the command and it was felt that the Department of Orthopaedics and Rehabilitation would be better served by two separate departments. On January 1, 2013, the Department of Orthopaedics and the Department of Rehabilitation were established. With this initiation, seven services were developed within the Department of Orthopaedics, representing the major areas of orthopaedic sub-specialization.

This year also saw the initiation of the Walter Reed Bethesda Orthopaedic Alumni Association, of which this journal is a product. The mission of the association is to promote camaraderie of past and present members of Walter Reed Bethesda Orthopaedics, have an annual retreat with continuing medical education, publish an annual journal, and promote education. Membership is open to anyone who has served within the former National Naval Medical Center Department of Orthopaedics, the Walter Reed Army Medical Center Orthopaedic Surgery Service, the Walter Reed National Military Medical Center Orthopaedic Surgery Service, or the newly formed Walter Reed Department of Orthopaedics. Members can be residents, staff physicians, physician assistants, nurses, enlisted staff, or support staff. Service is defined as anyone who worked within our organization, including physicians who have been credentialed here while on reserve duty or who assisted with casualty care.

With regard to the things that make an academic orthopaedic department excel (patient care, education, and research), Walter Reed Orthopaedics has certainly flourished. Over the past year, our staff has cared for thousands of patients and been the primary facility treating our country's wounded warriors. Our residents continue to score in the top 25% of all orthopaedic training programs. With regard to research and academics, our department outperformed all others in the hospital, with over 100 peer-reviewed publications in the highest level orthopaedic journals, and hundreds of presentations given at national and international meetings.

Romney C. Andersen, M.D.
COL, MC, USA
Chairman, Orthopaedic Surgery, Walter Reed National Military Medical Center
Professor of Surgery, Uniformed Services University
Bethesda, MD
romney.andersen@us.army.mil
301-295-4289 Office

Residency Program Director's Letter

NATIONAL CAPITAL CONSORTIUM
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The orthopaedic surgery residency program at the Walter Reed National Military Medical Center has never been stronger. Over the last four years, numerous changes have happened to our immediate hospital system, combining Walter Reed Army Medical Center and National Naval Medical Center into the current hospital complex on the Bethesda campus. As a residency program, working with the Department and at that time, Service leadership, we were able to make many changes that have greatly benefitted resident training. Increased PA support, a dedicated trauma team, a revised academic program, broad educational opportunities, and staff physicians dedicated to resident education make this into what I consider to be the best training program in the military.

We are one of the largest residency programs in the military, with three Army and three Navy residents at each training level. The incoming interns for the 2013-14 academic year comprise what I consider to be one the strongest classes in years. We welcome CPT Christopher Daniels (Army), LT Kyle Nappo (Navy), CPT Rick Purcell (Army), LCDR Jonathan Seavey (Navy), LT Benjamin Wheatley (Navy), and CPT Jared Wolfe (Army) to the Orthopaedic Surgery Team. I feel that each of these individuals is extremely talented and will add tremendously to the residency program as well as the field of orthopaedic surgery in the years to come.

The graduating class of 2013 will be sorely missed as they head out into fellowship and practice. Their efforts made this a very successful year, with an excellent academic program as well as leadership. MAJ Jonathan Dickens is in a sports medicine fellowship at West Point; LCDR Steve Grijalva has transitioned to practice in Pensacola, Florida; MAJ Kelly Kilcoyne is in a shoulder/elbow fellowship at Johns Hopkins; MAJ Matthew Kluk has transitioned to practice at Ft. Hood, Texas; LCDR Anthony O'Daniel has transitioned to practice at Naval Station Great Lakes; and LCDR Kevin Wilson is at Camp Lejeune, North Carolina.

We have had another very successful academic year, with more than 100 publications involving both residents and staff. The basic science labs, including Walter Reed Spine/Biomechanics, National Institutes of Health/NIAMS, and Naval Medical Research Center at Forest Glen as well as the clinical research programs at the Naval Academy and Walter Reed NMMC, continue to be producers of cutting edge research. The residents have received multiple local and national awards for their efforts.

Most recently, Lt Col Wade Gordon has been selected to become the new Program Director for the residency program starting July 1, 2013. He is a great leader with boundless energy, who will lead this program into the future. I look forward to working with the staff and residents for many more years to come.

COL Scott B. Shawen

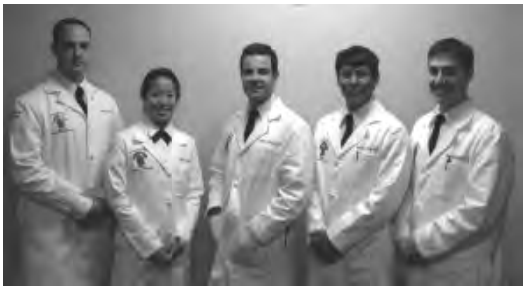
Residents/Fellows

To view the 2013 Graduation pictures, go to www.wrboaa.org.

2013 Graduate Class

Left to Right: MAJ Jonathan Dickens, MAJ Matthew Kluk, LCDR Steven Grijalva, MAJ Kelly Kilcoyne, LCDR Joseph Anthony O'Daniel, LCDR(S) Kevin Wilson

2013-2014 Chief Resident Class



Left to Right: LT James Flint, CPT Emily Shin, CPT Adam Bevevino, CPT Daniel Kang, LCDR Reed Heckert, not pictured: LCDR Keith Alfieri

2013-2014 Senior Resident Class

First Row: CPT Elizabeth Polfer
Second Row: LT Louis Lewandowski, LCDR Robert Tracey, CPT John Cody, CPT Husain Bharmal

2013-2014 Research Fellows

Left to Right: CPT Donald Hope, CPT Adam Pickett, LT Scott Wagner, LT Benjamin Chi, LT Patrick Jones, CPT Gregory Van Blarcum

2013-2014 Junior Resident Class

Left to Right: CPT Alaina Brelin, CPT Brett Smith, LT Daniel Griffin, CPT Michael Donohue, LCDR Theodore Steelman, LT Theodora Dworak

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Front Row: Ellyce Johnson, PA; Betty Spacciapoli, RN; Susan Foster, RN
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Hand Surgery

Left to Right: MAJ Justin Mitchell, LTC Christina Cawley, LTC Leon Nesti, CDR George Nanos, CAPT Patricia McKay, LTC Derek Ipsen (Chief), and PA-C Merri-Beth Cully

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Third Row: LCDR Billy Burk, MAJ Jean-Claude D'Alleyrand, CDR Jonathan Forsberg

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Left to Right: Morayma Rivera, LCDR Terrance Anderson, MAJ Melvin Helgeson, Barbara Goudarzi, LTC Ronald Lehman, not pictured: LTC Jefferson Jex

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Front Row: RN Gloria Martin-Smith, CDR Monique Gourdine-Shaw (Chief)
Second Row: LPN Nancy Soto, LTC Tobias Glister
Back Row: MAJ Bill Michie

Sports/Shoulder

Left to Right: CAPT Dan Hebert, LCDR Michael McCabe, Mrs. Joyce Yesupria, PA Susan Sinnott, PA Kimberly Farnsworth, Mrs. Bridgett Hott, MAJ Jeffrey Giuliani, Col Jeffrey Davila

Physician Assistants

Front Row: Ellyce Johnson
Second Row: Merri-Beth Cully, Susan Sinott
Third Row: LCDR Billy Burk, Kimberly Farnsworth, Thomas Koontz

Editorial

When COL Andersen approached me about starting this journal, I had no idea what it would involve, given our department does not have a history of putting together anything like it. I have to admit I was a little skeptical at first. However, I realized that because of the great things being done here, creating a journal worthy of publication wouldn't be a difficult job. (Unfortunately, there are still a few residents who seem to enjoy other aspects of their job, i.e., patient care, more than they do research.) The professional staff at Data Trace has also made this process a seamless and enjoyable one.

The goals of the journal are:

1) Increase awareness of the significant research being performed in the Department of Orthopaedics,

2) Provide a brief overview of the department's productivity, and

3) Update all alumni and personnel associated with the department on the great things we are doing.

The graduating chief residents and research fellows were instructed to compose a summarized version of the best product they produced during either their entire residency or their research year, respectively. Additionally, three papers were selected from our department's performance at the Society of Military Orthopaedic Surgeons Annual Meeting this past year, representing some of the best our residents have to offer. Taking into consideration that several of these papers may already be published or in the process of being published, we instructed the residents not to include any images already being used elsewhere. Fortunately (or unfortunately, depending on your perspective), we are all employees of the government, so there is no copyright to transfer our work.

Finally, the products here are presented by our residency training program, which adequately reflects the outstanding leadership provided over the past four years by COL Scott B. Shawen, MD. The past four years have seen unprecedented growth in the academic program and we are deeply indebted to his leadership. I am hopeful you will enjoy reading this collective sample of our program as much as I have. Thank you!

MAJ Melvin D. Helgeson, MD, MC, USA
Orthopaedic Spine Surgeon
Director, Orthopaedic Research
Walter Reed National Military Medical Center
Assistant Professor, Uniformed Services University of the Health Sciences
Bethesda, MD

Walter Reed Bethesda Orthopaedic Journal

Chief Resident Papers

Subpectoral Biceps Tenodesis: an Anatomical Study and Evaluation of At-Risk Structures

[1]MAJ Jonathan F. Dickens, MD, MC, USA; [1]MAJ Kelly G. Kilcoyne, MD, MC, USA; [1]LCDR Scott M. Tintle, MD, MC, USN; [1]MAJ Jeffrey Giuliani, MD, MC, USA; [1,2] COL Richard A. Schaefer, MD, MC, USA; [2]CDR John-Paul Rue, MD, MC, USN

INTRODUCTION

Pathology afflicting the proximal portion of the long head of the biceps has long been recognized as a common source of shoulder pain.[11-3] Numerous biceps tenodesis procedures have been described which secure the biceps tendon within[1-5] or inferior to the bicipital goove.[6-8] In 2005, Mazzocca, et al.[7] described an open subpectoral biceps tenodesis (OSPBT) technique securing the tendon below the intertubercular groove using an interference screw. The benefits of this technique include improved surgical efficiency, maintenance of the biceps length-tension relationship, removal of the tendon from the bicipital groove, and secure fixation.[7,9,10] Limited series have demonstrated favorable outcomes using the OSPBT technique,[11] with failure of fixation and persistent bicipital pain as the most commonly reported complications.[12]

The OSPBT with interference screw fixation has been increasingly performed for the treatment of multiple conditions of the proximal biceps tendon and associated shoulder pathology. There are numerous neurovascular structures in the proximal arm potentially at-risk during open subpectoral biceps tenodesis. Recently several studies have reported complications associated with the OSPBT technique.[11-13] Despite the potential for a catastrophic neurovascular injury during this procedure, there have been no studies that we are aware of in the English language which characterize the anatomic structures at risk in this relatively new surgical procedure. Additionally, the effect of arm rotation on the position of the neurovascular structures in the proximal arm has not been described. The purpose of this study was to define the anatomic relationships and at-risk structures during OSPBT and to quantify the effect of arm rotation on the position of the neurovascular structures of the proximal arm.

METHODS

After institutional review board approval, 17 whole intact fresh-frozen cadaveric upper extremities from nine donors (six male and three female) were studied. Nine right- and eight left-sided extremities were utilized, with eight paired specimens. The mean age at time of death was 77 years (range, 57 to 96 years). All specimens thawed to room temperature before experimentation. No limbs had visual evidence of prior shoulder surgery or trauma. All shoulders maintained at least 160° of passive abduction and 160° of passive forward flexion.

[1]Department of Orthopaedics and Rehabilitation, Walter Reed National Military Medical Center, Bethesda, MD; [2]United States Naval Academy, Department of Orthopaedics, Annapolis, MD.

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MAJ Jonathan F. Dickens MD, MC, USA

MAJ Dickens attended Davidson College and received a bachelor of science in biology. Following his undergraduate education MAJ Dickens served as a platoon leader and operations officer in 161st Airborne Medical Support Battalion at Fort Bragg, NC. He then entered medical school at Indiana University School of Medicine where he was inducted into the *Alpha Omega Alpha* honor medical society. After medical school he began orthopaedic surgery residency at Walter Reed National Medical Center. MAJ Dickens completed the Walter Reed research fellowship under the mentorship of Dr. John-Paul Rue and Benjamin K. Potter. MAJ Dickens' research has focused on combat casualty care and sports medicine, with interests particularly in open calcaneus and elbow fractures, proximal biceps pathology, and shoulder instability. He is the principal or co-principal investigator for nine on-going projects and has received over $350,000 in funding for his research efforts. His research has produced over 20 peer reviewed publications, five chapters, and more than 50 presentations to date. MAJ Dickens will complete the John A. Feagin Jr. Sports Medicine Fellowship at West Point in 2013 and he aspires to continue his research interests and sports medicine practice at an academic tertiary care hospital.

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The open subpectoral biceps approach, as described by Mazzocca, et al.[7] was performed by two investigators. As originally described, a pointed Hohman was placed directly against the lateral aspect of the humerus to retract the pectoralis major tendon proximally and laterally. A blunt Chandler was placed medially to retract the coracobrachialis and short head of the biceps. The retractors were positioned on the medial and lateral border of the humerus and centered at the point where the long head biceps intersected the inferior border of the pectoralis major. One cm proximal to the inferior border of the pectoralis major and centered at the inferior aspect of the bicipital groove, a guidewire was placed to identify and represent the proposed tenodesis site. The correct tenodesis position was confirmed in all specimens when the musculotendinous portion of the long head of the biceps rested at the inferior border of the pectoralis major tendon. A tenodesis screw was not placed in order to facilitate subsequent identification of neurovascular structures.

A careful dissection was then performed and structures were measured in a straight line from the at-risk structure to the preassigned reference points (described below) using standard digital calipers. Subcutaneous dissection was performed to identify the cephalic vein, medial brachial cutaneous nerve, medial antebrachial cutaneous nerve, and the intercostal brachial cutaneous nerve. Superficial structures were measured from the superior and inferior aspect of the 4-cm incision. Deep dissection was performed to identify the brachial artery, deep brachial artery, brachial vein, musculocutaneous nerve, median nerve, axillary nerve, and radial nerve. With the arm in the recommended position of 30° abduction and neutral rotation, the deep structures were measured from the tenodesis site and the nearest retractor. Additionally, the musculocutaneous nerve was measured with the arm in 45° of internal rotation and 45° of external rotation to determine the effect of rotation on the musculocutaneous nerve. Care was taken to minimize dissection and measure each structure in its native anatomic location.

RESULTS

Superficial Structures

With the arm at 30° of abduction and neutral rotation, the cephalic vein was 9.2 mm ± 6.1 mm lateral to the superior margin of the incision and 13.7 mm ± 5.8 mm lateral to the inferior margin of the incision. The medial brachial cutaneous nerve of the arm, medial brachial cutaneous nerve of the forearm, and intercostal brachial cutaneous nerves were 38.8 mm ± 4.2 mm, 33.8 mm ± 7.5 mm, and 45.9 mm ± 7.6 mm medial to the superior aspect of the incision, respectively.

Deep Structures

With the arm at 30° of abduction and neutral rotation, the musculocutaneous nerve was 10.1 mm ± 3.3 mm medial to the tenodesis location and 2.9 mm ± 1.4 mm medial to the medially placed retractor Table 1, Table 2). The radial nerve and deep brachial artery were 16.6 mm ± 5.9 mm and 14.5 mm ± 6.0 mm deep and medial to the tenodesis location, respectively. With the medial retractor in place, the radial nerve and deep brachial artery were 7.4 mm ± 3.0 mm and 5.7 mm ± 2.9 mm deep and medial to the retractor, respectively. The median nerve, brachial artery, and brachial vein were 27.6 mm ± 5.5 mm, 32.0 mm ± 5.7 mm, 32.5 mm ± 6.4 mm medial to the tenodesis site, respectively.

The distance between the musculocutaneous nerve and the tenodesis site was significantly less in internal rotation (8.1 mm ± 3.3mm) versus external rotation (19.4 mm ± 8.2 mm, $p = 0.009$) (Table 3). In 18% of specimens (3/17), the musculocutaneous nerve was in direct contact with the medial retractor with the arm in an internally rotated position.

Table 1. Distance from Tenodesis Site to Anatomic Structure in Neutral Rotation

Structure	Mean (mm)	Standard deviation	Range (mm)
Musculocutaneous nerve	10.1	± 3.3	6-18
Axillary nerve	33.8	± 6.9	20-45
Median nerve	27.6	± 5.5	18-49
Radial nerve	16.6	± 5.9	10-32
Deep brachial artery	14.5	± 6.0	9-30
Brachial vein	32.5	± 6.4	19-45
Brachial artery	32.0	± 5.7	20-43

Table 2. Distance from Retractor to Anatomic Structure

Structure	Mean (mm)	Standard deviation	Range (mm)
Musculocutaneous nerve*	2.9	± 1.3	1-6
Median nerve*	20.9	± 6.1	13-31
Radial nerve*	7.4	± 3.0	2-12
Deep brachial artery*	5.7	± 2.9	1-10
Axillary nerve^	11.5	± 4.3	4-21

* indicates medial retractor; ^ indicates lateral retractor

Table 3. Variation in Musculocutaneous Nerve Relationship to the Tenodesis Site in Internal, Neutral, and External Rotation and the Number of Specimens in Contact with the Medial Retractor

Position	Internal rotation	Range	Neutral rotation	Range	External rotation	Range	*p* value
Mean (mm)	8.1 ± 3.3	3.3 to 16.1	10.1 ± 3.3	6.4 to 14.5	19.4 ± 8.2	10.6 to 32.3	< 0.01
No. in direct contact	3		0		0		

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Variations of musculocutaneous nerve innervations to the biceps and brachialis were observed and classified.[14,15] A type I biceps innervation, defined as a single motor branch from the musculocutaneous nerve was observed in 76% (13/17) of specimens. A type II biceps innervation, defined as two distinct motor branches from the musculocutaneous nerve was observed in 24% (4/17).[14,15] A type III innervation pattern, defined as three distinct musculocutaneous motor branches, was not observed.[14,15] The site of origin of the first branch was approximately half the distance between the lateral border of the acromion and the tip of the medial epicondyle of the humerus. A type I brachialis innervation was observed in 71% (12/17) and a type II brachialis was observed in 29% (5/17).[14,15] The first branch to the brachialis was consistently inferior to the branch to the biceps. There was no significant difference in measurements made by either investigator ($p > 0.05$).

DISCUSSION

Limited series have evaluated the outcomes following OSPBT.[12,16,17] The incidence of complications following open subpectoral tenodesis have been reported to be between 2% and 7%,[12,18] however, the incidence of musculocutaneous neuropraxia following OSPBT is not reported. Nho, et al.,[12] in the largest clinical series of OSPBT, reviewed the complications in 353 patients and found a 2.0% complication rate. Persistent bicipital pain and failure of fixation with a Popeye deformity were the most common complications, 0.57% each. One patient (0.28%) developed a musculocutaneous nerve neuropathy, presenting 10 days postoperatively with forearm numbness and weakness in elbow flexion and forearm supination six weeks postoperatively. Musculocutaneous nerve exploration six weeks following the index surgery demonstrated the nerve was in continuity and at six months postoperatively, the patient had complete resolution of the neurologic deficits.

Ma, et al.[13] reported another case of musculocutaneous nerve injury following OSPBT. Five months after OSPBT, the patient underwent musculocutaneous nerve exploration, demonstrating that the long head of the biceps tendon was transferred deep to the nerve, providing continued traction on the nerve. The nerve was found to be in continuity and following revision of the tenodesis with placement of the long head of the biceps superficial to the nerve, the patient regained full neurological function.

The proximity of the musculocutaneous nerve to the tenodesis site makes it the most at-risk structure during OSPBT. Additionally, the use of a deep, levering medial retractor places the nerve at increased risk of iatrogenic injury. The mean distance from the medial retractor to the musculocutaneous nerve with the arm in internal rotation was 2.9 mm ± 1.4 mm, and in 18% of specimens, the nerve was in direct contact with the retractor. Therefore, if the surgeon's preference is for medial retraction of the conjoined tendon and medial soft tissues, then a non-levering retractor with gentle retraction during the critical portions of the procedure is recommended to minimize iatrogenic injury to the musculocutaneous nerve.

External rotation of the arm significantly increased the distance from the tenodesis site by 11.3 mm. OSPBT is frequently performed following shoulder arthroscopy in either the lateral decubitus or beach chair positions. Mounted arm positioners may also be utilized to minimize the need for a surgical assistant and improve arthroscopic visualization. These techniques, however, limit the ability to position the extremity safely for OSPBT. We recommend positioning the arm in an externally rotated position to maximize the distance of the musculocutaneous nerve from the operative field.

Although no reported deep brachial artery or radial nerve injuries have been reported with OSPBT, the location of these structures as they course lateral and posterior into the spiral groove immediately posterior to the tenodesis is demonstrated and may represent a potential site of injury. Cox, et al.[19] reported that the radial nerve traversed the midpoint of the spiral groove 14.7 cm ± 2.2 cm distal to the greater tuberosity of the humerus at a point approximately 48% from the most proximal point of the humerus. Guse, et al.[20] found that the radial nerve passed posterior to the medial cortex of the humerus at a point 41% of the humeral length (12.4 cm ± 1.2 cm from the acromiom) and exited the spiral groove lateral to the lateral cortex of the humerus at a point 58% of the humeral length (17.6 cm ± 1.7 cm from the tip of the acromiom). A medially placed retractor that penetrates the fascia of the short head of the biceps may come in direct contact with the radial nerve and deep brachial artery as they course into the spiral groove. Additionally, inadvertent bicortical drill penetration during tenodesis preparation may compromise the structures within the spiral groove. In all specimens, the structures of the spiral groove were within 1.5 cm and at the level of the proposed tenodesis site. Drilling techniques to avoid bicortical penetration of the proximal humerus should be employed. Knowledge of the proximity and location of these structures may prevent iatrogenic injury.

There have been no cases of axillary nerve or artery damage following OSPBT. Although unlikely, a retractor placed on the lateral humerus under the pectoral major muscle may jeopardize the axillary nerve if vigorously retracted. In this series, the axillary nerve was a mean 11.5 mm ± 4.3 mm from the retractor. Care should be taken to limit deep placement and excessive force during lateral retraction.

REFERENCES

1. Gilcreest E. Two cases of spontaneous rupture of the long head of the biceps flexor cubiti. *Surg Clin North Am.* 1926;6:539-554.
2. Lippman R. Frozen shoulder, periarthritis, bicipital tenosynovitis. *Arch Surg.* 1943;47:283-296.
3. Hitchcock HH, Bechtol CO. Painful shoulder: observations on the role of the tendon of the long head of the biceps brachii in its causation. *J Bone Joint Surg Am.* 1848;30:263-273.
4. Boileau P, Krishnan SG, Coste JS, Walch G. Arthroscopic biceps tenodesis: a new technique using bioabsorbable interference screw fixation. *Tech Shoulder Elbow Surg*. 2001;2:153–165.
5. Edwards TB, Walch G. Open biceps tenodesis: the interference screw technique. *Tech Shoulder Elbow Surg*. 2003;4(4):195-198.
6. Froimson AI, O I. Keyhole tenodesis of biceps origin at the shoulder. *Clin Orthop Relat Res.* Oct 1975(112):245-249.
7. Mazzocca AD, Rios CG, Romeo AA, Arciero RA. Subpectoral biceps tenodesis with interference screw fixation. *Arthroscopy.* Jul 2005;21(7):896.
8. Weber SC. Arthroscopic "mini-open" technique in the treatment of ruptures of the long head of the biceps: Stephen C. Weber. Sacramento, California, U.S.A. *Arthroscopy.* 1993;9(3):365.
9. Mazzocca AD, Rios CG, Romeo AA, Arciero RA. Subpectoral biceps tenodesis with interference screw fixation. *Arthroscopy.* Jul 2005;21(7):896.
10. Provencher MT, LeClere LE, Romeo AA. Subpectoral biceps tenodesis. *Sports Med Arthrosc.* Sep 2008;16(3):170-176.
11. Mazzocca AD, Cote MP, Arciero CL, Romeo AA, Arciero RA. Clinical outcomes after subpectoral biceps tenodesis with an interference screw. *Am J Sports Med.* Oct 2008;36(10):1922-1929.

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12. Nho SJ, Reiff SN, Verma NN, Slabaugh MA, Mazzocca AD, Romeo AA. Complications associated with subpectoral biceps tenodesis: low rates of incidence following surgery. *J Shoulder Elbow Surg.* Jul 2010;19(5):764-768.
13. Ma H, Van Heest A, Glisson C, Patel S. Musculocutaneous nerve entrapment: an unusual complication after biceps tenodesis. *Am J Sports Med.* Dec 2009;37(12):2467-2469.
14. Chiarapattanakom P, Leechavengvongs S, Witoonchart K, Uerpairojkit C, Thuvasethakul P. Anatomy and internal topography of the musculocutaneous nerve: the nerves to the biceps and brachialis muscle. *J Hand Surg Am.* Mar 1998;23(2):250-255.
15. Yang ZX, Pho RW, Kour AK, Pereira BP. The musculocutaneous nerve and its branches to the biceps and brachialis muscles. *J Hand Surg Am.* Jul 1995;20(4):671-675.
16. Becker DA, Cofield RH. Tenodesis of the long head of the biceps brachii for chronic bicipital tendinitis. Long-term results. *J Bone Joint Surg Am.* Mar 1989;71(3):376-381.
17. Berlemann U, Bayley I. Tenodesis of the long head of biceps brachii in the painful shoulder: improving results in the long term. *J Shoulder Elbow Surg.* Nov-Dec 1995;4(6):429-435.
18. Millett PJ, Sanders B, Gobezie R, Braun S, Warner JJ. Interference screw vs. suture anchor fixation for open subpectoral biceps tenodesis: does it matter? *BMC Musculoskelet Disord.* 2008;9:121.
19. Cox CL, Riherd D, Tubbs RS, Bradley E, Lee DH. Predicting radial nerve location using palpable landmarks. *Clin Anat.* May 2010;23(4):420-426.
20. Guse TR, Ostrum RF. The surgical anatomy of the radial nerve around the humerus. *Clin Orthop Relat Res.* Nov 1995(320):149-153.

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Complications and Reoperations Associated with Combat-Related Tibial Plafond Fractures

[1]CPT Husain Bharmal, MD; [1]LT Louis Lewandowski, MD; [3]MAJ Korboi N. Evans, MD, MS; [1]LCDR Steven Grijalva, MD, MC, USN; [1,2]CDR Mark E. Fleming, DO, MC, USN

INTRODUCTION

Since the onset of the war on terror, nearly 46,000 U.S. military personnel have been listed as wounded in action.[1] Recent analyses have shown that a majority of the sustained injuries are the result of explosions from mortars, rockets, and improvised explosive devices (IEDs).[2] Because of effective modern body armor and Kevlar that protect the torso and head relatively well, it is the extremities that absorb most of the energy from blast mechanisms. Consequently, a high number of these extremity injuries are long bone fractures.[3,4]

Combat-related injury to the tibia has been the subject of many articles in the literature over the past several years. However, while there is a significant amount of literature regarding tibial shaft fractures, there is a relative paucity of literature on periarticular injuries to the tibia among wounded soldiers. Open fractures secondary to blast trauma have a high incidence of complications and open periarticular injuries portend an even worse prognosis.[5-8] Fractures to the tibial plafond among the war-wounded have not been a subject directly addressed since the recent war efforts efforts began. The complications and outcomes of these devastating injuries have yet to be elucidated in the literature. In this study, we aim to report the experience at our institution with these injuries, as well as identify and describe the complications and re-operations following treatment of combat-related tibial plafond fractures.

METHODS

After obtaining approval from our institutional review board (IRB), we performed a retrospective review of all patients with tibial plafond fractures treated at one of our three institutions, Walter Reed Army Medical Center, National Naval Medical Center–Bethesda, or Walter Reed National Military Medical Center, between 2003 and 2012. Only patients who were active duty military at the time of injury, sustained the pilon fracture as a result of combat operations, and had definitive care rendered at one of our three affiliated institutions met criteria for inclusion in our study. Patients who sustained fractures secondary to non-combat etiology or who were non-active duty military were excluded.

Based on our inclusion criteria, a total of 63 fractures in 62 patients were identified (one patient sustained bilateral pilon fractures). Patient demographic data to include age and gender were obtained. For each fracture, we recorded mechanism of injury (blast, gunshot, motor vehicle collision, fall, etc.), open versus closed fracture, associated injuries, time from injury to definitive fixation, type of definitive fixation (open reduction with internal fixation (ORIF), external fixation, or hybrid fixation), number of unplanned re-operations after definitive fixation, reason for any re-operations, and total length of follow-up. Additionally, open fractures were classified based on the Gustilo-Anderson classification[9,10] and recorded according to the type of definitive soft tissue coverage used in relevant cases.

Patients were then stratified into three cohorts based on type of fixation: ORIF, external fixation, or hybrid fixation. These cohorts were subsequently compared with the previously described variables to determine any difference in complication rate based on type of fixation.

[1]Department of Orthopaedics, Walter Reed National Military Medical Center, Bethesda, MD; [2]Uniformed Services University of Health Sciences, Bethesda, MD; [3]Fort Belvoir Community Hospital, Fort Belvoir, VA. Address correspondence to: CPT Husain M. Bharmal, MD, husain.bharmal@gmail.com.

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LCDR Steven Grijalva MD, MC, USN

LCDR Grijalva grew up in Tucson, AZ. Shortly after graduation, he enlisted in the Navy becoming a hospital corpsman. He spent seven years enlisted prior to receiving his bachelor of science degree from Excelsior College in Albany, NY. He received his doctor of medicine from the Uniformed Services University of the Health Sciences. Shortly after completing his orthopaedic internship at the National Naval Medical Center, he transferred to Camp Lejeune, NC and was assigned to 2nd Marine Division. During his stay, he was attached to 2nd Amphibian Assault Battalion, and 1st Battalion, 8th Marines. He completed a tour overseas in support of Operation Iraqi Freedom. Currently, he is an orthopaedic resident at the Walter Reed National Military Medical Center assigned to The Naval Medical Research Center for his research fellowship. His research has focused on heterotopic ossification (HO) and the effects of HO prophylactic agents on wound healing. He plans to apply for an orthopaedic trauma fellowship following residency graduation.

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RESULTS

All Fractures (Tables 1 & 2)

The average age of subjects was 26.8 years. Fifty-five of the 63 fractures were secondary to blast mechanism of injury; four secondary to falls; three secondary to gunshot wounds; and one secondary to motor vehicle collision. Twenty-nine of the fractures were open while 34 were closed. The average time to fixation from injury among all fractures was 19 days. Forty-three of the 63 ankles exhibited residual pain at long-term follow-up (greater than 12 months).

The average number of unanticipated re-operations was 1.82 among all patients. Infection was the reason for revisit to the operating room in 24% (15/63) of fractures; wound dehiscience in 20.6% (13/63); symptomatic hardware requiring removal in 9.5% (6/63); and 23.8% of fractures returned to the operating room for elective amputa-

Table 1. All Fractures

	No. of pilons N = 63	ORIF N = 41 (65.1%)	Ex-fix N = 11 (17.5%)	Hybrid N = 11 (17.5%)	*p* value
Age in years (mean ± standard)	26.8	27.8 ± 1.03	26.2 ± 2.00	23.6 ± 2.00	0.1
MOI					0.6
Fall	4	4 (100%)	0 (0%)	0 (0%)	
GSW	3	2 (66.67%)	1 (33.33%)	0 (0%)	
Blast	55	34 (61.8%)	10 (18.2%)	11 (20%)	
MVC	1	1 (100%)	0 (0%)	0 (0%)	
Open/closed					0.03*
Open	29	14 (48.3%)	8 (27.6%)	7 (24.1%)	
Closed	34	27 (79.4%)	3 (8.8%)	4 (11.8%)	
Time of definitive fixation (days)	19.06	15.02 ± 8.9	30.55 ± 17.5	22.64 ± 25	0.0068*
Total no. of re-operations	1.82	2.07 ± 3.62	1.81 ± 2.75	0.91 ± 0.70	0.56
Pain at > 12 months	43 (68.3%)	27 (62.8%)	7 (16.3%)	9 (20.9%)	0.56

ORIF, open reduction and internal fixation; ex-fix, external fixation; MOI, mode of injury; GSW, gun shot wound; MVC, motor vehicle collision; *, not significant

Table 2. All Fractures Complications

	No. of pilons N = 63	ORIF N = 41 (65.1%)	Ex-fix N = 11 (17.5%)	Hybrid N = 11 (17.5%)	*p* value
Infection	15 (23.8%)	10 (66.7%)	3 (20.0%)	2 (13.3%)	0.87
Wound complications	13 (20.6%)	9 (69.2%)	3 (23.1%)	1 (7.7%)	0.5
Symptomatic hardware	6 (9.5%)	6 (100%)	0 (0%)	0 (0%)	0.1
Amputation	15 (23.8%)	9 (60%)	4 (26.7%)	2 (13.3%)	0.5
Union	57 (90.5%)	38 (92.7%)	10 (90.9%)	9 (81.2%)	0.5
Average follow-up (months)	23.4	23.1 ± 17.7	30.3 ± 25.1	17.7 ± 7.4	0.2

ORIF, open reduction and internal fixation; ex-fix, external fixation

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tion secondary to persistent residual pain and limited function. Overall, 90.5% (57/63) of fractures exhibited evidence of radiographic union regardless of complications. We defined union as osseous bridging at six months post fixation.

Open Fractures (Table 3)

Re-operations were further stratified into open fractures alone and analyzed. All 20 open fractures were classified at Gustilo-Anderson type III fractures. Seventeen were type IIIA, 10 were type IIIB, and two were type IIIC. A total of 20.1% (6/29) required a flap (free or rotational) for adequate soft tissue coverage. The average number of unanticipated re-operations for open fractures was 2.17. Thirty-one percent (9/29) were secondary to infection; 31% (9/29) for wound complications; 13.8% (4/29) for symptomatic hardware; and 27.6% (8/29) underwent elective amputation. Eighty-two percent (24/29) of the open fractures showed evidence of radiographic union regardless of complications.

Complications Based on Different Treatment Modalities (Tables 1 to 3)

Of the total 63 fractures, 65% (41/63) were treated with ORIF alone, 17.5% (11/63) with external fixation alone, and 17.5% (11/63) with hybrid fixation. There was no significant difference with respect to age between the three treatment modalities ($p = 0.1$) nor was there a significant difference among mechanisms of injury ($p = 0.6$). With respect to open versus closed fractures and treatment, 48.3% (14/29) of open pilons were treated with ORIF alone, while the other 15 underwent external fixation alone or hybrid fixation, 27.6% (8/29) and 24.1% (7/29), respectively. Of the 34 closed fractures, 79.4% (27/34) underwent ORIF while 8.8% (3/34) and 11.8% (4/34) underwent external fixation and hybrid fixation, respectively. This difference in treatment modality based on open versus closed fractures was significant ($p = 0.03$).

The difference in time to definitive fixation was also shown to be significant between treatment cohorts, with ORIF alone being performed an average of 15 days (+/- 8.9 days) post injury, external fixation alone at 30.55 days (+/- 17.5 days), and hybrid fixation at 22.6 days (+/- 25 days) ($p < 0.01$). Differences in total number of re-operations and ankles with pain at long-term follow-up were not found to be significant between treatment cohorts. There was no significant difference in reasons for re-operations based on treatment type. Among open fractures stratified based on treatment, the only significant difference ($p = 0.042$) was found with respect to utilization of a flap for soft tissue coverage, as 33.3% (2) of the total six flaps were performed in the ORIF group and 66.6% (4) were in the external fixation groups.

DISCUSSION

Because of recent improvements in rehabilitative care of combat casualties, limb salvage for high-energy traumatic injury to the lower limb has become more practical.[11-13] However, the functional outcome and complications following limb salvage for combat-related tibial

Table 3. Open Fractures

	No. of open pilons N = 29	ORIF N = 14 (48.3%)	Ex-fix N = 8 (27.6%)	Hybrid N = 7 (24.1%)	*p* value
Gustilo-Anderson classification					0.08
IIIA	17 (59%)	10 (58.8%)	2 (11.8%)	5 (29.4%)	
IIIB	10 (34%)	4 (40%)	4 (40%)	2 (20%)	
IIIC	2 (6.9%)	0 (0%)	2 (100%)	0 (0%)	
Infection	9 (31%)	5 (55.6%)	2 (22.2%)	2 (22.2%)	0.86
Flap for soft tissue coverage	6 (20.1%)	2 (33.3%)	4 (66.7%)	0 (0%)	0.042*
Total no. of re-operations	2.17	2.85 ± 2.54	2.25 ± 3.10	0.71 ± 0.75	0.18
Wound complications	9 (31%)	6 (66.7%)	2 (22.2%)	1 (11.1%)	0.37
Symptomatic hardware	4 (13.8%)	4 (100%)	0 (0%)	0 (0%)	0.08
Amputation	8 (27.6%)	4 (50%)	3 (37.5%)	1 (12.5%)	0.60
Union	24 (82.8%)	12 (50%)	7 (29.2%)	5 (20.8%)	0.66

ORIF, open reduction and internal fixation; ex-fix, external fixation; *, not significant

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plafond fractures has yet to be elucidated. Our goal in this study was to identify risk factors for return trips to the operating room and describe our institution's experience with these difficult injuries. Additionally, we aim to compare different treatment options with respect to these complications, potentially in order to make improved surgical recommendations to patients with complex pilon fractures.

A number of previous studies have profiled the complications associated with pilon fractures in the civilian population. The primary reasons for re-operations in these studies are deep infection or elective amputation for persistent pain and/or disability.[14-17] Sirkin, et al. evaluated outcomes and complications of surgical management of pilon fractures in 56 patients, finding 5% and 11% infection rates in closed and open fractures, respectively.[15] A later study by Conroy, et al. of 32 open pilons showed an 18% infection rate and a 6.2% amputation rate.[16] Boraiah, et al. found an infection rate of 3% and an amputation rate of 2% among 59 pilon fractures.[17] Our study, in comparison, revealed a much higher complication rate. Among all pilon fractures in our patient population, we found an overall infection rate of 24% and an amputation rate of 20.8%. In open fractures alone, the infection and amputation rates were 31% and 27%, respectively. Additionally, 20% of the open fractures were Gustilo-Anderson type IIIB fractures requiring rotational or free flap soft tissue coverage. This complication rate is significantly higher than that reported in the civilian literature.

The reason for this stark difference in complication rates is not completely clear. We hypothesize, as previous studies on the war-wounded have also indicated, that the high-energy nature of injuries sustained in combat are the foundations for subsequent complications in this patient population.[7,18,19] The majority (55 of 63) of the fractures in our study were sustained secondary to blast mechanisms; this is in stark contrast to the mechanisms of injury for tibial plafond fractures in the civilian population, which are usually secondary to falls or motor vehicle collisions.

We feel that the high complication rate in our study reflects not the treatment actually rendered, but rather the severity of the initial injury. Despite this high complication rate, over 90% of the pilon fractures in our patient population showed evidence of radiographic union at six months follow-up, indicating that it is soft tissue insult that likely causes the increased re-operation rate.

Since Ruedi and Allgower's landmark study in 1973,[20] surgical management of pilon fractures has been the mainstay of treatment for these injuries. They showed promising outcomes with operative intervention, as opposed to the previous dogma of non-operative management.[21] Numerous reports have since documented various treatment options for pilon fractures, to include ORIF, definitive external fixation, and hybrid fixation.[15,22-28] Bone, et al. showed generally favorable outcomes in patients treated with external fixation in combination with ORIF using small plates and percutaneous screws near the articular surface to limit soft tissue dissection.[24] In a prospective study of 26 patients comparing ORIF alone with hybrid treatment, Tornetta, et al. revealed overall similar outcomes and less soft tissue complications in the hybrid cohort.[28] A later study by Anglen, et al. showed results inconsistent with earlier reports on the improved outcomes and complication rates of hybrid fixation. They found lower clinical scores, slower return to function, a higher rate of complications, more infections, and a higher incidence of malunions and nonunions in 63 patients treated with hybrid fixation.[22] As a result of these disparities in the literature, there remains no clear consensus on the ideal form of management of these injuries.

Our study showed no significant difference in re-operation rates between treatment cohorts. The only significant differences with respect to the different treatment protocols were time to definitive fixation and whether the fracture was an open or closed injury. Patients treated with an external fixator, either alone or using a hybrid technique, were much more likely to have a lengthier delay in definitive treatment from initial injury. This is likely due to the fact that more severe injuries involved greater soft tissue insult, resulting in a lack of feasibility of adequate internal fixation; these fractures consequently were more likely to benefit from some form of definitive external fixation. We believe that for similar reasons, open fractures were more likely to be treated definitively with external fixation, as open injuries portended to more significant soft tissue compromise.

Although not found to be statistically significant, we observed a much higher proportion of patients with deep infection had been treated with ORIF alone (66.7%), in contrast to external fixation alone (20%) and hybrid fixation (13.3%). If our sample size had been larger, we may have found a statistical difference, but it appears necessary to highlight this difference nevertheless.

We recognize that our study has several limitations. First, the retrospective nature of the study limits the extent to which we can make conclusions from our results. Second, our study lacks a detailed profile of outcomes of fractures, as we did not perform objective measures or surveys to assess functionality and long-term follow-up. Finally, our small sample size limits the power of our study and the potential to make sound conclusions. Our study, however, is the first to describe the complexity in treatment of tibial plafond fractures among the combat-wounded population. Further studies are needed to make definitive recommendations with regard to these injuries.

REFERENCES

1. U.S. Department of Defense. DefenseLINK US Casualty Status 2011. http://www.defense.gov/news/casualty.pdf. Accessed April 2013.
2. Belmont PJ, Schoenfeld AJ, Goodman G. Epidemiology of combat wounds in Operation Iraqi Freedom and Operation Enduring Freedom: orthopaedic burden of disease. *J Surg Orthop Adv*. 2010;19;2-7.
3. Cross JD, Ficke JR, Hsu JR, Masini BD, Wenke JC. Battlefield orthopaedic injuries cause the majority of long-term disabilities. *J Am Acad Orthop Surg*. 2011;19 Suppl 1:S1-S7.
4. Mabry RL, Holcomb JB, Baker AM, et al. United States Army Rangers in Somalia: an analysis of combat casualties on an urban battlefield. *J Trauma*. 2000 Sep;49(3):515-529.
5. Cross JD, Stinner DJ, Burns TC, Wenke JC, Hsu JR. Return to duty after type III open tibia fracture. *J Orthop Trauma*. 2012 Jan;26(1):43-47. doi: 10.1097/BOT.0b013e31821c0ec1.
6. Huh J, Stinner DJ, Burns TC, Hsu JR. Infectious complications and soft tissue injury contribute to late amputation after severe lower extremity trauma. *J Trauma*. 2011 Jul;71(1 Suppl):S47-S51. doi: 10.1097/TA.0b013e318221181d.
7. Pollak AN, Ficke JR. Extremity war injuries: challenges in definitive reconstruction. *J Am Acad Orthop Surg*. 2008;16:628-634.
8. Mack AW, Groth AT, Frisch HM, Doukas WC. Treatment of open periarticular shoulder fractures sustained in combat-related injuries. *Am J Orthop* (Belle Mead, NJ). 2008;37:130-135.
9. Gustilo RB, Anderson JT. Prevention of infection in the treatment of one thousand and twenty-five open fractures of long bones: retrospective and prospective analyses. *J Bone Joint Surg Am*. 1976;58:453-458.

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10. Gustilo RB, Mendoza RM, Williams DN. Problems in the management of type III (severe) open fractures: a new classification of type III open fractures. *J Trauma*. 1984;24:742-746.
11. Belmont PJ Jr, Goodman GP, Zacchilli M, Posner M, Evans C, Owens BD. Incidence and epidemiology of combat injuries sustained during "the surge" portion of operation Iraqi Freedom by a U.S. Army brigade combat team. *J Trauma*. 2010 Jan;68(1):204-210. doi: 10.1097/TA.0b013e3181bdcf95.
12. Owens BD, Kragh JF Jr, Macaitis J, Svoboda SJ, Wenke JC. Characterization of extremity wounds in Operation Iraqi Freedom and Operation Enduring Freedom. *J Orthop Trauma*. 2007;21:254-257. doi:10.1097/BOT.0b013e31802f7 8fb.
13. Owens BD, Kragh JF Jr, Wenke JC, Macaitis J, Wade CE, Holcomb JB. Combat wounds in operation Iraqi Freedom and operation Enduring Freedom. *J Trauma*. 2008;64:295-299. doi:10.1097/TA.0b013e318163b875.
14. Sirkin M, Sanders R. The treatment of pilon fractures. *Orthop Clin North Am*. 2001;32:91-102.
15. Sirkin M, Sanders R, DiPasquale T, Herscovici D Jr. A staged protocol for soft tissue management in the treatment of complex pilon fractures. *J Orthop Trauma*. 2004;18:S32-S38.
16. Conroy J, Agarwal M, Giannoudis PV, Matthews SJ. Early internal fixation and soft tissue cover of severe open tibial pilon fractures. *Int Orthop*. 2003;27:343-347. doi:10.1007/s00264-003-0486-1.
17. Boraiah S, Kemp TJ, Erwteman A, Lucas PA, Asprinio DE. Outcome following open reduction and internal fixation of open pilon fractures. *J Bone Joint Surg Am*. 2010;92:346-352. doi:10.2106/JBJS.H.01678.
18. Dickens JF, Kilcoyne KG, Kluk MW, Gordon WT, Shawen SB, Potter BK. Risk factors for infection and amputation following open, combat-related calcaneal fractures. *J Bone Joint Surg Am*. 2013;95:e241-e248. doi:10.2106/JBJS.L.00003.
19. Andersen RC, Fleming M, Forsberg JA, et al. Dismounted complex blast injury. *J Surg Orthop Adv*. 2012 Spring;21(1):2-7.
20. Ruedi T. Fractures of the lower end of the tibia into the ankle joint: results 9 years after open reduction and internal fixation. *Injury*. 1973;5:130-134.
21. Jergesen F. Open reduction of fractures and dislocations of the ankle. *Am J Surg*. 1959;98:136-151.
22. Anglen JO. Early outcome of hybrid external fixation for fracture of the distal tibia. *J Orthop Trauma*. 1999;13:92-97.
23. Ayeni JP. Pilon fractures of the tibia: a study based on 19 cases. *Injury*. 1988;19:109-114.
24. Bone L, Stegemann P, McNamara K, Seibel R. External fixation of severely comminuted and open tibial pilon fractures. *Clin Orthop Rel Res*. 1993;101-107.
25. Brumback RJ, McGarvey WC. Fractures of the tibial plafond. Evolving treatment concepts for the pilon fracture. *Orthop Clin North Am*. 1995;26:273-285.
26. Kellam JF, Waddell JP. Fractures of the distal tibial metaphysis with intra-articular extension--the distal tibial explosion fracture. *J Trauma*. 1979;19:593-601.
27. Patterson MJ, Cole JD. Two-staged delayed open reduction and internal fixation of severe pilon fractures. *J Orthop Trauma*. 1999;13:85-91.
28. Tornetta P 3rd, Weiner L, Bergman M, et al. Pilon fractures: treatment with combined internal and external fixation. *J Orthop Trauma*. 1993;7:489-496.

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Reported Concussion Rates for Three Division I Football Programs: an Evaluation of New NCAA Concussion Policy

[1]MAJ Kelly G. Kilcoyne, MD; [2]MAJ Jonathan F. Dickens, MD; [3]LTC Steven J. Svoboda, MD; [3]LTC Brett D. Owens, MD; [4]LTC Robert T. Sullivan, MD; [5]CDR John-Paul Rue, MD

INTRODUCTION

Concussions are common injuries in young athletes, but the diagnosis and treatment remains a challenge.[1,2] On April 29, 2010 the NCAA released a new concussion management plan which provided a best practices model for concussion treatment. The purpose of this study is to determine the number of concussions that occurred on three collegiate Division I football teams during the two most recent seasons, 2009-2010 and 2010-2011, in order to compare the incidence of concussion before and after the implementation of these new policies. We hypothesized that the number of reported concussions and concussion rate would be consistent among the three teams, and from season to season.

MATERIALS AND METHODS

Injury surveillance reports were reviewed for three NCAA Division I football teams: the United States Military Academy, the United States Naval Academy, and the United States Air Force Academy. All subjects included in the study were males between the ages of 18 to 22, who were on the varsity football roster at their respective institution for the 2009-2010 season and/or the 2010-2011 season.

Regardless of institution, and in accordance with the NCAA Injury Surveillance System definition of a reportable injury, a concussion was defined as an injury that occurred as a result of participation in organized intercollegiate practice or competition that required medical attention by a team certified athletic trainer or physician that resulted in restriction of student athlete play for one or more calendar day after injury, and was documented in the injury report by the athletic trainer as a concussion.[3]

The primary outcome of interest in the current study was the annual incidence rate of concussion injuries per 1,000 athlete-exposures during the study period. Incidence rates are calculated by dividing the total number of injuries observed in a population by a measure of exposure or person-time at risk to injury.[4] The annual incidence rates of concussion for the 2009-2010 and 2010-2011 seasons were calculated, along with the 95% confidence intervals, by dividing the total number of concussions by the total number of athlete-exposures and multiplying by 1,000. The incidence rates for the 2009-2010 and 2010-2011 seasons were compared by calculating the incidence rate ratio and 95% confidence interval using the 2009-2010 season as the referent category. Similarly, we calculated the annual incidence rate with 95% confidence intervals for each team for the season prior to, and the season following implementation of the new NCAA concussion management policy. The incidence rates for the 2009-2010 and 2010-2011 seasons were also compared within each team by calculating the incidence rate ratio and 95% confidence interval using the 2009-2010 season as the referent category. All statistical analyses were completed using STATA/SE software version 10.1 (StataCorp, College Station, TX).

[1]Walter Reed National Military Medical Center, Bethesda, MD; [2]Walter Reed National Military Medical Center; Washington, DC; [3]Keller Army Hospital, West Point, NY; [4]Eglin Hospital, Eglin Air Force Base, FL; [5]United States Naval Academy, Annapolis, MD. Address correspondence to: MAJ Kelly G. Kilcoyne, MD, Kelly.G.Kilcoyne.mil@health.mil.

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MAJ Kelly G. Kilcoyne, MD

MAJ Kilcoyne obtained his doctor of medicine degree at the University of Maryland on a health profession scholarship. He was selected for orthopaedic residency at Walter Reed Army Medical Center and is currently in his final year. During his residency MAJ Kilcoyne co-authored over 15 peer-reviewed articles and three book chapters and completed over 45 research presentations at national and local research meetings. His research interest has primarily focused on sports injuries, however, he has also co-authored articles or chapters on war-related injuries. In addition to several research grants, MAJ Kilcoyne's research projects have also won awards; he was a finalist for the Founders Award at the SOMOS annual meeting. He has been selected to complete a shoulder and elbow fellowship at The Johns Hopkins University upon graduation.

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RESULTS

The incidence rate and number of reported concussions increased at each institution from the 2009-2010 season to the 2010-2011 season after the implementation of the new NCAA concussion management policy. Overall, the incidence rate across all three institutions studied was two times higher in 2010-2011, when compared to 2009-2010 (IRR 2.04, 95% CI: 1.20, 3.55, $p = 0.005$). Similar increases were observed across all three institutions when they were examined independently.

DISCUSSION

The combined incidence rate of reported concussions from three Division I football programs for the 2010-2011 season doubled from the previous season after the implementation of new NCAA policies on concussion management. The two-fold increase in the combined concussion incidence rate between the two consecutive seasons is striking. While the institution of a more formalized concussion plan on the part of medical staff is one possible factor, the largest difference may have been from previous under-recognition and under-reporting on the part of players and coaches prior to the new policy. Additional studies are needed to determine the true incidence of concussions in Division I football as awareness continues to increase among healthcare professionals, coaches, and athletes. Furthermore, as similar policies are implemented across the United States, systematic evaluations are needed to assess fully whether these policy changes are reducing the impact of concussion among athletes.

REFERENCES

1. Booher MA, Wisniewski J, Smith BW, Sigurdsson A. Comparison of reporting systems to determine concussion incidence in NCAA Division I collegiate football. *Clin J Sport Med.* Clin J Sport Med. 2003 Mar;13(2):93-95.
2. Standaert CJ, Herring SA, Cantu RC. Expert opinion and controversies in sports and musculoskeletal medicine: concussion in the young athlete. *Arch Phys Med Rehabil*. 2007 Aug;88(8):1077-1079.
3. Cantu RC. Chronic traumatic encephalopathy in the National Football League. *Neurosurgery*. 2007 Aug;61(2):223-225.
4. Knowles SB, Marshall SW, Guskiewicz KM. Issues in estimating risks and rates in sports injury research. J Athl Train. 2006 Apr-Jun;41(2):207-215.

ADDITIONAL REFERENCES

Aubry M, Cantu R, Dvorak J, et al. Summary and agreement statement of the First International Conference on Concussion in Sport, Vienna 2001. Recommendations for the improvement of safety and health of athletes who may suffer concussive injuries. *Br J Sports Med*. 2002 Feb;36(1):6-10.

Cantu RC, Aubry M, Dvorak J, et al. Overview of concussion consensus statements since 2000. *Neurosurg Focus*. 2006 Oct 15;21(4):E3.

Dick R, Ferrara MS, Agel J, et al. Descriptive epidemiology of collegiate men's football injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train*. 2007 Apr-Jun;42(2):221-233.

Dunkle D. Concussion Management Plan. *Memorandum: National Collegiate Athletic Association*. 2010:1-5.

Ellenbogen RG, Berger MS, Batjer HH. The National Football League and concussion: leading a culture change in contact sports. World Neurosurg. 2010 Dec;74(6):560-565.

Gessel LM, Fields SK, Collins CL, Dick RW, Comstock RD. Concussions among United States high school and collegiate athletes. *J Athl Train*. 2007;42(4):495-503.

Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train.* 2007;42(4):311-319.

Klossner D. Concussion or Mild Traumatic Brain Injury in the Athlete. NCAA Sports Medicine Handbook. 2009-2010: 52-55.

Klossner D. Concussion or Mild Traumatic Brain Injury in the Athlete. NCAA Sports Medicine Handbook. 2010-2011.

Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil*. 2006;21(5):375-378.

McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA.* 2003;290(19):2556-2563.

McCrory P, Johnston K, Meeuwisse W, et al. Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. Br J Sports Med. 2005;39(4):196-204.

McCrory P, Meeuwisse W, Johnston K *et al*. (2009) Consensus statement on concussion in sport: the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. *J Athl Train*. 2009;44(4):434-448.

The N.C.A.A. re-evaluating concussion rules. *The New York Times*. 15 Dec 2009.

Thurman DJ, Branche CM, Sniezek JE. The epidemiology of sports-related traumatic brain injuries in the United States: recent developments. *J Head Trauma Rehabil.* 1998;13(2):1-8.

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BMP Regulation of Mesenchymal Progenitor Cells in Regenerating Muscle Tissue

[1,2]CPT Matthew W. Kluk, MD, MC, USA; [2]Youngmi Ji, PhD; [2]Orna Amrani, MD; [2]Wesly M. Jackson PhD; [1,2]LTC Leon J. Nesti, MD, PhD, MC, USA

INTRODUCTION

Post-traumatic heterotopic ossification (HO) is condition characterized by ectopic bone formation during muscle regeneration that occurs following orthopaedic injury. However, traumatic HO occurs much more frequently in patients who have experienced high-energy extremity injury and polytrauma. More than 60% of patients who sustained extremity blast-related trauma during Operation Enduring Freedom and Operation Iraqi Freedom were diagnosed with HO within one year of their injuries.[1] Ectopic bone formation can lead to impaired prosthetic fitting, skin breakdown, decreased joint range of motion, and painful joint range of motion, leading to significant morbidity to the men and women of our armed forces. Given the high incidence of this disease in the war-wounded population, there is a substantial need to characterize the microenvironment of the injured muscle tissue to identify factors that may be dysregulating the process of regeneration and to propose new treatment options that will minimize the formation of ectopic bone. The roles of bone morphogenetic proteins (BMPs) are of particular interest, as they have recently been associated with a variety of functions in healthy and injured muscle tissue,[2,3] and are also capable of inducing osteogenic differentiation.

Our laboratory has previously identified a population of multipotent mesenchymal progenitor cells (MPCs) that are present in regenerating muscle tissue after high-energy trauma.[4] Although these cells are capable of osteogenic differentiation, they also perform many of the functions that are characteristic of bone marrow-derived mesenchymal stem cells, specifically, promoting tissue regeneration by enhancing angiogenesis, regulating fibrogenesis, and modulating inflammation.[5] The effect of BMPs secreted by the traumatized muscle tissue on MPC function and the precise role of these cells in ectopic bone formation is unknown. Therefore, the goal of this study is to better define the interactions between MPCs and the BMPs that are present in the traumatized muscle tissue environment. Our overall hypothesis was that the BMPs dysregulate the pro-regeneration functions of the MPCs to promote pathological wound healing over muscle regeneration. We propose the following specific aims:

1) To compare the gene- and protein-level expression of BMPs that were expressed in the traumatized and uninjured muscle tissue.

2) To determine the effect of the secreted BMPs on the anti-fibrotic properties of the traumatized muscle-derived MPCs.

[1]Department of Orthopaedics and Rehabilitation, Walter Reed Army Medical Center, Washington, DC; [2]Clinical and Experimental Orthopaedics Laboratory, National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health, Bethesda, MD. Address correspondence to: leonnesti@gmail.com.

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METHODS

Muscle samples were obtained from the zone of injury following blast trauma according to an IRB-approved protocol. Control muscle tissue was obtained from patients undergoing elective orthopaedic anterior cruciate ligament reconstruction with hamstrings autograft. After the tendons were harvested with a tendon stripper, the remaining muscle on the tendon was removed. Muscle fragments approximately 0.2 cc in volume were taken from all control and traumatized muscle samples. One fragment was homogenized to determine the BMP gene expression with qPCR. Protein-level measurements of BMP were determined using the other fragments by determining their wet-weight and placing them in 12-well transwell plates containing 2 ml of growth medium (DMEM supplemented with 10% fetal bovine serum and 1% penicillin and

CPT Matthew W. Kluk, MD, MC, USA

While CPT Kluk attended Quince Orchard High School in Gaithersburg, MD he achieved the rank of Eagle Scout in the Boy Scouts of America. After graduating he attended Virginia Military Institute on an athletic scholarship. Following graduation, he accepted the Armed Forces Health Profession Scholarship and was commissioned into the United States Army. He obtained his doctor of medicine degree at the Virginia Commonwealth University School of Medicine. CPT Kluk was selected for orthopaedic residency at Walter Reed Army Medical Center and is currently in his fourth year. During his research fellowship he concentrated on the mechanisms of heterotopic ossification at the National Institutes of Health. He plans to complete an orthopaedic traumatology fellowship.

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streptomycin). The growth medium was collected every three days, and the concentration of BMP-2, -4 and -6 was measured in the collected medium with ELISAs (R&D Systems).

MPCs were harvested from the debrided muscle samples by following a previously described protocol.[4] The protocol for extracting muscle-derived multiprogenitor cells was based on a modification of previous work in isolating mesenchymal stem cells that was performed in our laboratory. Fat, fascia, other connective tissue, and necrotic tissue were dissected away from the healthy margin of the debrided muscle sample. Approximately 0.2 cc of the remaining muscle tissue was processed for cell extraction. The tissue was washed three times in Hanks' Balanced Salt Solution (Gibco, Carlsbad, California) and then was extensively minced in a 10-cm culture dish containing Dulbecco's Modified Eagle Medium (Gibco) and 3· penicillin/streptomycin/Fungizone (Gibco) until it could pass through the tip of a 25-mL serological pipette (Falcon; BD Biosciences, San Jose, California). The minced tissue was transferred to a 50-mL conical vial with digestion medium containing Dulbecco's Modified Eagle Medium, 3· penicillin/streptomycin/Fungizone, and 0.5 mg/mL collagenase type 2 (Worthington Biochemical, Lakewood, New Jersey). The tissue slurry was agitated gently at 37° C for two hours, and the resulting digest was filtered through a 40-mm cell strainer (Falcon), pelleted by means of centrifugation, resuspended in growth medium (Dulbecco's Modified Eagle Medium with 10% fetal bovine serum; Gibco) and 5· penicillin/streptomycin/Fungizone, and then plated onto tissue culture polystyrene (150-cm^2 flask; Falcon). The cells were incubated at 37° C in a 5% CO2-humidified cell incubator for two hours and then were extensively washed with Hanks' Balanced Salt Solution before fresh growth medium was added with 3· penicillin/streptomycin/Fungizone. Once multiprogenitor cell colony forming units were observed, the concentration of penicillin/streptomycin/Fungizone was lowered to 1·. Cell confluence was obtained after approximately two weeks. The cell cultures were routinely passaged at 80% to 90% confluence and split 1:4.

The cells were seeded in 12-well plates in growth medium (Dulbecco's Modified Eagle Medium with 10% fetal bovine serum; Gibco) and 5· penicillin/streptomycin/Fungizone, allowed to adhere overnight, and then treated with either BMP-4 over the range of concentrations that was observed during the BMP release kinetics experiment. The cell supernatants were collected after 72 hours and one week. These time points were chosen because they correlated with the largest spike in concentration of BMP-4 in the original explant data. The supernatant was stored in a -80° C freezer. The effect of the BMPs on the ability of MPCs to regulate fibrogenesis was assayed by measuring the concentration of matrix metalloproteinease-1 (MMP-1) in the cell supernatants with ELISA (DuoSet ELISA Development System, R&D Systems).

MPCs isolated from traumatized muscle tissue were exposed to BMP-4 in concentrations of 5 ng/ml, 50 ng/ml, and 200 ng/ml in growth medium. Quantitative real-time polymerase chain reaction (qRT-PCR) was preformed on cells exposed to BMP-4 using an RT^2 profiler PCR array for the human osteogenisis pathway. The MPCs were exposed to BMP-4 for a total of seven days and then lysed with Trizol. RNA was extracted using the RNeasy Minikit, and RNA quality was assessed using the ND 1000 Nanodrop Spectrophotometer prior to performing the qRT-PCR assay.

RESULTS

We measured substantial gene-level expression of BMP-2, BMP-4, BMP-5 and BMP-6 in control muscle. The gene expression of BMP-2 and BMP-4 was significantly lower in the traumatized muscle tissue ($p < 0.015$, Student's *t*-tests), and this was contrary to what we initially expected. Protein-level expression of BMP peaked at one week in culture, but was detected in the explant supernatants for up to 21 days, as determined by ELISA, indicating that BMP-4 is expressed by muscle and its surrounding microenvironment as it degenerates, despite decreased translation. We also measured a significant increase in the amount of MMP-1 expressed by the MPCs that were cultured with BMP-4 at concentrations of 50 ng/ml and 200 ng/ml ($p < 0.05$, Repeated Measures ANOVA with n = 3. Cartilage oligomeric matrix protein (COMP) was significantly up-regulated in cells exposed to 200 ng of BMP 4 for seven days when compared with controls ($p < 0.05$). Conversely, tumor necrosis factor (TNF) was significantly down-regulated in cells exposed to 200 ng of BMP 4 for seven days when compared to controls ($p < 0.05$), as measured by PCR.

DISCUSSION

It is unclear whether traumatized muscle-derived MPCs have a direct or an indirect role in the formation of ectopic bone following high-energy extremity injury. The MPCs are capable of osteogenic induction; although other wound healing cells have also been implicated in the formation of HO. MPCs which have a potent response to BMPs in vitro do not have the same robust response in vivo. However, cells expressing vascular endothelial markers do contribute to the generation of a fibroproliferative, chondrogenic, and ossification in the fibrodysplasia ossificans progressiva (FOP) model.[6] Alternatively, the MPCs may also play an indirect role in promoting HO formation by changing the biochemical microenvironment to favor fibrosis and ectopic osteogenesis over muscle regeneration.

BMP-4 gene expression is down-regulated in response to injury, which was contrary to our original hypothesis. There is a significant amount of data from the literature regarding FOP, a congenital disorder leading to ectopic bone formation, indicating that BMP-4 is dysregulated.[11,12] Specifically, the negative feedback loop normally present in BMP-4 signaling is dysregulated, leading to a hyperresponsiveness to ligand exposure.[13] We therefore continued to investigate protein expression with ELISA data for BMP 4, and there was an increase in BMP-4 accumulation in the explant. BMP-4 could be released from the extracellular matrix during the early remodeling stages of wound healing. BMP-4 has previously been shown to promote anti-fibrotic muscle regeneration by down-regulation of TGF-β1 and up-regulation of MMPs.[7] We found that increased BMP concentration resulted in a corresponding increase in MMP-1 concentration, which is an extracellular matrix protein essential in matrix remodeling in wound healing and decreased fibrosis.[8] These results indicate that MPCs may contribute to local wound healing, even when exposed to BMP-4. However, chronic exposure to BMP-4 may have deleterious effects.

Additionally, when MPCs were exposed to BMP-4, there were significant changes in the osteogenic gene expression profile. BMP-4 exposure led to an up-regulation of COMP expression. COMP is an extracellular matrix calcium binding protein found in cartilage and is essential for normal endochondral ossification and longitudinal development of the physis. COMP mutations are associated with several

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different growth abnormalities resulting in rhizomelic shortening, including multiple epiphyseal dysplasia and pseudoachondroplasia.[9] There was also a significant decrease in TNF. BMP-4 has previously been shown to have an anti-apoptotic effect on mesenchymal pluripotent cells via a suppression of TNF-mediated apoptosis,[10] indicating that the BMP-4 found in traumatized muscle tissue may exert a protective effect on the MPCs resident in the tissue.

Our results suggest that there may be a window following injury, during which functional muscle regeneration is promoted via BMP-4 release from the muscle tissue. In cases of severe injury, the initial stress response is exaggerated, leading to a longer period of time when MPCs are present in the wound bed. In this setting of prolonged or amplified muscle regeneration, MPCs may also survive longer via the anti-apoptotic effect of BMP-4; the regenerative response may shift to form fibrotic tissue. This, in turn, generates an environment with the up-regulation of COMP that is susceptible to HO formation.

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REFERENCES

1. Potter BK, Burns TC, Lacap AP, Granville, RR, Gajewski DA. Heterotopic ossification following traumatic and combat-related amputations. Prevalence, risk factors, and preliminary results of excision. *J Bone Joint Surg Am*. 2007 Mar;89(3):476-486.
2. Frank NY, Kho AT, Schatton T, et al. Regulation of myogenic progenitor proliferation in human fetal skeletal muscle by BMP4 and its antagonist Gremlin. *J Cell Biol.* 2006 Oct 9;175(1):99-110.
3. Clever JL, Sakai Y, Wang RA, Schneider DB. Inefficient skeletal muscle repair in inhibitor of differentiation knockout mice suggests a crucial role for BMP signaling during adult muscle regeneration. *Am J Physiol Cell Physiol.* 2010 May;298(5):C1087-1099.
4. Nesti LJ, Jackson WM, Shanti RM, et al. Differentiation potential of multipotent progenitor cells derived from war-traumatized muscle tissue. *J Bone Joint Surg Am.* 2008 Nov;90(11):2390-2398.
5. Jackson WM, Lozito TP, Djouad F, Tuan RS, Nesti LJ. Pro-regenerative functions of mesenchymal progenitor cells derived from traumatically injured muscle. Poster No. 733. Presented at the 56th Annual Meeting of the Orthopaedic Research Society. New Orleans, LA, 2010.
6. Lounev VY, Ramachandran R, Wosczyna MN, et al. Identification of progenitor cells that contribute to heterotopic skeletogenesis. *J Bone Joint Surg Am.* 2009 Mar 1;91(3):652-653.
7. Pegorier S, Campbell GA, Kay AB, Lloyd CM. Bone morphogenetic protein (BMP)-4 and BMP-7 regulate differentially transforming growth factor (TGF)-beta1 in normal human lung fibroblasts (NHLF). *Respir Res.* 2010 Jun 23;11:85.
8. Goffin L, Seguin-Estevez Q, Alvarez M, Reith W, Chizzolini C. Transcriptional regulation of matrix metalloproteinase-1 and collagen 1A2 explains the anti-fibrotic effect exerted by proteasome inhibition in human dermal fibroblasts. *Arthritis Res Ther.* 2010;12(2):R73.
9. Ballock RT, O'Keefe RH. The biology of the growth plate. *J Bone Joint Surg Am.* 2003 Apr;85-A(4):715-726.
10. Chen S, Guttridge DC, Tang E, Shi S, Guan K, Wang CY. Suppression of tumor necrosis factor-mediated apoptosis by nuclear factor kappaB-independent bone morphogenetic protein/Smad signaling. *J Biol Chem*. 2001 Oct 19;276(42):39259-39263.
11. Jackson WM, Nesti LJ, Tuan RS. Potential therapeutic applications of muscle-derived mesenchymal stem and progenitor cells. *Expert Opin Biol Ther*. 2010;10:505-517.
12. Billings PC, Fiori JL, Bentwood JL, et al. Dysregulated BMP signaling and enhanced osteogenic differentiation of connective tissue progenitor cells from patients with fibrodysplasia ossificans progressiva (FOP). *J Bone Miner Res*. 2008;23:305-313.
13. Kaplan FS, Fiori J, Serrano de la Pena L, et al. Dysregulation of the BMP-4 signaling pathway in fibrodysplasia ossificans progressiva. *Ann N Y Acad Sci*. 2006;1068:54-65.

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Application of the Orthoplastic Reconstructive Ladder to Preserve Lower Extremity Amputation Length

[1,2]CDR Mark E. Fleming, MC, USN; [1,2]LCDR J. Anthony O'Daniel, MC, USN; [1]CPT Husain Bharmal, MC, USA; [2,3]LCDR Ian Valerio, MC, USN

INTRODUCTION

Since the Global War on Terror commenced in 2001, over 1,200 U.S. service members have sustained in excess of 1,600 amputations.[1] A primary goal in lower extremity amputation management is limb length preservation and the maintenance of viable joints.[2] Energy expenditure during ambulation directly correlates with residual limb length, preservation of functional segments, and preservation of a stable joint.[3,4] These tenants directly contribute to the resumption of a more normal gait pattern, increased functional capacity, and decreased energy expenditure.[5] The ability to preserve limb length, functional segments, and joints is significantly dependent on achieving soft tissue coverage. The reconstructive ladder serves as a guide for surgeons to employ the best possible tactic based on the soft tissue defect.[6]

The aim of this paper is to illustrate through case reports the application of the reconstructive ladder for preserving residual limb length in lower extremity traumatic amputations. Modalities employed to achieve soft tissue coverage for preservation of limb length are presented. Concepts from the reconstructive ladder[7] were utilized to determine the optimal method for achieving soft tissue coverage and thus preserving amputation residual length.

CASE 1

A U.S. soldier injured by an improvised explosive device (IED) blast sustained multisystem trauma, including a traumatic transtibial amputation (Figure 1). The level of bony amputation was distal to the tibia tubercle and the knee extensor mechanism was intact. However, the zone of soft tissue injury extended well above the knee joint. There was inadequate soft tissue to achieve primary closure, to perform an effective myodesis or myoplasty, or to provide a well-padded residual limb. Treatment options included revising the amputation to a knee disarticulation or a transfemoral amputation. To preserve length, limb segment, and a functional joint, the patient underwent soft tissue coverage with a latissimus free flap, followed by split thickness skin coverage. The patient progressed to ambulation with a functional below-knee amputation without assist devices.

[1]Department of Orthopaedics, Walter Reed National Military Medical Center, Washington, DC; [2]Uniformed Services University of the Health Sciences, Bethesda, MD; [3]Plastic and Reconstructive Service, Walter Reed National Military Medical Center, Washington, DC.

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CASE 2

ACell (ACell, Inc, Columbia, MD) is a porcine-derived biomatrix scaffold that assists in tissue regeneration. In this case, ACell was employed to regenerate granulation tissue over avascular retinaculum and patellar ligament. Once adequate granulation tissue developed, it was amenable for split thickness skin grafting (STSG). This patient, who additionally sustained significant soft tissue injuries to his left lower extremity and bilateral upper extremities, is currently able to ambulate on his below-knee prosthesis without assist devices.

LCDR Joseph Anthony O'Daniel, MD

LCDR O'Daniel graduated with merit from the U.S. Naval Academy in 1996. Upon graduation, he served for five years as a surface warfare officer, stationed in Sasebo, Japan and Virginia Beach, VA. In 2001, he took a health professions scholarship and returned home to attend the University of Louisville School of Medicine. After graduating in 2005, he did his internship at Bethesda National Naval Medical Center and then served as the Battalion Surgeon for Naval Mobile Construction Battalion (NMCB) One in Gulfport, MS for two years. While there, NMCB One deployed to Okinawa, Japan for six months and then to Camp Ramadi, Iraq for seven months. LCDR O'Daniel returned for his orthopaedic residency at Walter Reed Bethesda from 2008 through June 2013. Upon graduation, he and his wife Andrea have received orders to Great Lakes Naval Station just north of Chicago, IL.

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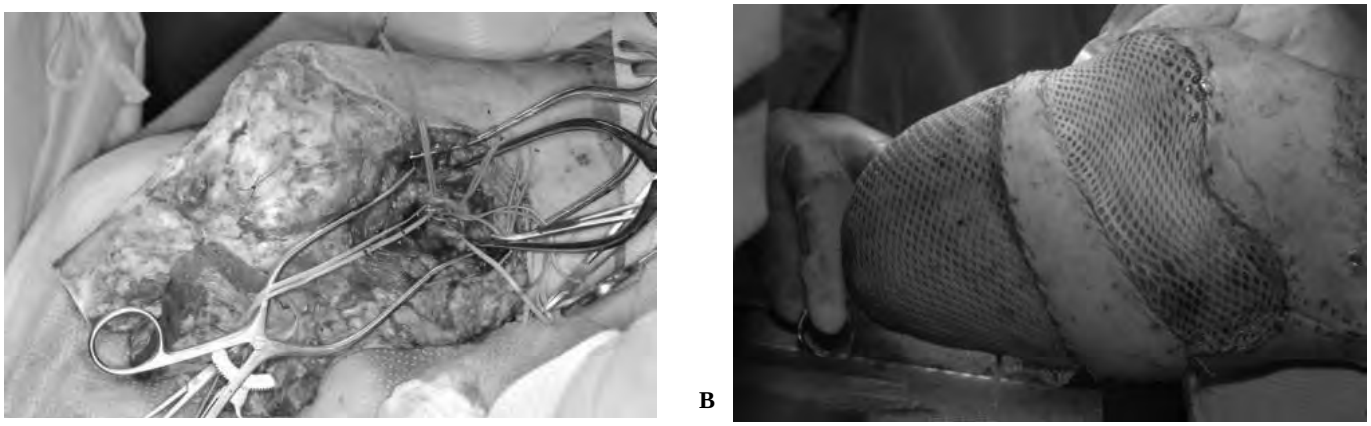

Figure 1. (**A**) Use of free flaps and skin grafting. This wounded soldier sustained a traumatic below-knee amputation with significant soft tissue loss about his right knee and residual proximal tibia from a blast injury. (**B**) A latissimus free flap allowed coverage over the distal tibia, with split thickness skin grafting, as seen here.

DISCUSSION

The preservation of residual limb length in lower extremity amputations is critical to optimize prosthetic fitting and to allow maximal function for ambulation. Although intuitive, a longer limb, preservation of joints, and more distal segments allow for decreased energy requirements when ambulating. As described by Waters, et al., amputees use a significantly higher energy requirement with a transfemoral versus a transtibial amputation.[3]

With respect to mangled extremity trauma, the soft tissue envelope is the greatest deciding factor for limb salvage versus amputation[8] and soft tissue availability often determines amputation salvage level. A goal in amputation surgery is the provision of a well padded durable surface for prosthetic fitting. Careful handling and preservation of all available soft tissue is critical. However, it is also important to keep in mind that muscle balancing is critical in order to preserve a functional residual limb. Often, soft tissue coverage can only be achieved by significant shortening of the residual bone. In this regard, salvage of limb length can be accomplished utilizing the same reconstruction principles for salvage of an intact limb.

Multiple authors, including Levin, have described the reconstructive ladder principal whereby soft tissue reconstruction begins at the lowest possible rung and advances upward based on the need and degree of soft tissue injury.[9-11] This traditional ladder approach includes techniques such as local wound care, primary closure, skin grafting, local skin flaps, pedicles flaps, and up to utilization of a free flap for soft tissue coverage. More recently, we are employing so-called hybrid reconstruction (Figure 2), whereby we are utilizing regenerative medicine modalities in the management of composite tissue loss. These include the use of dermal regenerative templates such as Integra (Integra LifeSciences, Plainsboro, NJ), external tissue expanders such as Dermaclose (Wound Care Technology, Chanhassen, MN), extra-cellular matrices such as ACell, local rotation flaps, and free tissue transfer to achieve a functional residual limb. This also entails proceeding directly to free flap, if necessary, as soon as wounds allow, skipping many or all lower rungs of the traditional reconstructive ladder (Figure 3). Regenerative medicine therapies offer significant enhancements to traditional coverage methods, such as extending the indications for a particular rung on the ladder.

In addition to regenerative medicine modalities, we've additionally incorporated nanotechnology into amputation wound management. We frequently employ dressings which release nanocrytalline silver crystals which can eradicate bacteria.[12] Studies suggest that this technology alters wound inflammatory events and facilitates the early phase of wound healing.[13] We strive for amputated limb length salvage for today's Wounded Warriors with the end-state in mind of enhancing their performance 30 to 40 years from now, when a 25% to 65% increase in energy expenditure above baseline means a mobile versus wheelchair-dependent 60-year-old.

We use an abundant amount of Integra (originally designed for burn management), which is a bilayer matrix wound dressing consisting of cross-linked bovine tendon collagen and glycosaminoglycan with a semi-permeable silicone layer that controls water vapor loss, provides a flexible adherent covering, allows increased sheer strength, and appears to biodegrade for cell and capillary ingrowth.[14] The dressing is typically

Figure 2. The hybrid reconstructive ladder employs techniques such as dermal regenerative templates, external tissue expanders, extracellular matrices, and nerve conduits to achieve the most functional residual limb.

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Figure 3. The hybrid reconstructive ladder express. The complex wound care demanded by today's high energy amputations may require skipping some or all lower rungs of the traditional reconstructive ladder and proceeding directly to the highest levels of limb salvage, including pedicle or free flaps combined with newer regenerative medicine therapies.

utilized in conjunction with negative pressure wound therapy (NPWT) and is followed by an ultra-thin STSG (12 micrometers) at approximately two to three weeks. The dermal substitute effectively recreates adequate subcutaneous tissue to allow for gliding or movement of the skin over the muscle and it has been objectively demonstrated that the elastic properties of areas treated with Integra are comparable to normal skin.[15]

There have been several case reports describing the use of NPWT to granulate areas of soft tissue loss such as over tendons and fascia. An adjunct to NPWT that we have employed is the use of porcine urinary bladder matrix as a biologic scaffold. This biologic scaffold attracts adult stem cells[16] to the site of injury and converts them into active progenitor cells.[17] It also sets up non-crosslinked temporary scaffolding for tissue reconstruction, mimicking surrounding healthy tissue.[18] This scaffolding maintains an intact epithelial basement membrane[19] and typically results in a robust bed of granulation tissue. STSG would have likely failed if applied directly to the retinaculum and patella ligament (Figure 4). In this case, 100% take of the STSG was achieved.

Several authors have described the use of free or rotational flaps to facilitate lower extremity amputation length salvage.[20-23] Although the latissimus free flap has been the most frequently reported, other microvascular techniques have included use of an anteroloateral thigh fasciocutaneous flap[24] and parascapular flaps for transtibial amputation salvage. Kasabian, et al. published the largest series with 22 patients and were able to maintain a below-knee amputation in all patients.[20]

CONCLUSION

The preservation of residual limb length in lower extremity amputations is crucial to optimize prosthetic fitting for the amputee to allow for his or her recovering maximal function with ambulation. Applying principles of the reconstructive ladder may facilitate the achievement of soft tissue coverage, which is paramount in lower extremity amputees.

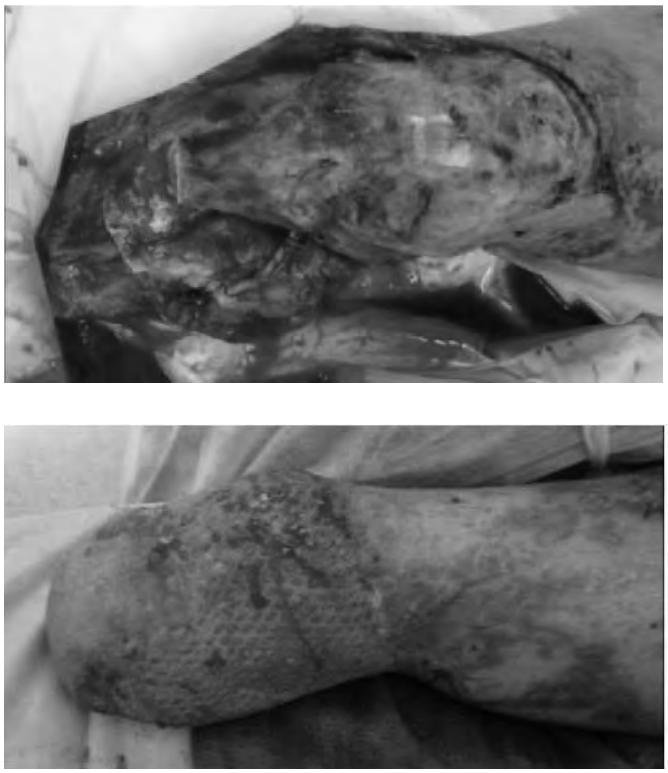

Figure 4. This patient, with significant soft tissue loss above a high below-knee amputation, underwent treatment with ACell followed by split thickness skin grafting.

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REFERENCES

1. Krueger CA, Wenke JC, Ficke JR. Ten years at war: comprehensive analysis of amputation trends. *J Trauma Acute Care Surg*. 2012 Dec;73(6 Suppl 5):S438-S444.
2. Ghali S, Harris PA, Khan U, Pearse M, Nanchahal J. Leg length preservation with pedicled fillet of foot flaps after traumatic amputations. *Plast Reconstr Surg*. 2005 Feb;115(2):498-505.
3. Waters RL, Perry J, Antonelli D, Hislop H. Energy cost of walking of amputees: the influence of level of amputation. *J Bone Joint Surg Am*. 1976 Jan;58(1):42-46.
4. Göktepe AS, Cakir B, Yilmaz B, Yazicioglu K. Energy expenditure of walking with prostheses: comparison of three amputation levels. *Prosthet Orthot Int*. 2010 Mar;34(1):31-36.
5. Gonzalez EG, Corcoran PJ, Reyes RL. Energy expenditure in below-knee amputees. *Arch Phys Med Rehabil*. 1974 Mar;55(3):111-119.
6. Levin LS. The reconstructive ladder. An orthoplastic approach. *Orthop Clin North Am*. 1993 Jul;24(3):393-409.
7. Janis JE, Kwon RK, Attinger CE. The new reconstructive ladder: modifications to the traditional model. *Plast Reconstr Surg*. 2011 Jan;127 Suppl 1:205S-212S.
8. MacKenzie EJ, Bosse MJ, Kellam JF, et al. Factors influencing the decision to amputate or reconstruct after high-energy lower extremity trauma. *J Trauma*. 2002 Apr;52(4):641-649.
9. Tintle SM, Levin LS. The reconstructive microsurgery ladder in orthopaedics. *Injury*. 2013 Jan 24. doi:pii: S0020-1383(13)00018-1. 10.1016/j.injury.2013.01.006. [Epub ahead of print].
10. Knobloch K, Vogt PM. The reconstructive ladder in light of evidence-based medicine. *Plast Reconstr Surg*. 2011 Feb;127(2):1017-1018.
11. Giordano V, Napoli S, Quercioli F, Mori A, Dini M. The solar system model for the reconstructive ladder. *Plast Reconstr Surg*. 2011 Jul;128(1):336-337.
12. Leaper DJ. Silver dressings: their role in wound management. *Int Wound J*. 2006 Dec;3(4):282-294.
13. Fong J, Wood F. Nanocrystalline silver dressings in wound management: a review. *Int J Nanomedicine*. 2006;1(4):441-449.
14. Helgeson MD, Potter BK, Evans KN, Shawen SB. Bioartificial dermal substitute: a preliminary report on its use for the management of complex combat-related soft tissue wounds. *J Orthop Trauma*. 2007 Jul;21(6):394-399.
15. Nguyen DQ, Potokar TS, Price P. An objective long-term evaluation of Integra (a dermal skin substitute) and split thickness skin grafts, in acute burns and reconstructive surgery. *Burns*. 2010;36(1):23-28.
16. Reing JE, Zhang L, Myers-Irvin J, et al. Degradation products of extracellular matrix affect cell migration and proliferation. *Tissue Eng Part A*. 2009 Mar;15(3):605-614.
17. Beattie AJ, Gilbert TW, Guyot JP, Yates AJ, Badylak SF. Chemoattraction of progenitor cells by remodeling extracellular matrix scaffolds. *Tissue Eng Part A*. 2009 May;15(5):1119-1125.
18. Gilbert TW, Nieponice A, Spievack AR, Holcomb J, Gilbert S, Badylak SF. Repair of the thoracic wall with an extracellular matrix scaffold in a canine model. *J Surg Res*. 2008 Jun 1;147(1):61-67.
19. Brown B, Lindberg K, Reing J, Stolz DB, Badylak SF. The basement membrane component of biologic scaffolds derived from extracellular matrix. *Tissue Eng*. 2006 Mar;12(3):519-526.
20. Kasabian AK, Colen SR, Shaw WW, Pachter HL. The role of microvascular free flaps in salvaging below-knee amputation stumps: a review of 22 cases. *J Trauma*. 1991 Apr;31(4):495-500.
21. Tukiainen EJ, Saray A, Kuokkanen HO, Asko-Seljavaara SL. Salvage of major amputation stumps of the lower extremity with latissimus dorsi free flaps. *Scand J Plast Reconstr Surg Hand Surg*. 2002;36(2):85-90.
22. Kim YH, Youn S, Sung IH, Kim JT, Hwang KT. Latissimus dorsi flap coverage of soft tissue defect following below-knee amputation: emphasis on flap design and recipient vessels. *Eur J Orthop Surg Traumatol*. 2012 Jun 15. [Epub ahead of print]
23. Gallico GG 3rd, Ehrlichman RJ, Jupiter J, May JW Jr. Free flaps to preserve below-knee amputation stumps: long-term evaluation. *Plast Reconstr Surg*. 1987 Jun;79(6):871-878.
24. Yildirim S, Calikapan GT, Akoz T. Reliable option for reconstruction of amputation stumps: the free anterolateral thigh flap. *Microsurgery*. 2006;26(5):386-390.

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Heterotopic Ossification Resection after Open Peri-articular Combat-Related Elbow Fractures

LCDR(s) Kevin W. Wilson, MD, MC, USN; MAJ Jonathan F. Dickens, MD, MC; LCDR Reed Heckert, MD, MC, USN; LCDR Scott M. Tintle, MD, MC, USN; CDR(r) John J. Keeling, MD, MC, USN; COL Romney C. Andersen, MD, MC, USN; MAJ(P) Benjamin K. Potter, MD, MC, USA

INTRODUCTION

Heterotopic ossification (HO) can have devastating effects on achieving a successful outcome in the treatment of elbow trauma, resulting in prolonged rehabilitation and subsequent procedures to improve range of motion (ROM) lost to bone impingement and arthrofibrosis.[1] Surgical excision of heterotopic ossification to improve functional elbow ROM has been shown to be safe and effective among several published series of closed, civilian trauma.[2-9] Given that combat-related injuries are characterized by high energy blast and ballistic mechanisms, wide zones of injury, soft tissue loss, systemic inflammation from concomitant injuries, and high incidence of traumatic brain injury (TBI), it can be expected that combat-related peri-articular elbow injuries may represent the worst case scenario for HO development and elbow injury outcomes. Surgical treatment of elbow contracture secondary to heterotopic ossification in blast-injured elbows has not yet been evaluated in the literature, to our knowledge. The objective of this analysis is to review the outcomes of HO resection to improve ROM in combat-related, open, peri-articular elbow fractures complicated by heterotopic ossification.

METHODS

A retrospective review of open, peri-articular, combat-related elbow fractures treated at the National Naval Medical Center at Bethesda and Walter Reed Army Medical Center (now Walter Reed National Military Medical Center) was approved by the respective institutional review boards. Open, peri-articular elbow injuries were defined as open fracture within 5 cm of the radiocapitellar or ulnohumeral joints. Patients treated with upper extremity amputation within the first 24 hours of injury were excluded. A review of our institution's electronic surgical scheduling system revealed surgical treatment of 132 consecutive peri-articular injuries to the elbow in 128 combat-injured male patients treated at our facility between 2004 and 2011. Heterotopic ossification was defined as ectopic bone formation within the zone of injury after initial definitive management. Ninety-two (69%) elbows developed HO on radiographic follow-up. Inclusion criteria were patients who underwent primary elbow HO excision surgery with concurrent capsulectomy/lysis of adhesions to improve flexion-extension arc of motion. Of the 43 elbows on which HO excision was performed, 13 elbows were excluded from review: seven had inadequate pre- and post-operative ROM documentation, two had proximal forearm amputations requiring HO excision for pain or prosthetic fitting, and three had procedures primarily to improve pronation-supination motion.

Abstracted data was collected from inpatient and outpatient electronic medical records. Radiographs demonstrating the most severe HO were used to determine Hastings classification.[10] Outcomes were derived from electronic medical record capture of follow-up orthopaedic

Department of Orthopaedic Surgery; Walter Reed National Military Medical Center, Bethesda, MD. Address correspondence to: Kevin Wilson, MD, kevinwilsonmd@gmail.com.

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LCDR(s) Kevin W. Wilson, MD, MC, USN

LCDR(s) Wilson earned a bachelor of science degree in biology from Gettysburg College in 2003. Following graduation, he accepted the Armed Forces Health Profession Scholarship and was commissioned into the U.S. Navy. He earned his doctor of medicine degree at Jefferson Medical College in Philadelphia, PA. LCDR(s) Wilson completed his orthopaedic surgery internship at the National Naval Medical Center in 2008 and was selected for orthopaedic surgery residency training. During his research fellowship, he focused his work on a variety of projects related to spine biomechanics, degenerative disc disease, hip arthroscopy, and outcomes of combat extremity injuries. He authored a protocol that was awarded $205,000 in funding from the Navy Bureau of Medicine and Surgery Clinical Investigations Program. After graduation in June 2013, LCDR(s) Wilson will begin his orthopaedic surgery career at Naval Hospital Camp Lejeune, North Carolina. His future plans include a fellowship and career in adult reconstructive surgery.

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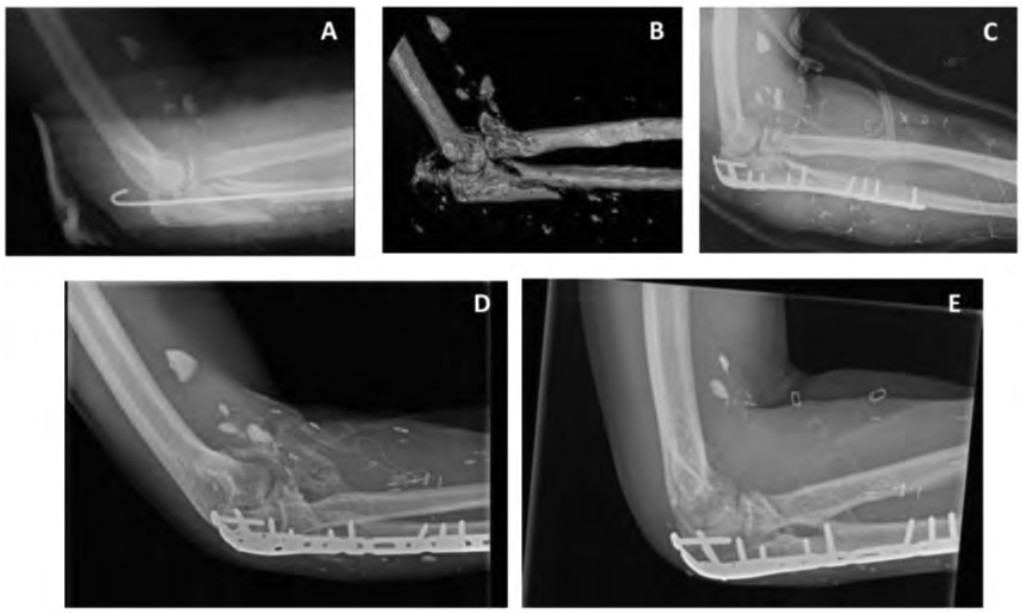

Figure 1. Serial radiographs of treatment course. Twenty-seven-year-old active duty male sustained improvised explosive device blast injury to the left upper extremity while serving in Afghanistan as an explosive ordinance disposal team leader, resulting in a Gustilo-Anderson type IIIB open proximal ulna and radial head fracture-dislocation. He was treated for TBI. He underwent irrigation and debridement and provisional stabilization prior to arrival at our facility. Radiographs (**A**) and CT 3D reconstruction (**B**) are shown. He underwent serial irrigation and debridement. After antero-lateral thigh free tissue transfer, we performed open reduction internal fixation (**C**) 11 days after injury. After three postoperative months, he returned with elbow HO and contracture (**D**) that was refractory to therapy and splinting. His arc of motion was 25 to 65 degrees of flexion. HO resection was performed six months after definitive fixation, followed by intensive occupational therapy. Post-resection (two weeks postoperative) radiographs are shown (**E**). At two years follow-up, his arc of motion was 30 to 115 degrees of flexion.

clinic and occupational therapy encounters, which routinely include ROM and complication details. Serial radiographs of a case example are displayed in Figure 1.

Surgical Details and Rehabilitation

A full discussion of surgical techniques and rehabilitation principles is beyond the scope of this report. After review of operative reports, the approach utilized was dictated by the anatomic location of the focus of heterotopic bone, presence of flaps, and need for hardware removal. HO prophylaxis regimens varied throughout the collection period. Routine follow-ups with exam occurred generally at 2 weeks, 6 weeks, 12 weeks, 6 months, and annually until loss of follow-up, after separation from the active duty military to the Veterans Affairs system.

The ROM at final follow-up, including cases of failed and repeat procedures, was used for outcome calculations, as per the intent-to-treat principle. Statistical analysis of the data included basic summary calculations for demographic variables and testing of the pre-operative and post-operative ROM between groups with independent samples *t*-tests, equal variances not assumed.

RESULTS

The demographic and injury characteristics for the cohort are summarized in Table 1. The mean age was 25 years (range, 19 to 42 years), and mean follow-up was 35 months (range, 12 to 51 months). The mean time from initial definitive management until HO resection was 10 months, (range, 3 to 18 months). The mechanism of injury was most commonly explosive blasts (90%, 27/30). The majority of injuries were Gustilo-Anderson type III injuries. Ten elbows (33%) were IIIB, requiring pedicled or free tissue transfer for definitive wound closure. Four (13%) were IIIC, associated with vascular injury requiring repair or revascularization procedure at time of injury. Seventeen elbows (57%) had associated nerve injuries. Fifty-three percent of patients (16/30) were diagnosed with TBI after known head injury or after mandatory TBI screening (Table 1).

Analysis of HO Resection Outcomes

The mean preoperative flexion-extension arc of motion was 36.4 degrees, compared with mean postoperative arc of motion of 83.6 degrees. A mean sustained gain of 47.2 degrees of flexion-extension ROM (range, -15 to 110 degrees, Table 2) was seen across the sample. The arc of motion preoperatively and postoperatively for the injured elbows in this series is significantly narrowed from the normal range of motion (0 to 140 degrees) for uninjured elbows (Figure 2). No significant difference was observed in the ROM gains between elbows with and without TBI diagnosis ($p = 0.102$), a well-established risk factor for heterotopic ossification.

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Table 1. Demographics and Injury Characteristics		
Age	25	(19-42) years
Follow-up	35	(12-51) months
Mechanism	27	(90%) blasts
	3	(10%) gun shot wounds
TBI	16	(53%) of patients
Time to HO resection	10	(3-18) months
Fracture		
Location	*# elbows*	*percentage*
Humerus	20	67%
Ulna	23	77%
Radius	7	23%
Combined	13	43%
Prior Procedures (mean)		
Downrange	2.7	procedures
Debridements	5.2	procedures
Gustilo-Anderson		
Type	*# elbows*	*percentage*
I	0	0%
II	8	27%
IIIa	8	27%
IIIb	10	50%
IIIc	4	20%
HO Classification		
Class	*# elbows*	*percentage*
I	0	0%
IIa	10	33%
IIb	5	17%
IIc	14	47%
III	1	3%

Table 2. Degrees of Motion Before and After HO Resection

Variable	#	Before	After	Gain	*p* value
All elbows	30	36.4	83.6	47.2	< 0.001
TBI	16	38.3	78.1	39.8	< 0.001
No TBI	14	34.2	89.9	55.7	< 0.001
Flap	10	37.9	79.6	41.7	0.003
No flap	20	35.6	85.6	50.0	< 0.001
Nerve injury	17	39.2	78.4	39.2	< 0.001
No nerve injury	13	32.6	90.4	57.8	< 0.001

The mean degrees of motion pre-operative, post-operative, and total gain measurements is displayed for the entire cohort (all elbows), and for elbows associated with and without TBI, need for flap coverage, and presence of nerve injury. Analysis of all subsets across the cohort demonstrated a significant gain in motion.

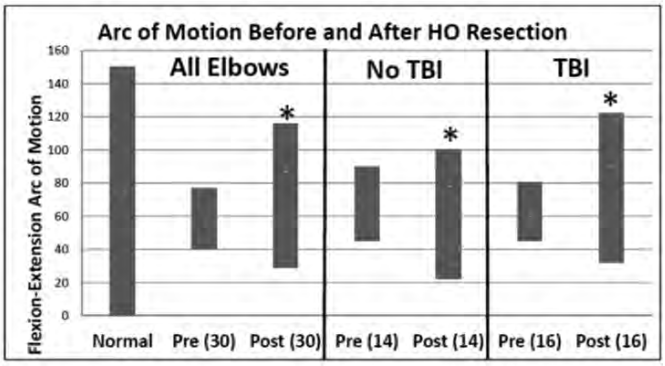

Figure 2. Arc of motion before and after HO resection. Arc of motion is displayed for normal elbows, pre-operative elbows, post-operative elbows for entire cohort, elbows without concomitant TBI, and elbows in individuals with TBI diagnosis. *denotes a significant difference between pre- and post-operative ROM values.

We noted significant mean gains in ROM from pre-operative measurements to final post-operative measurements across the sample, including subsets with and without potential confounding factors (Table 2). Sub-analysis of only elbows with concomitant TBI, need for flap, and nerve injury continued to demonstrate a significant gain in ROM in each subset, with and without the potential complicating variable. We found no significant difference in the pre-operative and post-operative motion for elbows with or without each of the potential complicating variables (Table 3). While there appeared to be a trend for elbows without TBI (55.6 vs. 39.9 degrees), flaps (50.0 vs 41.7 degrees), or nerve injuries (57.8 vs 39.2 degrees) to achieve a greater gain in range of motion, no statistically significant difference was found.

Table 3. Comparison of Pre- and Post-Operative Motion by Potential Risk Factors

Variable	Before	*p* value	After	*p* value	Gain	*p* value
TBI	38.3	0.358	78.1	0.115	39.9	0.102
No TBI	34.2		89.9		55.6	
Flap	37.9	0.419	79.6	0.300	41.7	0.274
No flap	35.6		85.6		50.0	
Nerve injury	39.2	0.538	78.4	0.203	39.2	0.136
No nerve injury	32.6		90.4		57.8	

A student's *t*-test of means was performed for the pre-operative, post-operative, and total gain measurements for elbows with concomitant TBI, need for flap coverage, and presence of nerve injury. No statistically significant differences were found among the mean pre-operative, post-operative, or gain measurements among elbows with any of the potential risk factors for stiffness.

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Complications

HO resections were complicated by one intraoperative distal humerus fracture, six episodes of recurrent arthrofibrosis (less than 15 degree improvement), and one re-injury of a previously-injured posterior interosseous nerve (PIN). Four of the six recurrent arthrofibrosis cases went on to repeat lysis of adhesion and manipulation under anesthesia procedures, with no significant lasting improvement. The PIN palsy improved with observation.

DISCUSSION

The current study may represent the largest series of HO resections involving peripheral nerve injuries, open fractures, or wounds requiring flap coverage. It can be implied that nerve injury and soft tissue deficits represent more serious insults to the peri-articular soft tissues that are involved in the elbow contractures, however, these characteristics were not found to play a role in the ROM outcomes of surgical resection of HO. The results of the present series demonstrate generally comparable results to HO resection following lower energy, closed injuries, with slightly decreased ROM gains and similar complication rates.

Resection of HO to improve functional elbow ROM has been shown to be successful in varied clinical settings, with documented improvements in objective performance scores and increases in ROM from 49 to 94 degrees.[2-8,11] Ring and Jupiter reported the successful operative release of complete ankylosis in 20 elbows among 15 severe trauma and burn patients, with a mean sustained arc of motion of 81 degrees for the burn cohort and 94 degrees for the trauma cohort.[11] The soft tissue injuries described are less severe than the combat injuries in the current series. Also, none of the Ring and Jupiter patients had concurrent TBI.[11] More recently, Baldwin, et al.[3] presented a mean gain in arc of motion of 49 degrees in a cohort of patients with TBI, direct elbow trauma, and combined etiologies. Our mean increase in flexion-extension arc of motion of 47.2 degrees is comparable, considering the complexity of these types of patients. Similarly, Baldwin, et al. reported that timing of resection and neurologic characteristics had no effect on outcomes.[3]

Our rate of complications (26.7%), including recurrence, is similar to the rates reported in other series.[2-9,11] Ring and Jupiter reported clinically significant recurrent HO in one-third of their trauma cohort.[11] Means for identifying those limbs at risk for complication or recurrence have not been established. Given the unremarkable influence of potential risk factors for HO and contracture in this and other series, potential etiologies for recurrent contracture remain unclear.

The shortcomings of this analysis are related to its retrospective nature and multiple treatment regimens carried out by multiple surgeons. No consistent regimen of chemo- or radiotherapy HO prophylaxis was used; however, recommendations for safe prophylaxis regimens after elbow injury or surgery have not yet been established in other patient populations.[1,2,9]

Based on our observations, HO resections in combat-related blast injuries to the elbow can produce reliable gains in the arc of elbow motion. Blast injuries are not commonly encountered in the orthopaedic community; nevertheless, it may be noteworthy that the utility of HO resections with concurrent lysis of adhesions is maintained following these complex injuries, even in what may be the worst-case scenario for post-traumatic elbow HO. Elbow contractures associated with open fracture, soft tissue loss, and nerve injury should not preclude attempts at improving ROM with surgical excision of HO.

REFERENCES

1. Summerfield SL, DiGiovanni C, Weiss AC. Heterotopic ossification of the elbow. *J Shoulder Elbow Surg.* 1997;6(3):321-332.
2. Viola RW, Hastings H. Treatment of ectopic ossification about the elbow. *Clin Orthop Rel Res.* 2000 Jan;(370):65-86.
3. Baldwin K, Hosalker HS, Donegan DJ, et al. Surgical resection of heterotopic bone about the elbow: an institutional experience with traumatic and neurologic etiologies. *J Hand Surg*. 2011;36(5):798-803.
4. McAuliffe JA, Wolfson AH. Early excision of heterotopic ossification about the elbow followed by radiation therapy. *J Bone Joint Surg Am*. 1997;79(5):749-755.
5. Evans PJ, Nandi S, Maschke S, et al. Prevention and treatment of elbow stiffness. *J Hand Surg*. 2009;34(4):769-778.
6. Moritomo H, Tada K, Yoshida T. Early, wide excision of heterotopic ossification in the medial elbow. *J Shoulder Elbow Surg*. 2001;10(2):164-168.
7. Gaur A, Sinclair M, Caruso E, Peretti G, Zaleske D. Heterotopic ossification around the elbow following burns in children: results after excision. *J Bone Joint Surg Am*. 2003;85A,8:1538-1543.
8. Park MJ, Chang MJ, Lee YB, Kang HJ. Surgical release for posttraumatic loss of elbow flexion. *J Bone Joint Surg Am*. 2010;92(16):2692-2699.
9. Maender C, Shajpal D, Wright TW. Treatment of heterotopic ossification of the elbow following burn injury: recommendations for surgical excision and perioperative prophylaxis using radiation therapy. *J Shoulder Elbow Surg*. 2010;19(8):1269-1275.
10. Hastings H II, Graham TJ. The classification and treatment of heterotopic ossification about the elbow and forearm. *Hand Clin*. 1994;10(3):417-437.
11. Ring D, Jupiter JB. Operative release of compete ankylosis of the elbow due to heterotopic bone in patients without severe injury of the central nervous system. *J Bone Joint Surg Am*. 2003;85-A(5):849-857.

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Research Fellow Papers

An Innovative Culture System for the Study of Post-Traumatic Heterotopic Ossification

[1,2]CPT Husain M. Bharmal, MD, MC, USA; [1]Gregory T. Christopherson, PhD; [1]Youngmi Ji, PhD; [3]Wesley M. Jackson, PhD; [1,2,3]LTC Leon J. Nesti, MD, PhD

INTRODUCTION

Following orthopaedic trauma, injured muscle tissue becomes populated with mesenchymal progenitor cells (MPCs) containing a cell surface epitope profile and multidifferentiation potential that is characteristic of bone marrow-derived mesenchymal stem cells (MSCs).[1] Our laboratory has hypothesized that these cells, which appear to be intimately involved in the healing process, also play a key role in wound healing pathologies such as heterotopic ossification (HO).

HO is defined as aberrant mature bone formation in non-osseous tissue. During recent military operations, there has been a significant increase in the prevalence of heterotopic ossification in the combat-wounded patient population, with rates as high 64%.[2] Symptomatic HO can significantly worsen morbidity, complicating internal fixation of fractures and prosthetic fitting in amputees, and requiring additional surgical procedures for symptomatic HO excision. Understanding the pathogenesis of this condition is essential in the prevention and potential treatment of the disease.

We hypothesize the physical microstructure (fibrosis) within a wound dysregulates muscle regeneration, working synergistically with inflammatory factors to confuse local MPC populations and generate an early osteoinductive region. In this study, our specific aims were (1) to examine the structure of decellularized early-stage traumatized muscle tissue taken from patients that develop HO and identify non-cellular structural components that may be instrumental in pathological wound development, (2) to create a biomimetic in vitro culture platform replicating the wound microarchitecture and evaluate the osteogenic potential of this microarchitecture compared to conventional 2D cell culture approaches. Our overall goal is to create an in vitro model system for studying the development of HO.

[1]Orthopaedic Research Group, National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health, Bethesda, MD; [2]Department of Orthopaedics and Rehabilitation, Walter Reed National Military Medical Center, Bethesda, MD; [3]Uniformed Services University of the Health Sciences, Bethesda, MD. Address correspondence to: CPT Husain M. Bharmal, MD, Husain.bharmal@gmail.com.

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MATERIALS AND METHODS

Tissue Decellularization

Surgical waste muscle tissue was obtained from consented patients injured during Operation Enduring Freedom; these patients were radiographically observed as developing HO in subsequent months (Figure 1). Tissue was sectioned into 5 mm^3 segments and incubated overnight in 0.1% sodium dodecyl sulfate (SDS) surfactant solution to remove all cellular and lipid components.

Scanning Electron Microscopy (SEM)

Decellularized tissue samples were fixed with paraformaldehyde/glutaraldehyde, secondarily fixed with osmium tetroxide, serially diluted with ethanol, hexamethyldisilazane (HMDS) critically point dried and sputter-coated with gold for SEM imaging.

Collagen Nanofibers

Collagen nanofibers were electrospun to replicate the tissue microarchitecture in vitro. Lyophilized calf-skin collagen I was dissolved in hexafluoroisopropanol (HFIP) at 3% w/w and electrospun onto grounded aluminum plates.[3] The fiber matrix was manipulated into coverslips (for 24-well plates samples) and 15-cm culture dishes for

Figure 1. Radiographs of a soldier injured during Operation Enduring Freedom, showing the development of heterotopic ossification (HO) in the weeks following blast injury.

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large-scale cell culture. Samples were glutaraldehyde vapor-saturated for 15 minutes for crosslinking stability, and thoroughly rinsed with phosphate buffered saline (PBS).

Cell Isolation and Culture

MPCs were harvested using a previously described protocol.[1] Tissue identical to that used for decellularization was minced, incubated in collagenase II, and filtered through a 40-µm cell strainer to obtain a cell solution. The cell solution was incubated for two hours on tissue culture-treated plastic flasks and non-adherent cells were vigorously rinsed away to obtain a mesenchymal progenitor population. Cells were expanded in high-glucose DMEM culture media containing 10% fetal bovine serum. To evaluate the osteogenic potential of the traumatized-tissue-isolated MPCs, cells were expanded on collagen-coated and fiber matrix dishes for 3 weeks, before ensuing culture in osteogenic media (Invitrogen) for 2 weeks. Calcium deposition was measured with alizarin red, and osteoblast activity was assayed with alkaline phosphatase. Protein lysates were also collected for western blotting analysis.

RESULTS

We have evaluated the physical microenvironment of traumatized muscle tissue in patients radiographically confirmed to form HO by lysing all cellular components from the tissue, leaving a preponderance of nanofiber matrix. This nanofiber component was identically replicated with electrospun collagen scaffolds (Figure 2A). MPCs cultured on this fiber surface have a significantly increased osteogenic potential, with greatly increased calcium deposition (as measured by alizarin red) and alkaline phosphatase expression, compared to cells cultured on 2D collagen (Figure 2C).

Western blotting analysis revealed increased vimentin expression for MPCs cultured on fiber substrates prior to osteogenesis (Figure 2B), as well as a decrease in alpha smooth muscle actin (αSMA), a prominent fibroblast marker. Vimentin has been shown to be essential for cartilage formation,[4] which is hypothesized to precede endochondral ossification of HO. It has also been shown that decreases in vimentin correlate with osteoblast differentiation and bone formation, perhaps acting as a trigger for osteocalcin signaling.[5]

DISCUSSION

Fibrotic tissue that forms in traumatized muscle (i.e., scar) is known to precede HO, a debilitating formation of ectopic bone in soft tissues whose cellular mechanisms are poorly understood. SEM characterization of fibrotic muscle tissue reveals an abundant fibrous network, a component which our findings indicate may be sufficient to promote cellular osteogenic differentiation in vitro. Recent studies show

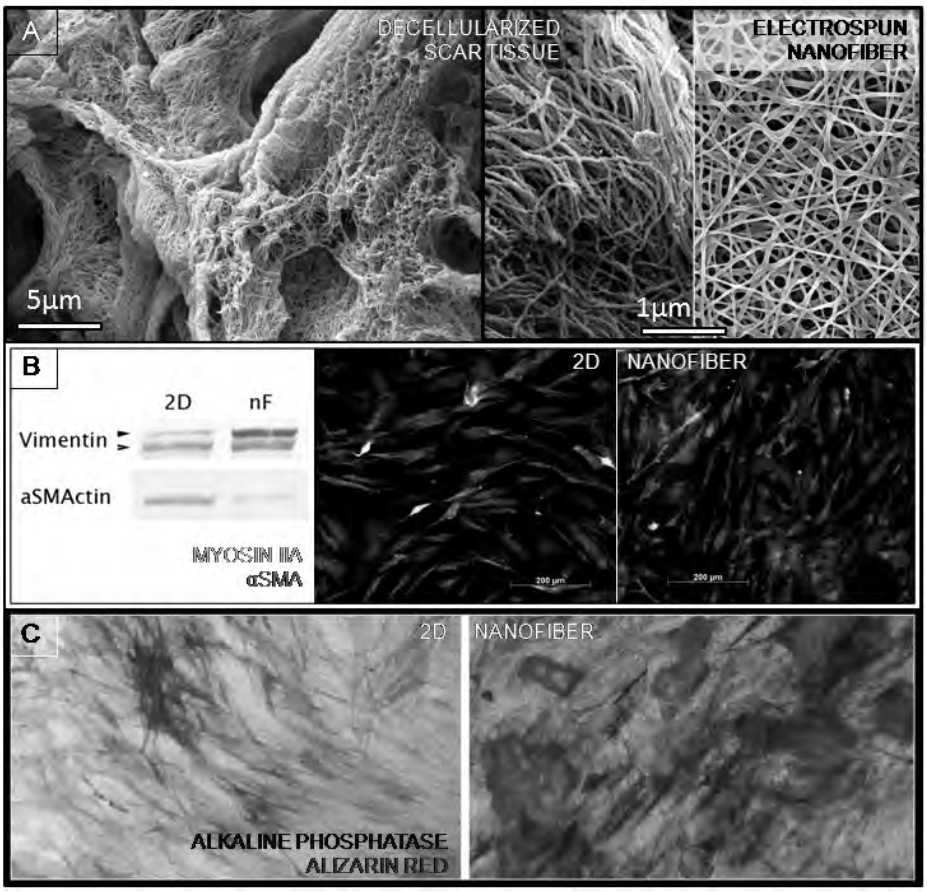

Figure 2. (A) Scanning electron microscopy (SEM) images of traumatized muscle tissue, decellularized with sodium dodecyl sulfate (SDS) detergent. The abundant nanofiber matrix was recreated with electrospinning. **(B)** Mesenchymal progenitor cells (MPCs) isolated from the traumatized muscle were cultured on 2D collagen and nanofiber substrates. Western blotting and immunofluorescence microscopy reveal an increase in vimentin (intermediate filament, known to play key role in chondrogenesis, fibrosis, and osteogenesis) and a decrease in alpha smooth muscle actin (fibrosis marker) for MPCs cultured on fiber matrix. **C**. MPCs cultured on nanofiber matrix in osteogenic media have a robust increase in alizarin red staining (calcium excretion) and ALP expression, indicating a heightened sensitivity to osteogenic induction.

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that a collagen fiber matrix precedes bone formation during development, indicating bone may spontaneously form if collagen matrix is present, likely from cells secreting mineral matrix through exocytosis.[6] This developmental cascade is replicated in our experimental results, which show a robust increase in calcium secretion from MPCs cultured on a biomimetic nanofiber matrix. The increase in vimentin expression before osteogenic induction correlates well with literature, with a corresponding decrease in fibrotic markers (αSMA) indicating a shift into preosteogenic state. The sensitivity of osteogenic phenotype to the nanofiber matrix suggests that it is likely a key component for properly elucidating HO development using in vitro cellular models.

This study helps to recreate in vivo elements associated with HO in a representative culture system, providing a suitable platform for studying the cellular parameters responsible for such pathological wound healing. Surface topography appears to contribute substantially to osteoinductive wound healing, making it an essential component for investigating and minimizing the risk of HO.

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REFERENCES

1. Nesti LJ, Jackson WM, Shanti RM, et al. Differentiation potential of multipotent progenitor cells derived from war-traumatized muscle tissue. *J Bone Joint Surg Am*. 2008 Nov;90(11):2390-2398. doi: 10.2106/JBJS.H.00049.
2. Forsberg JA, Pepek JM, Wagner S, et al. Heterotopic ossification in high-energy wartime extremity injuries: prevalence and risk factors. *J Bone Joint Surg Am*. 2009 May;91(5):1084-91. doi: 10.2106/JBJS.H.00792.
3. Li M, Mondrinos MJ, Gandhi MR, Ko FK, Weiss AS, Lelkes PI. Electrospun protein fibers as matrices for tissue engineering. *Biomaterials*. 2005 Oct;26(30):5999-6008. doi:10.1016/j.biomaterials.2005.03.030.
4. Bobick BE, Tuan RS, Chen FH. The intermediate filament vimentin regulates chondrogenesis of adult human bone marrow-derived multipotent progenitor cells. *J Cell Biochem*. 2010 Jan 1;109(1):265-76. doi: 10.1002/jcb.22419.
5. Lian N, Wang W, Li L, Elefteriou F, Yang X. Vimentin inhibits ATF4-mediated osteocalcin transcription and osteoblast differentiation. *J Biol Chem*. 2009 Oct 30;284(44):30518-25. doi: 10.1074/jbc.M109.052373.
6. Mahamid J, Sharir A, Gur D, Zelzer E, Addadi L, Weiner S. Bone mineralization proceeds through intracellular calcium phosphate loaded vesicles: a cryo-electron microscopy study. *J Struct Biol*. 2011 Jun;174(3):527-35. doi: 10.1016/j.jsb.2011.03.014.

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Outcomes Following Cervical Disc Arthroplasty: a Retrospective Review

[1]CPT John P. Cody, MD; [1]LCDR Robert W. Tracey, MD; [1]CPT Daniel G. Kang, MD; [1]CPT Adam J. Bevevino, MD; [2]LTC Michael K. Rosner, MD; [1,3]LTC Ronald A. Lehman, Jr., MD

INTRODUCTION

Cervical radiculopathy is a common diagnosis in both civilian and military populations that causes significant disability and loss of work.[1-3] In the military population specifically, radiculopathy may result in an inability to perform soldier tasks proficiently, preventing deployment and decreasing force strength. Patients may present with a constellation of symptoms, including dermatomal radicular pain and paresthesias, weakness, and sometimes myelopathic findings such as hyperreflexia and positive rudimentary reflexes (Hoffman's, Babinski, etc.).[4-7] Several surgical options are available for the treatment of cervical radiculopathy following a trial of conservative management. These options include posterior decompression and fusion, anterior discectomy and fusion, and cervical disc arthroplasty (CDA). CDA has been espoused in the literature as a viable alternative to anterior cervical discectomy and fusion (ACDF), with the added theoretical benefit of preventing adjacent segment degeneration, though this remains to be seen.[8-12] Based on our increasing experience in performing CDA, we sought to determine the outcomes of all patients who underwent this procedure at our institution.

MATERIALS AND METHODS

Following approval from our institutional review board, the surgical database at this institution was queried to identify all patients who had undergone CDA between August 2008 and August 2012. This search yielded 316 total patients. Of the total, 34 were lost to follow-up, leaving 282 patients for review. All construct types (single level CDA, hybrid, and multilevel CDA) were included. All data were collected via a retrospective chart analysis, which included inpatient and outpatient clinical notes, surgical databases, and radiographs. Data collected include patient demographic information (age, sex, tobacco use, body mass index (BMI)), patient-centered outcomes (relief of pre-operative symptoms, incidence/resolution of axial neck pain in the post-operative period, return to full activity), complications (recurrent laryngeal nerve injury, dysphagia, post-operative respiratory compromise, esophageal/tracheal disruption), and radiographic parameters (increase in disc height, segment range of motion, evidence of loosening, migration, or subsidence).

[1]Department of Orthopaedic Surgery, Walter Reed National Military Medical Center, Bethesda, MD; [2]Department of Neurosurgery, Walter Reed National Military Medical Center, Bethesda, MD; [3]Division of Orthopaedics, Department of Surgery, Uniformed Services University of the Health Sciences, Bethesda, MD. Address correspondence to: John P. Cody, MD, john.patrick.cody@gmail.com.

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RESULTS

There were 219 males (77.7%) and 63 females (22.3%). The average length of follow-up was 11.2 (± 11.0) months. The average patient age was 42.1 (± 8.4) years. The average BMI was 27.8 (± 3.7) kg/m^2. The most common levels addressed at the time of surgery were C5-6 and C6-7 (56.7% and 58.9%, respectively). The next most frequently diseased levels were C4-5 (19.5%), C3-4 (8.2%), and C7-T1 (2.5%). A majority of patients underwent single level CDA (59.9%), and 22.3% underwent two-level hybrid (CDA/ACDF) constructs. Twenty-five patients (8.9%) underwent two-level CDA; 11 (3.9%) of those patients had contiguous levels addressed, and 14 (5.0%) had non-contiguous levels addressed. Three patients had three-level contiguous CDA (Table 1). Of the patients studied, 73.8% (209) were active duty at the time of surgery. The Prestige™ (Medtronic, Memphis, TN) cervical arthroplasty system was utilized in the majority of patients (94.5%), while the ProDisc-C system (Depuy Synthes, Paoli, PA) was utilized in the remainder of patients (5.5%).

The primary indications for surgery were radiculopathy (86.5%), myelo-radiculopathy (9.2%), and myelopathy (1.8%). Flexion and extension lateral radiographs were available in 199 patients (60.9%), and the mean range of motion (ROM) at the CDA levels was 7.5 (± 4.1) degrees at latest follow-up. Of the 282 patients reviewed, 250 (88.7%) experienced complete relief of pre-operative complaints. Twenty-six patients (9.2%) had incomplete relief of their symptoms, to include complaints of persistent axial neck pain, residual paresthesias, or radiculopathy. Some patients (2.1%) experienced initial relief of symptoms, but later developed recurrence during follow-up. We found 52 (18.4%) patients who complained of axial neck pain at three months or greater, but that eight (15.3%) had resolution of their pain at one-year follow-up with conservative therapy, and 11 (21.2%) stated that their pain did not require treatment or affect their return to activity. A vast majority of patients were able to return to full activity (92.2%). In the active duty population, there was a 90.4% rate of return to full activity. Of the 24 patients who did not return to full activity, 20 were active duty at the time of surgery and required a medical board for inability to perform their job in the necessary capacity (Table 1).

The complication rate was 14.5%, which included dysphagia (8.9%), recurrent laryngeal nerve injury (3.2%), post-operative hematoma (0.4%), nerve root injury (0.4%), spinal cord injury (0.4%), and superficial infection (0.4%). There was a 5.3% re-operation rate, including conversion of CDA to ACDF, revision of ACDF or CDA, posterior decompressions, adjacent segment degeneration, and hematoma decompression (Table 2).

When the data were analyzed based on construct type, we found similar outcomes between single level, two-level hybrids, and two- and three-level CDA (Table 3). The multi-level hybrid constructs (most commonly CDA/ACDF/CDA) showed a decreased rate of symptom relief and return to full activity (77.8% and 72.2%, respectively), and higher rates of persistent axial neck pain (50%) and dysphagia (22.2%) (Table 3).

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Table 1. Patient Information and Outcomes	
Total patients	282
Men	71.7% (219)
Women	22.3% (63)
Age	42.1 ± 8.4 years
Body mass index	27.8 (± 3.7) kg/m^2
Tobacco use	26.6% (75)
Active duty military	73.8% (208)
Revision surgery	5.7% (16)
Average follow-up	11.2 ± 11.0 months
Levels of disease	
C3-4	8.2% (23)
C4-5	19.5% (55)
C5-6	56.7% (160)
C6-7	58.9% (166)
C7-T1	2.5% (7)
Primary indication for surgery	
Myelopathy	1.8% (5)
Radiculopathy	86.5% (244)
Myelo-radiculopathy	9.2% (26)
Neck pain	0.7% (2)
Outcomes	
Relief of neurologic symptoms	92.9% (262)
Complete relief of symptoms	88.7% (250)
Persistent axial neck pain (>3 mos)	18.4% (52)
Return to full activity	92.2% (260)
Return to active duty military	90.4% (189/209)

Table 2. Adverse Outcomes	
Complications	
Recurrent laryngeal nerve injury	3.2% (9)
Dysphagia	8.9% (25)
Post-op hematoma	0.4% (1)
Infection	0.4% (1, superficial)
Spinal cord injury	0.4% (1)
Dural tear	0.4% (1)
Recurrence of neurologic symptoms	2.1% (6)
Reoperation during follow-up	5.3% (15)
Posterior decompression	2.1% (6)
Adjacent level	1.8% (5)
Conversion to anterior cervical discetomy and fusion	0.7% (2)
Hematoma decompression	0.4% (1)

Table 3. Outcomes Based on Construct Type	
Single level CDA	59.9% (169)
Complete symptom relief	90.1%
Return to full activity	93%
Persistent axial neck pain	15.8%
Dysphagia	5.8%
Recurrent laryngeal nerve injury	2.9%
Two-level hybrid	22.3% (63)
Complete symptom relief	90.6%
Return to full activity	90.6%
Persistent axial neck pain	12.5%
Dysphagia	12.5%
Recurrent laryngeal nerve injury	3.1%
Two-level contiguous CDA	3.9% (11)
Complete symptom relief	96.0%
Return to full activity	96.0%
Persistent axial neck pain	24%
Dysphagia	8%
Recurrent laryngeal nerve injury	4%
Three-level hybrid	6.4% (18)
Complete symptom relief	77.8%
Return to full activity	72.2%
Persistent axial neck pain	50%
Dysphagia	22.2%
Recurrent laryngeal nerve injury	0.0%

CDA, cervical disc arthroplasty

DISCUSSION

To our knowledge, this is the largest, non-funded, single center review of CDA. When analyzing all construct types that included CDA at our institution, we found an 88.7% rate of complete pre-operative symptom relief and a 92.2% rate of return to full activity, with maintenance of 7.5 degrees at each CDA level on average. This included a majority subset population of active duty service members, which demonstrated a 90.4% rate of return to active duty. Furthermore, our review demonstrates a low complication rate with regard to post-operative dysphagia (8.9%) and recurrent laryngeal nerve injury (3.2%).

The rate of dysphagia in this review (8.9%) is lower than that reported in the literature (28% to 57%),[13-17] which is most likely due to the fact that dysphagia is often underreported clinically.[14] Most surgeons at our institution counsel patients to expect a normal two- to three-month period of "settling" posterior neck pain postoperatively. However, we found a high rate (18.4%) of persistent neck pain in the post-operative period, which was defined as pain lasting longer than three months and/or neck pain that required further non-operative intervention (extended physical therapy, facet injections, or nerve ablation). Unfortunately, we were unable to correlate this rate of axial neck pain with the presence

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of pre-operative axial neck pain as a presenting symptom, as this was unreliably documented.

Another pertinent finding was the lower rate of pre-operative symptom relief and return to full activity following multilevel hybrid constructs (77.8% and 72.2%, respectively) and a higher rate of dysphagia and persistent post-operative axial neck pain. These patients likely experienced a higher severity of pre-operative symptoms compared to the one- and two-level groups, with 27.8% of patients in the multi-level hybrid group experiencing myelopathic complaints compared to 10% in the remainder of constructs. These larger constructs also likely required longer operative times, which may have led to the increased rates of dysphagia.

While ACDF continues to be the "gold standard" in the management of cervical degeneration,[18-21] several recent studies have shown comparable short- and mid-range follow-up outcomes with CDA.[8-12,22,23] Long-term ACDF studies have shown approximately 3% per year adjacent segment degeneration rate.[24] In a mid-term follow-up study, Sun, et al. found a significantly decreased rate of adjacent segment degeneration in patients who had undergone CDA compared to ACDF (17.6% versus 60.4%, respectively) with five-year follow-up.[25] While these intermediate results are promising, there are currently no long-term studies (> 10 years) to demonstrate reduction in adjacent segment degeneration compared to ACDF.

Cervical disc arthroplasty is increasing in popularity for the treatment of cervical radiculopathy and myelopathy. To our knowledge, this is the largest, non-funded, single center study on this topic. Our review found an 89% rate of complete pre-operative symptom relief, with greater than 90% of patients returning to their pre-operative levels of activity and an acceptably low rate of complications. While there are currently no long-term studies demonstrating the superiority of CDA over ACDF, short- and mid-term results have shown that CDA is a safe and reliable alternative to ACDF for properly selected patients. However, further studies are necessary to determine if there is a long-term reduction in adjacent segment degeneration or re-operation.

REFERENCES

1. Woolf AD, Pfleger B. Burden of major musculoskeletal conditions. *Bull World Health Organ.* 2003;81(9):646-656.
2. Lawrence RC, Felson DT, Helmick CG, et al. Estimates of the prevalence of arthritis and other rheumatic conditions in the United States. Part II. *Arthritis Rheum.* Jan 2008;58:26-35.
3. Schoenfeld AJ, George AA, Bader JO, Caram PM Jr. Incidence and epidemiology of cervical radiculopathy in the United States military: 2000 to 2009. *J Spinal Disord Tech*. Feb 2012;25:17-22.
4. Carette S, Fehlings MG. Clinical practice. Cervical radiculopathy. *N Engl J Med.* Jul 2005;353:392-399.
5. Albert TJ, Murrell SE. Surgical management of cervical radiculopathy. *J Am Acad Orthop Surg*. Nov-Dec 1999;7:368-376.
6. Rao RD, Currier BL, Albert TJ, et al. Degenerative cervical spondylosis: clinical syndromes, pathogenesis, and management. *J Bone Joint Surg Am.* Jun 2007;89:1360-1378.
7. Kelsey JL. Epidemiology of radiculopathies. *Adv Neurol.* 1978;19:385-398.
8. Garrido BJ, Taha TA, Sasso RC. Clinical outcomes of Bryan cervical disc arthroplasty a prospective, randomized, controlled, single site trial with 48-month follow-up. *J Spinal Disord Tech.* Aug 2010;23:367-371.
9. Murrey D, Janssen M, Delamarter R, et al. Results of the prospective, randomized, controlled multicenter Food and Drug Administration investigational device exemption study of the ProDisc-C total disc replacement versus anterior discectomy and fusion for the treatment of 1-level symptomatic cervical disc disease. *Spine J.* Apr 2009;9:275-286.
10. Sasso RC, Smucker JD, Hacker RJ, Heller JG. Clinical outcomes of BRYAN cervical disc arthroplasty: a prospective, randomized, controlled, multicenter trial with 24-month follow-up. *J Spinal Disord Tech.* Oct 2007;20:481-491.
11. Mummaneni PV, Burkus JK, Haid RW, Traynelis VC, Zdeblick TA. Clinical and radiographic analysis of cervical disc arthroplasty compared with allograft fusion: a randomized controlled clinical trial. *J Neurosurg Spine*. Mar 2007;6:198-209.
12. Burkus JK, Haid RW, Traynelis VC, Mummaneni PV. Long-term clinical and radiographic outcomes of cervical disc replacement with the Prestige disc: results from a prospective randomized controlled clinical trial. *J Neurosurg Spine*. Sep 2010;13:308-318.
13. Cardoso MJ, Mendelsohn A, Rosner MK. Cervical hybrid arthroplasty with 2 unique fusion techniques. *J Neurosurg Spine*. Jul 2011;15:48-54.
14. Edwards CC 2nd, Karpitskaya Y, Cha C, et al. Accurate identification of adverse outcomes after cervical spine surgery. *J Bone Joint Surg Am.* Feb 2004;86-A:251-256.
15. Lee MJ, Bazaz R, Furey CG, Yoo J. Risk factors for dysphagia after anterior cervical spine surgery: a two-year prospective cohort study. *Spine J.* Mar-Apr 2007;7:141-147.
16. Lee MJ, Bazaz R, Furey CG, Yoo J. Influence of anterior cervical plate design on Dysphagia: a 2-year prospective longitudinal follow-up study. *J Spinal Disord Tech.* Oct 2005;18:406-409.
17. Smith-Hammond CA, New KC, Pietrobon R, Curtis DJ, Scharver CH, Turner DA. Prospective analysis of incidence and risk factors of dysphagia in spine surgery patients: comparison of anterior cervical, posterior cervical, and lumbar procedures. *Spine.* Jul 2004;29:1441-1446.
18. Lee CK, Langrana NA. A review of spinal fusion for degenerative disc disease: need for alternative treatment approach of disc arthroplasty? *Spine J.* Nov-Dec 2004;4:173S-176S.
19. Davis H. Increasing rates of cervical and lumbar spine surgery in the United States, 1979-1990. *Spine*. May 1994;19:1117-1123; discussion 1123-1124.
20. Bohlman HH, Emery SE, Goodfellow DB, Jones PK. Robinson anterior cervical discectomy and arthrodesis for cervical radiculopathy. Long-term follow-up of one hundred and twenty-two patients. *J Bone Joint Surg Am.* Sep 1993;75:1298-1307.
21. Herkowitz HN, Kurz LT, Overholt DP. Surgical management of cervical soft disc herniation. A comparison between the anterior and posterior approach. *Spine*. Oct 1990;15:1026-1030.
22. Heller JG, Sasso RC, Papadopoulos SM, et al. Comparison of BRYAN cervical disc arthroplasty with anterior cervical decompression and fusion: clinical and radiographic results of a randomized, controlled, clinical trial. *Spine*. Jan 2009;34:101-107.
23. Sasso RC, Anderson PA, Riew KD, Heller JG. Results of cervical arthroplasty compared with anterior discectomy and fusion: four-year clinical outcomes in a prospective, randomized controlled trial. *J Bone Joint Surg Am.* Sep 2011;93:1684-1692.
24. Hilibrand AS, Robbins M. Adjacent segment degeneration and adjacent segment disease: the consequences of spinal fusion? *Spine J*. Nov-Dec 2004;4:190S-194S.
25. Sun Y, Zhao YB, Pan SF, Zhou FF, Chen ZQ, Liu ZJ. Comparison of adjacent segment degeneration five years after single level cervical fusion and cervical arthroplasty: a retrospective controlled study. *Chin Med J.* Nov 2012;125:3939-3941.

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The Use of Dilute Dakin's Solution for the Treatment of Invasive Fungal Infection in the Combat Wounded: a Case Series

[1,2]LT Louis Lewandowski, MD, MC, USN; [2]CPT Richard Purcell, MD, MC, USA; [1,2]CDR Mark Fleming, DO, MC, USN; [1,2]Lt Col Wade T. Gordon, MD, MC, USAF

INTRODUCTION

Blast injury-related invasive fungal infections (IFIs) have dramatically shaped the treatment and outcomes of individuals injured in current combat operations. These infections are traditionally seen in immunocompromised patients in the civilian literature and are typically managed with aggressive debridement and systemic antifungal medications, with limited success.[1-8]

In the current report, we describe the use of dilute Dakin's solution (0.025% buffered sodium hypochlorite solution)[9] and negative pressure wound therapy (NPWT) as an adjunct to the aggressive surgical debridement required to address aggressive fungal infections. Sodium hypochlorite solution has been previously utilized for treatment of combat-related wound infections since the Civil War;[10] however, the use of dilute Dakin's solution has not been described to date in the management of IFI in patient with severe traumatic wounds.

CASE STUDY

Our patient is a 24-year-old male Marine who sustained injures while conducting combat operations in support of Operation Enduring Freedom. His vehicle encountered an improvised explosive device (IED) causing multiple injuries, including a left transfemoral amputation, right transtibial amputation, and transradial amputation; additionally, he sustained a severely mangled left upper extremity. His initial management included obtaining hemorrhage control, decontamination, and resuscitation in Afghanistan. He underwent a revascularization utilizing a local vein graft for his left upper extremity. Once stabilized, he was evacuated to Landstuhl Regional Medical Center and underwent additional irrigation and debridement procedures prior to transferring to our facility. Upon arrival at our facility six days from the date of injury, he was febrile to 104º F with exposed left forearm vein grafts, an open abdomen, and malfunctioning Wound Vacuum Assisted Closure (V.A.C.)™ (KCI, San Antonio, TX). Therefore, a decision was made to urgently take him to the operating room for wound assessment and aggressive debridement and irrigation.

Intraoperatively, his right knee disarticulation appeared viable. However, his vein grafts were nonviable and appeared necrotic. He did have a dopplerable arch, which is presumed to be from dorsal collateral flow. His right transradial amputation was largely nonviable and the radius and ulna were removed, along with large amounts necrotic soft tissue. The high left transfemoral amputation was malodorous and had obvious necrosis (Figures 1 to 3). Following aggressive debridement and irrigation of all wounds, the patient was started on broad spectrum antibiotics and tissue was sent for culture. Based on the appearance and presence of extensive necrosis in all wounds, a decision was made to return to the operating room in 24 hours for repeat debridement and irrigation. During the next procedure, due to the extent of tissue necrosis around the left transfemoral amputation, his left transfemoral amputation was revised to a hip disarticuation. Several specimens from the left lower extremity were sent to pathology for histological evaluation, as well as to microbiology. Histologic analysis revealed angioinvasive fungal elements. Wound cultures eventually grew *Aspergillus fumigatus*.

On post-injury day 10, the patient underwent repeat debridement of his bilateral lower extremity wounds. During this trip to the operating room, he also required a left transradial amputation, as a result of extensive tissue necrosis, and an inability to maintain adequate tissue perfusion to the hand. Serial debridements continued every 48 hours. Once positive fungal cultures were obtained, Dakin's solution was added to the intra-operative irrigation solution at the next debridement. The patient's left hip disarticulation wound was then treated with Dakin's solution infused utilizing Instill therapy Wound V.A.C.™. This allowed for timed administration and removal of the solution from the wound bed. The Dakin's solution utilizing the Instill Wound V.A.C.™ was subsequently placed on his right lower extremity and his open abdomen following positive fungal cultures and concern for continued necrosis at these sites. On post injury day 16 it was also noted that he had grossly necrotic and caseating tissue in his abdomen, which was later shown to be culture positive for *Aspergillus*. The patient continued to undergo serial irrigation and debridement every 48 hours. The patient's wounds were ultimately closed without further complications on post-injury day 37.

DISCUSSION

Zygomycetes and *Aspergillus* are found ubiquitously on decomposing organic material and are regularly inhaled in spore form without concern to immunocompetent patients,[5,7] however, IFIs continue to be among the most aggressive and devastating complications to affect our combat-injured patients. To date, we have had 77 patients diagnosed with IFI from Iraq and Afghanistan since 2001. Of these 77 patients, there have been only 4 fatalities, which is a 5.2% mortality rate compared to a reported 30% mortality rate associated with nosocomial acquired cutaneous mucormycosis following traumatic injury in the civilian literature[11] and the 25% mortality rate seen following the tornados in Joplin, Missouri.[12] Previous reports describe a mortality rate approaching 100% with disseminated angioinvasive fungal infections, such as in our case where multiple extremities and the abdomen are involved.[2] This high mortality rate in the civilian literature is despite utilization of aggressive debridement and appropriate antifungal therapy similar to what has been utilized in the military treatment facilities. Current systemic antifungal agents for IFI have been defined by the infectious disease literature as intravenous amphotericin B because of its in vitro activity and lower toxicity or the newer azole preparations, such as voriconazole and posaconazole in resistant cases.[2,9,13,14]

These infections lead to anecdotal reports of dramatic shortening, and frequently the ablation of residual limbs secondary to the

[1]Integrated Department of Orthopaedics and Rehabilitation, Walter Reed National Military Medical Center, Bethesda, MD; [2]Uniformed Services University of Health Sciences, Bethesda, MD.

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Figure 1. Right elbow disarticulation following revision amputation.

Figure 2. Left forearm with prominent soft tissue loss and tissue necrosis.

Figure 3. Left transfemoral amputation with evidence of fat necrosis on presentation.

aggressive debridement of tissue necessary to gain control of the advancing necrosis. With the addition of Dakin's solution through either Instill Wound V.A.C.™ or intravenous tubing in conjunction with traditional negative pressure wound therapy, we successfully managed critically ill patients whose outcome may have been dramatically worse without this novel treatment modality.

Recently, Barsoumian, et al. have looked at the in vitro activity and toxicity of dilute Dakin's solution in comparison to mafenide acetate and amphotericin B and found that Dakin's solution possessed a more reliable efficacy and toxicity balance.[15] Our continued experience with Dakin's solution and initial research from the Trauma Infectious Disease Outcome Study has led to the establishment of a Joint Theater Trauma System Clinical Practice Guideline for the treatment of suspected invasive fungal infection in war wounds.[16] The clinical practice guidelines currently recommend commencement of Dakin's irrigation during the first debridement in theater if the patient has three of the four following risk factors, 1) dismounted blast injury, 2) above-knee immediate traumatic amputation or progressive transition from below-knee to through-knee to above-knee amputation, 3) extensive perineal, genitourital, and/or rectal injury, or 4) super massive transfusion > 25 units packed red blood cells and whole blood.[17]

Further direction of investigation will allow for quantitative evaluation of the loss of residual limb length and functional levels in comparison to a control group with similar blast injuries. We as well hope to define further risk factors and methods for diagnosis in order to decrease the rate of disseminated infections, and therefore decrease the morbidity and mortality of IFI.

CONCLUSION

We have described our relative success in the treatment of IFI with the addition of Dakin's solution administration with negative pressure wound therapy as an adjunct to standard surgical management. Although this may demonstrate returning to a 150-year-old technique of wound care,[10] we feel that this treatment modality, in addition to aggressive debridement, and culture-directed intravenous antifungal chemotherapy can help dramatically decrease the mortality rate associated with these catastrophic infections.

This article contains the authors' most current findings, however, for a complete report of cases, refer to Lewandowski L, Purcell R, Fleming M, Gordon WT. The Use of Dilute Dakin's Solution for the Treatment of Angioinvasive Fungal Infection in the Combat Wounded: a Case Series. Mil Med. 2013 Apr;178(4):e503-e507.

REFERENCES

1. Belfiori R, Terenzi A, Marchesini L, Repetto A. *Absidia Corymbifera* in an immune competent accident victim with multiple abdominal injuries: case report. *BMC Infect Dis.* 2007;7:46.
2. Bouza E, Munoz P, Guinea J. Mucormycosis: an emerging disease? *Clin Microbiol Infect.* 2006;12 (suppl 7):7-23.
3. Vega W, Orellana M, Zaror L, Gené J, Guarro J. Saksenaea vasiformis infections: case report and literature review. *Mycopathologia*. 2006;162:289-294.
4. Constantinides J, Misra A, Nassab R, Wilson Y. *Absidia corymbifera* fungal infection in burns: a case report and review of the literature. *J Burn Care Res.* 2008;29:416-419.
5. Garbino J, Uçkay I, Amini K, Puppo M, Richter M, Lew D. Absidia post-traumatic infection: successful treatment with posaconazole. *J Infect*. 2005;51:e135-e138.
6. Johnson PC, Satterwhite TK, Monheit JE, Parks D. Primary cutaneous mucormycosis in trauma patients. *J Trauma* 1987;27:437-441.
7. Kontogiorgi M, Floros I, Koroneos A, et al. Fatal post-traumatic zygomycosis in an immunocompetent young patient. *J Clin Microbiol*. 2007;56:1243-1245.
8. Roden M, Zaoutis T, Buchanan W, et al. Epidemiology and outcome of zygomycosis: a review of 929 reported cases. *Clin Infect Dis.* 2005;41:634-653.
9. Dakin HD. On the use of certain antiseptic substances in treatment of infected wounds. *Br Med J*. 1915; 2(2852):318-320.
10. Murray CK, Hinkle MK, Yun HC. History of infections associated with combat-related injuries. *J Trauma*. 2008;64(3suppl):S221–S231.
11. Simbli M, Hakim F, Koudieh M, Tleyjeh IM. Nosocomial post-traumatic cutaneous mucormycosis: a systematic review. *Scand J Infect Dis*. 2008;40:577-582.
12. Notes from the field: fatal fungal soft-tissue infections after a tornado --- Joplin, Missouri, 2011. *MMWR Morb Mortal Wkly Rep*. 2011;60:992.
13. Hay RJ. Mucormycosis: an infectious complication of traumatic injury. *Lancet*. 2005;365:830-831.
14. Dannaoui E, Afeltra J, Meis JF, Verweij PE. In vitro susceptibilities of zygomycetes to combinations of antimicrobial agents. *Antimicrob Agents Chemother.* 2002;46:2708-2711.
15. Barsoumian A, Sanchez CJ, Mende K, et al. In vitro toxicity and activity of Dakin's solution, Mafenide Acetate, and Amphotericin B on filamentous fungi and human cells. *J Orthop Trauma*. 2013 Jan 2. [Epub ahead of print].
16. Warkentien T, Rodriguez C, Lloyd B, et al. Invasive mold infections following combat-related injuries. *Clin Infect Dis*. 2012 Dec;55(11):1441-1449.
17. Treatment of Suspected Invasive Fungal Infection in War Wounds. Joint Theater Trauma System Clinical Practice Guideline. 2012.

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Neurovascular Entrapment due to Combat-Related Heterotopic Ossification

[1,2,3]CPT Elizabeth M. Polfer, MD; [1,2,3]CDR Jonathan A. Forsberg, MD; [1,3]CDR Mark E. Fleming, DO; [1,2,3]MAJ(P) Benjamin K. Potter, MD

INTRODUCTION

Heterotopic ossification (HO) is the ectopic formation of mature lamellar bone in nonosseous tissue. HO frequently develops in the upper and lower extremities following blunt trauma and is most common after elbow and actetabular fractures, burns, traumatic brain injury (TBI), and spinal cord injury.[1] The prevalence of HO following combat injuries, including traumatic amputations, is much higher than civilian data would suggest. Between 63% and 65% of all combat casualties with open extremity injuries or amputations develop HO.[2,3] In amputees, nearly 20% of affected amputations require surgical excision.[3] In select cases, the aberrant bone formation can envelop major neurovascular structures, such as the sciatic or tibial nerves, as well as the femoral or posterior tibial arteries, leading to symptomatic neurovascular entrapment.[4]

Sciatic nerve entrapment secondary to HO was first described by Kleiman and Pankovich[5] in 1971. Their initial case report described sciatic nerve dysfunction secondary to HO following operative fixation of a posterior fracture-dislocation of the hip. A review of the literature, summarized in Table 1, demonstrates that sciatic nerve dysfunction associated with HO is rare and most commonly reported after acetabular fractures;[5-9] however, two cases involved neurogenic HO[10,11] and another developed following repetitive trauma attributed to weight lifting.[12] One case report described HO leading to dysfunction of the common peroneal nerve following burn injury.[13] In the upper extremities, nerve entrapment by HO has been reported following trauma,[14] traumatic brain injury[15-17] and severe burns.[17-19] Though the relationship between systemic inflammation and HO is well-established, neurologic entrapment in the lower extremities secondary to blast trauma has not been reported to our knowledge, nor has the pre-operative planning and surgical technique been adequately discussed. Likewise, we are not aware of any reported cases of major vessel incarceration.

We present a series of five consecutive patients, two of which are detailed below, treated at our institution, who developed neurovascular entrapment secondary to severe HO after blast injury (Table 2). In doing so, we describe our preferred method of patient assessment, preoperative planning, and surgical excision.

[1]Department of Orthopaedics, Walter Reed National Military Medical Center, Bethesda, MD; [2]Regenerative Medicine, Naval Medical Research Center, Silver Spring, MD; [3]Department of Surgery, Uniformed Services University of the Health Sciences, Bethesda, MD.

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CASE SERIES

Case 1

A 26-year-old male sustained a blast injury due to an improvised explosive device (IED) while on foot patrol (dismounted IED). He presented with an injury severity score (ISS) of 22, mild TBI, large left anteromedial thigh soft tissue injury with volumetric muscle and soft tissue loss, as well as other minor musculoskeletal injuries to other extremities. For management of his left thigh injury, he underwent multiple irrigation and debridements until wound coverage with split-thickness skin graft (STSG). He presented at his five-month follow-up with significantly decreased knee range of motion (ROM) (0º to 15°) and focal wound ulceration over palpable, underlying HO. Pre-operative radiographs demonstrated severe HO about the medial distal femur, as shown in Figure 1. A CT angiogram demonstrated encasement of the superficial femoral vessels by HO, which was also tethering his quadriceps musculature. He returned to the operating room six months after injury for HO excision, vascular decompression, and lysis of knee adhesions with quadricepsplasty. Multiple branches of the superficial femoral artery and vein were ligated intraoperatively, but femoral and popliteal artery and vein patency and continuity were preserved. Postoperatively, the patient required additional procedures – a repeat lysis of adhesions at two months and irrigation and debridement shortly thereafter to treat a subsequent deep post-surgical infection. At final follow-up, six months after the index procedure, the patient regained active knee ROM from 0° to 90° and had no vascular symptoms. This patient, and all subsequent patients in this series, received secondary HO prophylaxis in the form of off-label use of celecoxib, 100 mg twice daily or 200 mg once daily, beginning immediately postoperative for four weeks. We observed no radiographically-evident HO recurrence in any patient.

Case 2

A 19-year-old male sustained a dismounted IED blast and presented with an ISS of 20, mild TBI, open distal comminuted right femur fracture, right leg soft tissue injury with posterior tibial artery transection requiring fasciotomies, and other musculoskeletal injuries. His femur fracture was initially stabilized using a knee spanning external fixator that was later converted to an intramedullary nail. His soft tissue injuries were closed with STSG following serial debridements. At his ten-month follow-up, he presented with progressive neurological deficits, continued pain, ulcerations due to underlying HO, and decreased knee and ankle ROM. He reported paraesthesias in the sural, saphenous, tibial, and superficial peroneal nerve distributions and decreased motor function (3/5 strength for tibialis anterior, extensor hallicus longus, flexor hallicus longus, and triceps surae). Pre-operative radiographs depicted in Figure 2 demonstrate moderate and severe HO about the right distal femur and tibia,

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Table 1. Previous Case Reports of Heterotopic Ossification Involving Neurologic Entrapment

Authors	Number of patients	Inciting event	Entrapped structures	Symptoms	Electro-diagnostic studies	Treatment	Results of treatment
Kleiman, et al.[5]	1	Right posterior hip dislocation with posterior wall fracture s/p ORIF	Right sciatic nerve	Partial sensory and motor deficits in peroneal nerve distribution	N/A	Neurolysis and excision at 4.5 months after injury	Complete return of sensation at 2 months and no return of motor after 24 months
Derian, et al.[6]	1	Right posterior hip dislocation with acetabular fracture s/p closed reduction and traction	Right sciatic nerve	Complete right sciatic nerve deficit	N/A	Neurolysis and excision at 2 months after injury	Near complete return of function (all motor groups ≥ 4/5) 20 months post op
Manidakis, et al.[8]	1	Left posterior hip dislocation with posterior wall acetabular fracture s/p ORIF	Left sciatic nerve	Paraesthesiae in L5/S1 dermatomes, decreased motor function in TA and EHL	Conduction block consistent with a lesion of the sciatic nerve at the hip	Neurolysis and excision at 8 weeks	Full sensory (2 months) and motor (6 months)
Safaz, et al.[11]	1	TBI s/p MVA	Bilateral sciatic nerves	Weakness in bilateral lower extremities (2/5 right 4/5 left)	Bilateral axonal degeneration of the sciatic nerves (total on right, partial on left)	Physical therapy	
Jones, et al.[12]	1	Recurrent minor trauma from weight lifting	Left sciatic nerve	Paraesthesias of left L5/S1, complete paralysis of left TA, EHL, EDL, PL, PB weakness of GS, loss of Achilles reflex	Normal conduction of the left sciatic nerve to the level of the HO but not distal to it	Exploration and excision 2 months after symptoms	At 24 months, no detectable motor weakness, improved but decreased sensation, no improvement in Achilles reflex
Thakker, et al.[9]	1	Left posterior hip dislocation with acetabular fracture and sciatic nerve laceration s/p ORIF and nerve repair	Left sciatic nerve	Pain and paraethesias along medial aspect of his leg and foot drop	None	Exploration, excision, neurolysis	Resolution of pain and paraesthesias with continued foot drop at 2 years post op
Brooke, et al.[21]	1	Closed head injury after motorcycle accident	Right femoral nerve	0/5 motor in the quadriceps; decreased hip ROM	4+ positive sharp waves and fibrillations without voluntary motor units in the quadriceps	Exploration and excision of HO with epineuriolysis	Improved hip ROM with near normal return of motor function at 19 months
Laborde, et al.[10]	1	Respiratory distress and intubation x 3 weeks	Right sciatic nerve	Weakness in right leg in the tibial nerve distribution	N/A	Medical management with cox-2 inhibitors	Not reported

s/p, status post; ORIF, open reduction and internal fixation; TA, tibialis anterior; EHL, extensor hallicus longus; TBI, traumatic brain injury; MVA, motor vehicle accident; EDL, extensor digitorium longus; PL, peroneus longus; PB, peroneus brevis; GS, gastroc-soleus

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Table 2. Description of Cases

Case	Age	ISS	TBI	Injury leading to HO	Grade of HO	Symptoms	Enveloped structures	Post surgery
1	26	22	Mild	Left thigh STI	Severe	Left knee decreased ROM (flexion-extension arc 0°-15°), ulceration, pain	Superficial femoral vessels	Improved active knee ROM (flexion-extension arc 0°-140°), resolution of ulcerations, and no vascular compromise
2	19	20	Mild	Open right femur fracture and right leg STI	Moderate (femur); severe (tibia)	Foot paraesthesias and decreased motor function (3/5 TA, EHL, FHL, and GS)	Profunda femoris artery and vein, posterior tibial and peroneal vessels, tibial nerve	Improvement in sensation and pain, resolution of paraesthesias, regained full motor strength
3	22	29	Mild	Open right femur fracture	Severe	Right thigh discomfort, decreased knee ROM plantar paraesthesias	Sciatic nerve	Regained full knee ROM; paraesthesias resolved
4	25	29	Mild	Right thigh STI	Severe	Progressive neurologic deficits (3/5 TA, 2/5 GS, 2/5 HS), ulceration, pain, and decreased R hip ROM (10°-50° flexion, 10° adduction, 15° abduction)	Sciatic nerve	Improved hip ROM, distal dysesthesias, and motor function (3/5 TA, 4/5 GS, 3/5 HS) improved
5	27	29	Mild	Left transfemoral amputation	Severe	Decreased left hip ROM (4° adduction, °0-10° hip flexion-extension arc), pain	Sciatic nerve	Improvement in hip ROM (flexion-extension arc 0-90° actively and 0-105° passively)

ISS, injury severity score; TBI, traumatic brain injury; HO, heterotopic ossification; STI, soft tissue injury; ROM, range of motion; TA, tibialis anterior; EHL, extensor hallicus longus; FHL, flexor hallicus longus; GS, gastrocnemius-soleus complex; HS, hamstrings

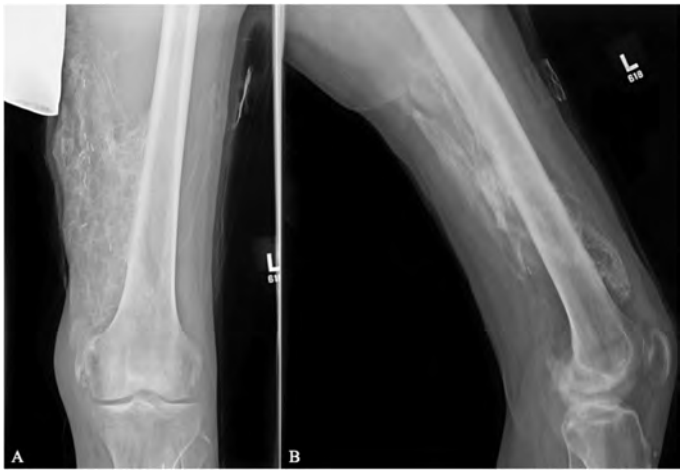

Figure 1. Pre-operative AP (**A**) and lateral (**B**) radiographs of the left distal femur of case 1 demonstrating severe HO.

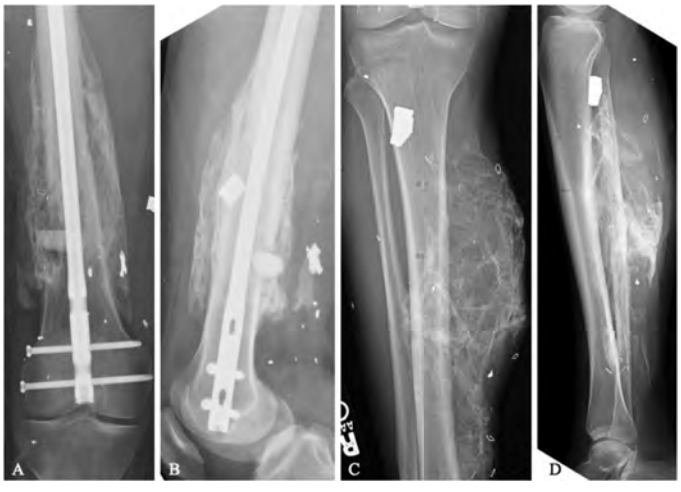

Figure 2. Pre-operative AP (**A**) and lateral (**B**) radiographs of the right distal femur, demonstrating moderate HO and AP (**C**) and lateral (**D**) radiographs of the right tibia, demonstrating severe HO in case 2.

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respectively. A CT scan demonstrated encasement of the profunda femoris artery and vein and the posterior tibial and peroneal vessels and the tibial nerve in the leg, shown in Figure 3. The CT scan was used to make a resin model, seen in Figure 4. Fourteen months after injury, he underwent HO excision of the right posterior thigh and leg, as well as excision of the entire STSG and overlying areas of ulceration. Intra-operative photographs are seen in Figure 5. Following excision, he reported immediate improvement in sensation and pain, and complete resolution of paraesthesias. At his 11-month follow-up, he had full motor strength in all distributions.

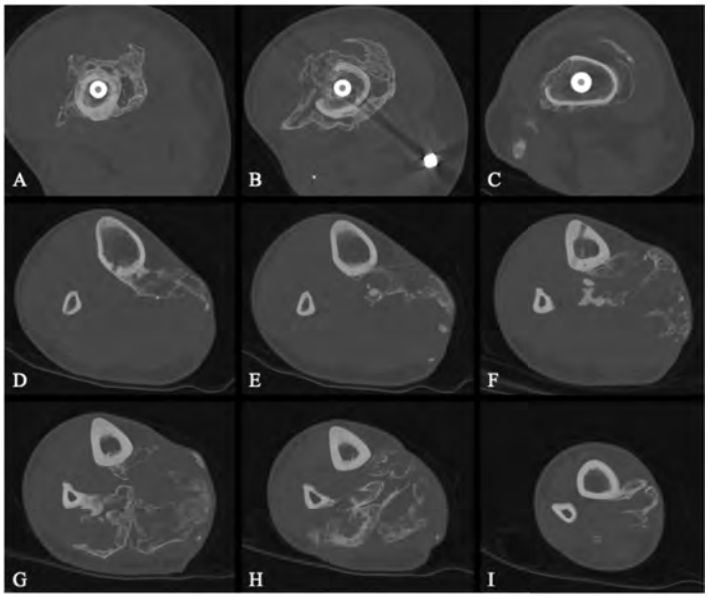

Figure 3. Axial CT scan, moving from proximal to distal, of case 2, demonstrating encasement of the deep artery and vein in the thigh (**A-C**) and the posterior tibial and peroneal arteries as well as the tibial nerve in the leg (**D-I**).

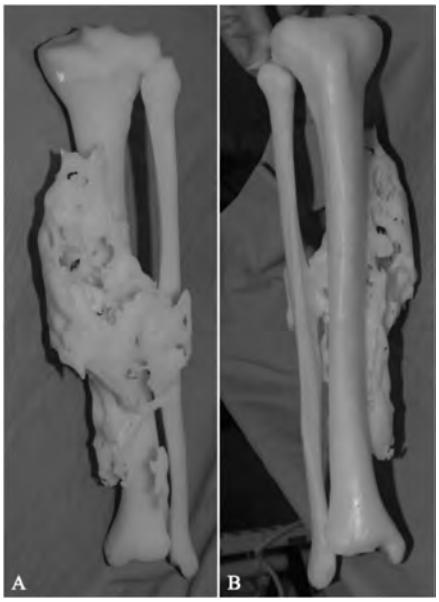

Figure 4. Posterior (**A**) and anterior (**B**) views of the 3D resin model constructed from the CT scan of case 2 and used intraoperatively.

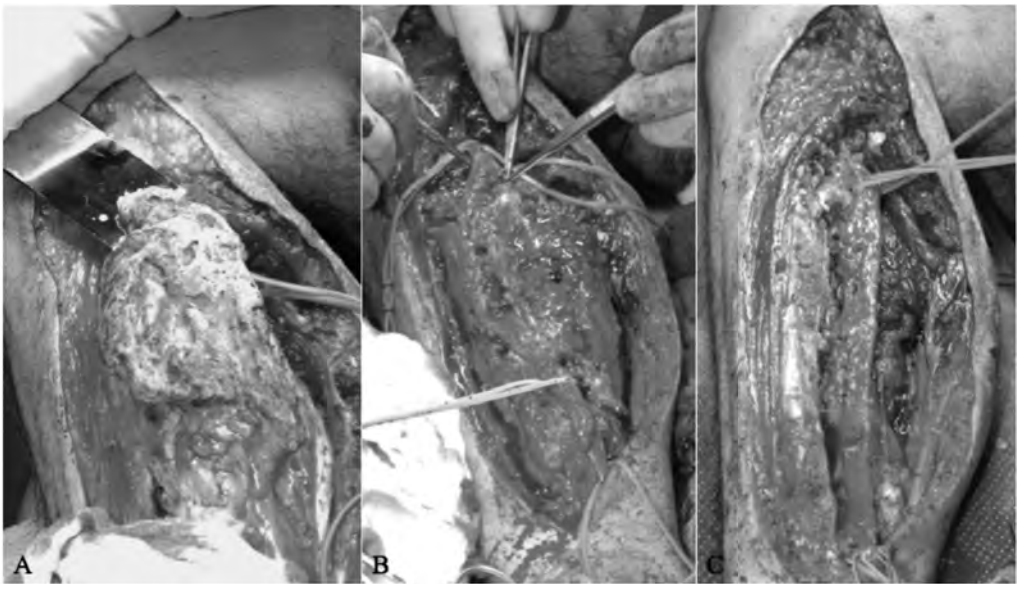

Figure 5. Intraoperative images demonstrating the initial mass of HO with proximal and distal identification of the neurovascular bundle marked with vessel loops (**A**), after removal of a portion of the HO that was directly over the neurovascular bundle (**B**). Final image after removal of the symptomatic HO (**C**).

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DISCUSSION

The cases presented herein demonstrate that severe heterotopic ossification can lead to late neurologic and vascular symptoms due to neurovascular entrapment. These symptoms can be seen in addition to the more commonly described sequelae of HO, such as pain, wound ulceration, and decreased joint ROM. All five patients sustained blast injuries and mild TBI. During outpatient rehabilitation, each developed debilitating symptoms that halted, and in some cases regressed, their progress with therapy. The patients returned to the operating room, on average, ten months after initial injury for HO excision, decompression or neurolysis of the entrapped neurovascular structures, and concurrent procedures such as soft tissue revisions or lysis of adhesions.

Previous reports of HO with symptomatic neurologic entrapment have focused predominantly on reporting singular cases and clinical outcomes, with respect to resolution of neurologic symptoms and recurrence, as opposed to the pre-operative planning and surgical techniques, which are the focus of this report. However, our clinical outcomes globally resulted in successful functional preservation of the entrapped neurovascular structures and improved ROM without clinical or radiologic evidence of HO recurrence.

Preoperative Planning

Preoperative assessment begins with a thorough physical examination. Neurological deficits should be characterized as static or progressive and focus on the distribution of the sensory deficits and degree of motor weakness. The soft tissue envelope should be examined for previous traumatic wounds, surgical incisions, STSG, and ulcerations that require excision. We obtain pre-operative CT scans to characterize the HO and the relationship between the HO and named neurovascular structures, as recommended.[4,7,8,20] CT angiograms can also yield important information when there is concern for vessel involvement.

At our institution, CT also allows for the construction of three-dimensional resin models, as seen in Figure 6. These models allow one to plan the operative approach and osteotomies, as well as to refer to the model intraoperatively. We find this helpful because each lesion is distinct and uniquely shaped, and the lesional topography becomes particularly important given the obfuscation of normal anatomy common in blast wounds that have undergone various types of surgical procedures, as well as tethering of structures to and within the HO. Intraoperatively, these models are referenced as anatomical guides to dissection and piecemeal resection.

Each patient is typed and cross-matched for at least two units of packed red blood cells. Additionally, we find the following equipment helpful during surgery: loupe magnification, bipolar coagulation in addition to standard monopolar electrocautery, a full array of ronguers and periosteal elevators (*e.g.*, Cobb, Key), as well as instruments and available expertise necessary to reconstruct/repair the involved nerve(s) or vessel(s)—although the latter have fortunately not been necessary to date. Koulouvaris and colleagues[20] also include cell saver and possible intra-operative electrical stimulation, which we have utilized twice, in their preparations for surgery as well as a pre-operative bone scan to determine the maturity of the HO prior to excision. There is no clear consensus on when ectopic bone lesions should be excised, however, in the setting of progressive neurological deficits and symptoms, early surgical exploration/excision of HO is advocated.[5,6,8,21]

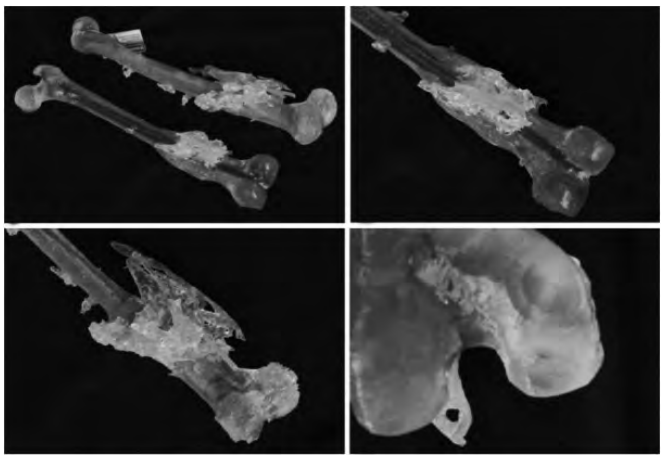

Figure 6. Examples of two resin models demonstrating heterotopic ossification of the femur. They were used to plan the operative approach and as anatomical guides to dissection and piecemeal resection.

Operative Technique

Excision of heterotopic ossification is associated with relatively high rates of major short-term complications, including neurovascular injury, substantial blood loss, increased hospital stay, fracture, and infection.[20,22] We attempt to use prior traumatic incisions whenever possible. If this is not a viable option, we use a direct approach over the most superficial symptomatic area and extend our exposure longitudinally from that region. The involved neurovascular structures are identified and isolated both proximal and distal to the area of entrapment whenever remotely feasible. Once adequate exposure or limited removal of the HO mass has been achieved, the nerve or vessels can be traced directly into the offending area and gradually mobilized via meticulous sharp and blunt dissection and pituitary rongeur removal of the overlying HO. Kleiman and coauthors[5] described removal of the entire mass of HO, but partial resection of only the symptomatic areas can also be successful in carefully selected patients.[3,4,20] Our aim is not necessarily to remove all HO if doing so would sacrifice a substantial amount of uninvolved soft tissue, although complete resection is performed when practicable. In these latter instances, we remove only that which is symptomatic—in this series, the HO that was entrapping/compressing the neurovascular structures.

Post-operative secondary prophylaxis has also been described such as the use of nonsteroidal anti-inflammatory drugs (indomethacin,[20,23,24] cyclooxygenase-2 inhibitors, naproxen, ibuprofen), local radiation therapy[25,26] (700 cGy preoperatively or within 24 hours postoperatively), a combination of both,[3,4,8,27,28] and no prophylaxis. In the present series, each patient received celecoxib, as described above, and no patient developed radiographically evident or symptomatic recurrence of HO.

In the short term, all patients who underwent excision demonstrated functional improvement. All patients who had complaints of neuropathic pain had improvement in their pain after the initial post-operative phase. Those with impaired ROM regained motion as described above. As might be expected, we found that sensory deficits resolved prior to motor deficits.

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Long-term complications of HO excisions include recurrence and wound breakdown. Heterotopic ossification recurrence has been described in the literature with varying rates, from zero to nearly 100%;[22-25] however, the severity of recurrence was not always described. Furthermore, the recurrence rate varies widely with the inciting event (*e.g.*, higher recurrence rates are typically associated with neurogenic HO), timing of excision, and secondary prophylaxis. Ebinger, et al.[26] reported a recurrence rate of 93% in the hip, although none of their patients required repeat excision, whereas Genet, et al.[28] had a recurrence rate of 6%, but only reported patients requiring repeat excision. A meta-analysis[27] evaluating recurrence of HO after TBI included 255 patients in 16 studies. The authors estimated the recurrence rate at 19.8%, but did not describe the clinical relevance of these recurrences. Fortunately, clinically significant HO recurrence has not been a frequent complication in combat casualties[3,29] and did not occur in this series. In the present series, however, one patient developed wound-healing complications leading to infection and operative intervention.

In conclusion, we found that HO entrapping major neurovascular structures following severe extremity trauma can be safely excised with careful pre-operative planning and meticulous operative excision. Excision is associated with a relatively low rate of recurrence and reliably appears to resolve the symptoms associated with neurovascular compression. Generally favorable clinical results are achievable despite the relative complexity of the dissections and excisions required.

REFERENCES

1. Kaplan FS, Glaser DL, Hebela N, Shore EM. Heterotopic ossification. *J Am Acad Orthop Surg.* Mar-Apr 2004;12(2):116-125.
2. Forsberg JA, Pepek JM, Wagner S, et al. Heterotopic ossification in high-energy wartime extremity injuries: prevalence and risk factors. *J Bone Joint Surg Am.* May 2009;91(5):1084-1091.
3. Potter BK, Burns TC, Lacap AP, Granville RR, Gajewski DA. Heterotopic ossification following traumatic and combat-related amputations. Prevalence, risk factors, and preliminary results of excision. *J Bone Joint Surg Am.* Mar 2007;89(3):476-486.
4. Potter BK, Forsberg JA, Davis TA, Granville RR, Gajewski DA. Heterotopic ossification following combat-related trauma. *J Bone Joint Surg Am.* Dec 2010;92 Suppl 2:74-89.
5. Kleiman SG, Stevens J, Kolb L, Pankovich A. Late sciatic-nerve palsy following posterior fracture-dislocation of the hip. A case report. *J Bone Joint Surg Am.* Jun 1971;53(4):781-782.
6. Derian PS, Bibighaus AJ. Sciatic nerve entrapment by ectopic bone after posterior fracture-dislocation of the hip. *South Med J.* Feb 1974;67(2):209-210.
7. Issack PS, Helfet DL. Sciatic nerve injury associated with acetabular fractures. *HSS J.* Feb 2009;5(1):12-18.
8. Manidakis N, Kanakaris NK, Nikolaou VS, Giannoudis PV. Early palsy of the sciatic nerve due to heterotopic ossification after surgery for fracture of the posterior wall of the acetabulum. *J Bone Joint Surg Br.* Feb 2009;91(2):253-257.
9. Thakkar DH, Porter RW. Heterotopic ossification enveloping the sciatic nerve following posterior fracture-dislocation of the hip: a case report. *Injury.* Nov 1981;13(3):207-209.
10. Laborde A, Hermier M, Cotton F. Clinical Vignette. Sciatic nerve entrapment secondary to heterotopic ossification: imaging findings and potential effect of selective cox-2 inhibitors. *Rheumatology (Oxford).* Jan 2005;44(1):110.
11. Safaz I, Alaca R, Bozlar U, Yaşar E. Bilateral sciatic nerve entrapment due to heterotopic ossification in a traumatic brain-injured patient. *Am J Phys Med Rehabil.* Jan 2008;87(1):65-67.
12. Jones BV, Ward MW. Myositis ossificans in the biceps femoris muscles causing sciatic nerve palsy. A case report. *J Bone Joint Surg Br.* Nov 1980;62-B(4):506-507.
13. Lippin Y, Shvoron A, Yaffe B, Zwas ST, Tsur H. Postburn peroneal nerve palsy--a report of two consecutive cases. *Burns.* Jun 1993;19(3):246-248.
14. Garland DE. A clinical perspective on common forms of acquired heterotopic ossification. *Clin Orthop Relat Res.* Feb 1991(263):13-29.
15. Denormandie P, Viguie G, Denys P, Dizien O, Carlier R. Results of excision of heterotopic new bone around the elbow in patients with head injuries. A series of 25 cases. *Chir Main.* 1999;18(2):99-107.
16. Fikry T, Saidi H, Madhar M, Latifi M, Essadki B. [Cubital tunnel syndrome and heterotopic ossification. Eight case reports]. *Chir Main.* Apr 2004;23(2):109-113.
17. Hamdi MF, Aloui I, Allagui M. [Ulnar nerve compression at the elbow and heterotopic ossification: a report of five cases]. *Neurochirurgie.* Aug 2010;56(4):340-343.
18. Tsionos I, Leclercq C, Rochet JM. Heterotopic ossification of the elbow in patients with burns. Results after early excision. *J Bone Joint Surg Br.* Apr 2004;86(3):396-403.
19. Vorenkamp SE, Nelson TL. Ulnar nerve entrapment due to heterotopic bone formation after a severe burn. *J Hand Surg Am.* May 1987;12(3):378-380.
20. Koulouvaris P, Tsailas P, Tsiavos K, Soucacos PN. Clinical observations on surgical details of resection of heterotopic ossification at the hip in traumatic brain-injured adult. *J Surg Orthop Adv.* Fall 2010;19(3):177-180.
21. Brooke MM, Heard DL, de Lateur BJ, Moeller DA, Alquist AD. Heterotopic ossification and peripheral nerve entrapment: early diagnosis and excision. *Arch Phys Med Rehabil.* May 1991;72(6):425-429.
22. Stover SL, Niemann KM, Tulloss JR. Experience with surgical resection of heterotopic bone in spinal cord injury patients. *Clin Orthop Relat Res.* Feb 1991(263):71-77.
23. Ippolito E, Formisano R, Caterini R, Farsetti P, Penta F. Operative treatment of heterotopic hip ossification in patients with coma after brain injury. *Clin Orthop Relat Res.* Aug 1999(365):130-138.
24. Wick M, Muller EJ, Hahn MP, Muhr G. Surgical excision of heterotopic bone after hip surgery followed by oral indomethacin application: is there a clinical benefit for the patient? *Arch Orthop Trauma Surg.* 1999;119(3-4):151-155.
25. Meiners T, Abel R, Bohm V, Gerner HJ. Resection of heterotopic ossification of the hip in spinal cord injured patients. *Spinal Cord.* Jul 1997;35(7):443-445.
26. Ebinger T, Roesch M, Kiefer H, Kinzl L, Schulte M. Influence of etiology in heterotopic bone formation of the hip. *J Trauma.* Jun 2000;48(6):1058-1062.
27. Chalidis B, Stengel D, Giannoudis PV. Early excision and late excision of heterotopic ossification after traumatic brain injury are equivalent: a systematic review of the literature. *J Neurotrauma.* Nov 2007;24(11):1675-1686.
28. Genet F, Jourdan C, Schnitzler A, et al. Troublesome heterotopic ossification after central nervous system damage: a survey of 570 surgeries. *PLoS One.* 2011;6(1):e16632.
29. Forsberg JA, Potter BK. Heterotopic ossification in wartime wounds. *J Surg Orthop Adv.* Spring 2010;19(1):54-61.

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Outcomes of Single-Level Cervical Disc Arthroplasty versus Anterior Cervical Discectomy and Fusion: a Single Center, Retrospective Review

[1]LCDR Robert W. Tracey, MD; [1]CPT John P. Cody, MD; [1]CPT Daniel G. Kang, MD; [1]CPT Adam J. Bevevino, MD; [2]LTC Michael K. Rosner, MD; [1,3]LTC Ronald A. Lehman, Jr., MD

INTRODUCTION

Cervical disc arthroplasty (CDA) has been espoused as a safe, segmental motion-sparing alternative to anterior discectomy and fusion (ACDF) in the treatment of cervical radiculopathy and myelopathy resulting from spondylosis and acute disc herniation. Although ACDF is the current standard for treatment of cervical radiculopathy and myelopathy, concerns exist over symptomatic adjacent-segment disc degeneration.[1-2] Furthermore, cadaver studies have demonstrated increased motion and intra-discal pressures adjacent to cervical fusion levels.[3-4] These concerns have led to the development and use of several cervical disc arthroplasty systems. Anticipated benefits of CDA include maintaining alignment and motion as well as decreasing stress on the adjacent-level disc, which may decrease symptomatic adjacent level disc degeneration.[5] General indications for CDA include reconstruction after neural decompression of disc herniation or foraminal osteophytes causing radiculopathy or myelopathy. Contraindications include deformity, immobile segments, instability, and facet joint degeneration. Relative contraindications include rheumatoid arthritis, renal failure, osteoporosis, cancer, and pre-operative corticosteroids.[6-7]

Short-term results from several small randomized controlled trials demonstrated that CDA was associated with better overall success, better neurologic success, and fewer revision procedures.[8-12] However, there are few single center comparison studies, and current studies do not contain large numbers of patients. Based on our experience with CDA, we performed a review comparing outcomes and complications in patients undergoing single-level CDA and single-level ACDF at a single institution.

MATERIALS AND METHODS

Following approval from our institutional review board, the surgical database at our institution was queried to identify all patients who had undergone single-level cervical disc arthroplasty or single-level anterior discectomy and fusion between August 2008 and August 2012. Seven surgeons (5 neurological surgeons and 2 spine fellowship-trained orthopaedic surgeons) were the primary surgeon performing the respective procedure. The search yielded 180 CDA patients and 95 ACDF patients. In the CDA group, 9 patients were lost to follow-up and 7 patients in the ACDF group were also lost to follow-up, which left 259 total patients (171 in the CDA group and 88 in the ACDF group) for review. Both groups included patients undergoing primary and revision surgery. All data were collected via a retrospective chart analysis, which included inpatient and outpatient clinical notes, surgical databases, and radiographs, and subsequently analyzed by independent researchers. Data collected included patient demographic information (age, sex, tobacco use, BMI), patient-centered outcomes (complete relief of pre-operative symptoms, relief of pre-operative neurologic symptoms, return to pre-operative level of activity, return to active duty for patients in the military), and complications (incidence of persistent post-operative posterior neck pain, recurrent laryngeal nerve injury, persistent dysphagia, post-operative respiratory compromise, esophageal/tracheal disruption, implant failure, adjacent segment degeneration, intra-operative fracture, dural tear, nerve root injury). Persistent posterior neck pain and dysphagia were defined in the study as symptoms lasting longer than 3 months in the post-operative period or requiring secondary intervention.

RESULTS

In the CDA group, there were 134 males (78.4%) and 37 females (21.6%) with an average age of 40.5 (± 8.3) years. In the ACDF group, there were 65 males (73.9%) and 23 females (26.1%) and the average age was 47.5 (± 12.4) years. The average follow-up was 9.8 (± 9.9) months for the CDA group and 11.8 (± 9.6) months for the ACDF group. The average BMI was 27.8 (± 3.8) kg/m^2 for CDA patients and 28.9 (± 5.7) kg/m^2 for ACDF patients. Tobacco use was higher in the CDA group at 28.1% (132 patients) as compared to the ACDF group at 17.0% (15 patients). Revision surgery was more common in the ACDF group than the CDA group (23.9% versus 4.7%). In the CDA group, 132 patients (77.2%) were on active duty in the military at the time of surgery compared to only 40 patients (45.5%) in the ACDF group.

The primary indication for CDA was radiculopathy in 154 patients (90.1%). Other indications included myelopathy (1.8%), myelo-radiculopathy (5.8%), and neck pain (2.3%). In the ACDF group, the primary indication for surgery was radiculopathy in only 63.6% of patients and myelopathy in 18.2% of patients. Other indications included myelo-radiculopathy (5.7%), neck pain (5.7%), trauma (3.4%), and pseudoarthosis (3.4%). The most common levels addressed at the time of surgery in the CDA group were C6-7 followed by C5-6 (50.9% and 38.0%, respectively). In the ACDF cohort, the most common levels of disease were C5-6 and C6-7 (44.3% and 23.9%, respectively). Levels C3-4 and C4-5 were commonly involved in the ACDF group (13.6% and 15.9%, respectively) as compared to the CDA group (2.3% and 8.2%, respectively for C3-4 and C4-5). One patient underwent anterior cervical discectomy and fusion at C2-3 and one patient in each group had surgery at C7-T1 (Table 1).

[1]Department of Orthopaedic Surgery, Walter Reed National Military Medical Center, Bethesda, MD; [2]Department of Neurosurgery, Walter Reed National Military Medical Center, Bethesda, MD; [3]Division of Orthopaedics, Department of Surgery, Uniformed Services University of the Health Sciences, Bethesda, MD. Address correspondence Robert W. Tracey, MD, rwtracey@gmail.com.

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Table 1. Patient Demographics		
	CDA	**ACDF**
Total patients	171	88
Males	134 (78.4%)	65 (73.9%)
Females	37 (21.6%)	23 (26.1%)
Age	40.5 ± 8.3 years	47.5 ± 12.4 years
BMI	27.8 (± 3.8) kg/m^2	28.9 (± 5.7) kg/m^2
Tobacco use	48 (28.1%)	15 (17.0%)
Active duty military	132 (77.2%)	40 (45.5%)
Revision surgery	8 (4.7%)	21 (23.9%)
Average follow-up	9.8 ± 9.9 months	11.8 ± 9.6 months
Levels of disease		
C2-3	0	1(1.1%)
C3-4	4 (2.3%)	12 (13.6%)
C4-5	14 (8.2%)	14 (15.9%)
C5-6	65 (38.0%)	39 (44.3%)
C6-7	87 (50.9%)	21 (23.9%)
C7-T1	1 (0.6%)	1 (1.1%)
Primary indication for surgery		
Myelopathy	3 (1.8%)	16 (18.2%)
Radiculopathy	154 (90.1%)	56 (63.6%)
Myelo-radiculopathy	10 (5.8%)	5 (5.7%)
Neck pain	4 (2.3%)	5 (5.7%)
Trauma	N/A	3 (3.4%)
Pseudoarthrosis	N/A	3 (3.4%)

CDA, cervical disc arthroplasty; ACDF, anterior discectomy and fusion; N/A, not applicable

The Prestige™ (Medtronic, Memphis, TN) cervical arthroplasty system was utilized in the majority of patients (94.7%), while the ProDisc-C system (Depuy Synthes, Paoli, PA) was utilized in the remainder of patients (5.3%). The most common surgical implant used in the ACDF group was the traditional anterior cervical plate and interbody spacer (78.4%). Other implants included the stand alone integrated spacer in 11.4% of patients and a spacer-only construct in 10.2% of ACDF patients (Table 2).

Table 2. Type of Surgical Implant		
Surgical Implant	**CDA**	**ACDF**
Prestige	162 (94.7%)	N/A
Pro-Disc C	9 (5.3%)	N/A
Anterior plate/spacer	N/A	69 (78.4%)
Stand alone integrated spacer	N/A	10 (11.4%)
Spacer only	N/A	9 (10.2%)

CDA, cervical disc arthroplasty; ACDF, anterior discectomy and fusion; N/A, not applicable

Of the 171 patients in the CDA group, 157 (91.8%) experienced complete relief of pre-operative neurologic symptoms and 154 patients (90.1%) had complete post-operative symptomatic relief. In the ACDF group, 78 (88.6%) patients had post-operative relief of neurologic symptoms and 76 (86.4%) patients had complete relief of all pre-operative symptoms. Seventeen patients (9.9%) in the CDA group and 12 patients in the ACDF group (13.6%) had incomplete relief of pre-operative symptoms. These patients had persistent posterior neck pain, continued radiculopathy, continued myelopathy, or a combination of the aforementioned symptoms. In both groups, a vast majority of patients were able to return to their pre-operative level of activity (93.0% in the CDA group and 88.6% in the ACDF group). In the active duty military population, 92.4% of patients in the CDA and 84.0% of patients in the ACDF group were able to return to active duty after surgery (Table 3).

Persistent posterior neck pain was observed post-operatively in both cohorts at rates of 15.4% (27 patients) in the CDA group and 12.5% (11 patients) in the ACDF group. Twenty patients (74.1%) in the CDA group who experienced persistent posterior neck pain post-operatively eventually had resolution of their symptoms without intervention at the last recorded follow-up appointment. Similarly, 5 patients (45.5%) in the ACDF group also had resolution by their last recorded follow-up visit. The complication rate was 9.9% in the CDA group, which included recurrent laryngeal nerve injury (2.9%), persistent dysphagia (5.8%), superficial infection (0.6%), and nerve root injury (0.6%). The ACDF complication rate was 9.1%, which included persistent dysphagia (3.4%), pseudoarthosis (3.4%), spinal cord injury (1.1%), and dural tear (1.1%). No implant failures, episodes of post-operative respiratory compromise, esophageal/tracheal disruptions, nor intra-operative fractures were observed in either group in our study. The reoperation rate in the CDA group was 3.5%, including posterior decompression and fusion, adjacent segment degeneration requiring surgery, and conversion of CDA to ACDF. In the ACDF group, the reoperation rate was 5.7%, including posterior decompression and fusion and revision ACDF (Table 4).

DISCUSSION

This study represents the largest, non-funded retrospective comparison review of single-level CDA and single-level ACDF. We found a 90.1% rate of complete pre-operative relief of symptoms and

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Table 3. Surgical Outcomes		
Outcomes	**CDA**	**ACDF**
Relief of neurologic symptoms	157 (91.8%)	78 (88.6%)
Complete relief of symptoms	154 (90.1%)	76 (86.4%)
Return to full activity	159 (93.0%)	78 (88.6%)
Return to active duty military	122/132 (92.4%)	32/40 (84.0%)

CDA, cervical disc arthroplasty; ACDF, anterior discectomy and fusion

Table 4. Surgical Complications		
Complications	**CDA**	**ACDF**
Persistent posterior neck pain	27 (15.4%)	11 (12.5%)
Recurrent laryngeal nerve injury	5 (2.9%)	0 (0.0%)
Persistent dysphagia	10 (5.8%)	3 (3.4%)
Infection (superficial)	1 (0.6%)	0
Pseudoarthrosis	N/A	3 (3.4%)
Nerve root injury	1 (0.6%)	0
Spinal cord injury	0	1 (1.1%)
Dural tear	0	1 (1.1%)
Reoperation during follow-up	6 (3.5%)	5 (5.7%)
Posterior decompression/ fusion	2 (1.2%)	3 (3.4%)
Adjacent segment degeneration	2 (1.2%)	0
Conversion to ACDF	2 (1.2%)	N/A
Revision ACDF	N/A	2 (2.3%)

CDA, cervical disc arthroplasty; ACDF, anterior discectomy and fusion; N/A, not applicable

93.0% rate of return to pre-operative level of activity in the CDA group, which compared to a complete pre-operative symptomatic relief rate of 86.4% and a return to full activity rate of 88.6% in the ACDF group. Active duty service members included in the study returned to active duty post-operatively at a rate of 92.4% in the CDA group and 84.0% in the ACDF group. The disparity in complete symptomatic relief and return to full activity between the groups can partially be attributed to differences in patient demographics. The percentage of patients undergoing revision was five times higher in the ACDF group. Additionally, the indication for surgery for over 90% of patients in the CDA group was radiculopathy, compared to only 64% of patients in the ACDF group.

This review also demonstrated a low complication rate for both groups, in particular for recurrent laryngeal nerve injury (2.9% in the CDA group, 0% in the ACDF group), persistent dysphagia (5.8% in the CDA group, 3.4% in the ACDF group), and adjacent segment degeneration requiring surgery (1.2% in the CDA group, 0% in the CDA group). The dysphagia rate observed for both groups was lower than traditionally reported in the literature for either single-level CDA or single-level ACDF.[13-17] Reoperation rates were lower in the CDA group compared to the ACDF group. These results are consistent with the rates observed in recent randomized controlled trials between CDA and ACDF.[9, 11]

While short-term results have demonstrated CDA as a safe and reliable alternative to ACDF, no long-term results currently exist comparing these two surgical techniques. At this point, ACDF continues to be the most common surgical treatment for cervical radiculopathy and other degenerative conditions in the neck.[18-19] Before CDA can be routinely implemented into clinical practice, studies must prove it to be at least as effective in symptomatic relief as ACDF, with similar or lower complication rates, and to reduce the incidence of adjacent segment degeneration. However, two recent prospective, multi-center, randomized, controlled Food and Drug Administration (FDA) Investigational Device Exemption (IDE) studies between single-level CDA and single-level ACDF with 48-month and 60-month follow-up, respectively, show promising mid-term results for two different cervical disc arthroplasty systems. The CDA groups demonstrated a higher rate of overall success, greater improvements in neck disability index (NDI), neck and arm pain scores, and SF-36 Physical Component Scores as compared with patients in the ACDF group. The adjacent segment degeneration rate was lower at 60 months for the CDA group. Additionally, normal segmental motion was maintained in the CDA group. Finally, revision rates and supplemental fixation surgical procedures were lower following CDA.[20-21] These two studies again demonstrate that CDA is a viable treatment option for cervical radiculopathy and myelopathy.

To our knowledge, this review represents the largest, non-funded, comparison study between single-level CDA and single-level ACDF. In the CDA group, we found a 90% rate of complete pre-operative symptom relief, with 93% of patients returning to their pre-operative level of activity, compared to rates 86% and 89%, respectively, in the ACDF group. Complication rates in both groups were lower than reported in the literature. This study demonstrates that CDA is a safe and reliable alternative to ACDF, but long-term studies are needed to ascertain differences in outcomes, complication rates, and adjacent segment degeneration.

REFERENCES

1. Hilibrand AS, Robbins M. Adjacent segment degeneration and adjacent segment disease: the consequences of spinal fusion? *Spine J.* Nov-Dec 2004;4:190S-194S.
2. Hilibrand AS, Carlson GD, Palumbo MA, Jones PK, Bohlman HH. Radiculopathy and myelopathy at segments adjacent to the site of a previous anterior cervical arthrodesis. *J Bone Joint Surg Am.* Apr 1999;81:519-528.
3. Eck JC, Humphreys SC, Lim TH, et al. Biomechanical study on the effect of cervical spine fusion on adjacent-level intradiscal pressure and segmental motion. *Spine*. Nov 2002;27:2431-2434.

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4. Park DH, Ramakrishnan P, Cho TH, et al. Effect of lower two-level anterior cervical fusion on the superior adjacent level. *J Neurosurg Spine*. Sep 2007;7:336-340.
5. Cason GW, Herkowitz HN. Cervical intervertebral disc replacement. *J Bone Joint Surg Am*. Feb 2013;95:279-285.
6. Pracyk JB, Traynelis VC. Treatment of the painful motion segment: cervical arthroplasty. *Spine*. Aug 2005;15:S23-S32.
7. Auerbach JD, Jones KJ, Fras CI, Balderston JR, Rushton SA, Chin KR. The prevalence of indications and contraindications to cervical total disc replacement. *Spine J*. Sep-Oct 2008;8:711-716.
8. Mummaneni PV, Burkus JK, Haid RW, Traynelis VC, Zdeblick TA. Clinical and radiographic analysis of cervical disc arthroplasty compared with allograft fusion: a randomized controlled clinical trial. *J Neurosurg Spine*. Mar 2007;6:198-209.
9. Heller JG, Sasso RC, Papadopoulos SM, et al. Comparison of BRYAN cervical disc arthroplasty with anterior cervical decompression and fusion: clinical and radiographic results of a randomized, controlled, clinical trial. *Spine*. Jan 2009;34:101-107.
10. Garrido BJ, Taha TA, Sasso RC. Clinical outcomes of Bryan cervical disc arthroplasty a prospective, randomized, controlled, single site trial with 48-month follow-up. *J Spinal Disord Tech.* Aug 2010;23:367-371.
11. Murrey D, Janssen M, Delamarter R, et al. Results of the prospective, randomized, controlled multicenter Food and Drug Administration investigational device exemption study of the ProDisc-C total disc replacement versus anterior discectomy and fusion for the treatment of 1-level symptomatic cervical disc disease. *Spine J.* Apr 2009;9:275-286.
12. Goffin J, van Loon J, Van Calenbergh F, Lipscomb B. A clinical analysis of 4- and 6-year follow-up results after cervical disc replacement surgery using the Bryan Cervical Disc Prosthesis. *J Neurosurg Spine*. Mar 2010;12:261-269.
13. Fountas KN, Kapsalaki EZ, Nikolakakos LG, et al. Anterior cervical discectomy and fusion associated complications. *Spine*. Oct 2007;32:2310-2317.
14. Riley LH 3rd, Skolasky RL, Albert TJ, Vaccaro AR, Heller JG. Dysphagia after anterior cervical decompression and fusion: prevalence and risk factors from a longitudinal cohort study. *Spine*. Nov 2005;30:2564-2569.
15. McAfee PC, Cappuccino A, Cunningham BW, et al. Lower incidence of dysphagia with cervical arthroplasty compared with ACDF in a prospective randomized clinical trial. *J Spinal Disord Tech*. Feb 2010;23:1-8.
16. Cardoso MJ, Mendelsohn A, Rosner MK. Cervical hybrid arthroplasty with 2 unique fusion techniques. *J Neurosurg Spine*. Jul 2011;15:48-54.
17. Edwards CC 2nd, Karpitskaya Y, Cha C, et al. Accurate identification of adverse outcomes after cervical spine surgery. *J Bone Joint Surg Am.* Feb 2004;86-A:251-256.
18. Lee CK, Langrana NA. A review of spinal fusion for degenerative disc disease: need for alternative treatment approach of disc arthroplasty? *Spine J.* Nov-Dec 2004;4:173S-176S.
19. Davis H. Increasing rates of cervical and lumbar spine surgery in the United States, 1979-1990. *Spine.* May 15 1994;19:1117-1123; discussion 1123-1114.
20. Burkus JK, Haid RW, Traynelis VC, Mummaneni PV. Long-term clinical and radiographic outcomes of cervical disc replacement with the Prestige disc: results from a prospective randomized controlled clinical trial. *J Neurosurg Spine*. Sep 2010;13:308-318.
21. Sasso RC, Anderson PA, Riew KD, Heller JG. Results of cervical arthroplasty compared with anterior discectomy and fusion: four-year clinical outcomes in a prospective, randomized controlled trial. *J Bone Joint Surg Am.* Sep 21 2011;93:1684-1692.

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Cervical Posterior Foraminotomy's Effect on Segmental Range of Motion in the Setting of Total Disc Arthroplasty

CPT Adam J. Bevevino, MD; LTC Ronald A. Lehman, Jr., MD; CPT Daniel G. Kang, MD; Divya Ambati, MS; Rachel Gaume, BS; CDR David E. Gwinn, MD; Anton E. Dmitriev, PhD

INTRODUCTION

Cervical disc arthroplasty (CDA) is being used with increasing frequency for the treatment of cervical radiculopathy.[1,2] Prospective randomized data has emerged over the past few years indicating that outcomes of CDA are comparable to anterior cervical discectomy and fusion (ACDF), which has long been considered the historic gold standard.[3-7] As CDA becomes more common and the number of patients living with a cervical disc implant increases, so will complications and the need to perform revision surgery.[8,9] Recurrent radiculopathy is a leading cause of revision surgery for both ACDF and CDA. In the setting of ACDF, recurrent symptoms can be secondary to inadequate nerve root decompression, pseudoarthosis, or implant failure. The surgical revision strategy may involve a repeat anterior approach, or decompression can be performed via a posterior laminoforaminotomy. In itself, posterior laminoforaminotomy has a proven track record and is an effective alternative to anterior procedures for primary cervical radiculopathy.[10-13] When posterior foraminotomy is executed in conjunction with a stable ACDF, the combination of procedures carry a minimal risk of iatrogenically induced instability. Conversely, ACDF can be safely performed as a revision procedure for recurrent symptoms following a primary posterior foraminotomy.

In comparison, CDA differs from ACDF in that it is not a fusion procedure and its intent is to maintain segmental cervical spine motion.[14,15] Furthermore, posterior foraminotomy can increase cervical spine range of motion (ROM), and potentially induce cervical spine instability.[13] The question that is unknown is whether CDA and foraminotomy can be safely performed without causing excessive cervical spine motion or iatrogenic instability. This point serves as the impetus for the current study, as we sought to investigate the effect on segmental cervical spine motion of CDA performed in combination with posterior foraminotomy.

METHODS

Following institutional review board (IRB) approval, 10 fresh human cadaveric spine specimens from occiput to sacrum were obtained from the Maryland State Anatomy Board. The medical history for each cadaver was reviewed and specimens were excluded for a history of primary or secondary bone disease. Upon receipt of the specimens, all muscular attachments were dissected free from the spinal column, with care taken to preserve the osseous and discoligamentous structures. Specimens were stored at -20° C until biomechanical testing was initiated, at which time they were thawed to room temperature. Prior to testing, dual X-ray absorptiometry (DEXA) using Hologic QDR-2000 (Boston, MA) was performed on each specimen to document pre-testing bone mineral density. Additionally, plain X-rays were taken to ensure normal gross anatomy and the absence of destructive bone lesions.

Each specimen was sectioned at the occ-C1 level cephalad and the T3-T4 level caudally. They were then secured using a K-wire fixation jig and polyester resin, proximally at C1 and distally at T3. Biomechanical testing was performed utilizing a MTS 858 Bionix Testing System configured with a custom-built 6 Degree-of-freedom Spine Simulator (MTS Corporation, Minneapolis, MN), allowing pure, unconstrained multi-directional load application. Intersegmental motion evaluation was analyzed with the use of specialized markers consisting of three non-co-linear infrared light emitting diodes (LEDs). One marker was rigidly attached to each vertebral level (C3-C7) and oriented to permit detection by an optoelectronic motion analysis system (OptoTrak Certus, Northern Digital Inc., Waterloo, Ontario, Canada). The specimens were non-destructively tested under axial rotation (Y-axis, ± 2 Nm), flexion/extension (X-axis, ± 2 Nm), and lateral bending (Z-axis, ± 2 Nm) testing modes using a pure moment loading system. Each test was repeated for two loading and unloading cycles, with data from the second cycle used for computational analysis. For non-destructive multi-directional flexibility analysis, the peak range of motion for each loading mode was calculated as the sum of motions [maximum ± rotation for torsion, flexion-extension and left + right bending (degrees)] observed in the neutral (NZ) and elastic (EZ) zones at the second loading cycle (ROM = NZ + EZ).

The specimens were initially tested, according to the above protocol, in the intact state (group 1) to establish baseline (control) ROM values. Each specimen was then sequentially tested four more times according to the following experimental groups: 2) C5-6 CDA, 3) C5-6 CDA with unilateral C5-6 foraminotomy, 4) C5-6 CDA with bilateral C5-6 foraminotomy, 5) C5-6 CDA with bilateral C5-6 foraminotomy and bilateral C4-5 foraminotomy.

The Prestige Cervical Disc (Medtronic, Memphis TN) served as the arthroplasty device for the study. The implants were placed following a complete C5-C6 discectomy in accordance with the manufacturer technique guide. The posterior foraminotomies were performed first by identifying the location of the cervical facet joint in the poste-

[1]Walter Reed National Military Medical Center, Bethesda, MD. Address correspondence to: Adam J. Bevevino, MD, a.bevevino@gmail.com.

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rior cervical spine. Approximately one-third of the cephalad lamina just medial to the inferior facet was resected with a high speed bur. The lateral aspect of the ligamentum flavum and remaining soft tissues were then resected with a Kerrison rongeur. From this point, the inferior medial half of the inferior articular facet was thinned and resected to expose the underlying superior articular facet. Once the medial half of the superior facet was sufficiently visualized, the superior and medial half of the facet was thinned and resected using a high speed bur and Kerrison ronguer. Care was taken to avoid resecting greater than 50% of the facet joint. A small nerve hook was utilized to ensure adequate decompression through direct palpation of the superior and lateral pedicle walls. When the lateral pedicle wall was easily reached by the probe, the posterior foraminotomy was considered complete.

ROM data was reported as degrees. The mean values of the intact group and each experimental group was defined in terms of axial rotation (AR), lateral bending (LB), and flexion/extension (FE) for each cervical segment from C3-C7. Statistical analysis was performed using SPSS version 18.0 software (SPSS, Inc., Chicago, IL) and included a repeated-measures analysis of variance (ANOVA), followed by a test of simple effects as a post-hoc intergroup evaluation using Sidak correction for multiple comparisons. Statistical results at $p < 0.05$ were considered significant.

RESULTS

A total of seven specimens underwent complete ROM testing and were included in the final statistical analysis. Of the ten specimens initially selected for study, one was eliminated secondary to iatrogenic fracture caused during fixation to the biomechanical testing jig, and two others were eliminated for ROM values that were greater than two standard deviations outside the mean.

ROM of the C5-C6 spinal segment was most affected across the experimental groups and within this segment; the flexion/extension plane experienced the greatest increases. Flexion and extension increased from 10.7° in the intact specimens (group 1) to 14.1° in the CDA specimens (group 2) and further to 16° to 17° in the CDA + foraminotomy groups (groups 3 to 5). The ROM difference between group 1 (intact/control) and groups 3 to 5 (CDA + foraminotomy) was statistically significant ($p < 0.007$). However, there was not a significant ROM increase between group 1 (intact) and group 2 (CDA), $p > 0.2$. Furthermore, there was no significant difference in ROM between group 2 (CDA) and groups 3 to 5 (CDA + foraminotomy), $p > 0.3$. A stepwise increase in axial rotation was observed from group 1 (7.6°) to group 5 (10.9°), although this increase was not statistically significant, $p > 0.3$. The lateral bending plane experienced the smallest ROM changes remaining relatively stable across the tested groups, yielding 7.5° in group 1 and increasing to 7.9° in group 5, $p > 0.9$ (see Table 1).

There were relatively small and universally insignificant ROM changes at the C4-5 and C6-7 spinal segments. At C4-5, flexion/extension had the largest change in ROM, increasing from 9.9° in group 1 (intact) to 13.2° in group 5 (CDA + C56 and C45 foraminotomy), but the difference was not statistically significant, $p > 0.8$. Axial rotation and lateral bending had minimal changes at C4-5 segment that did not reach statistical significance, $p > 0.6$. The C6-7 segment had a small but insignificant decrease in axial rotation from group 1 to groups 2 to 5, $p > 0.8$. Both lateral bending and flexion/extension remained relatively stable across all groups (1 to 5) at C6-7, $p > 0.7$ (see Tables 2 and 3).

Table 1. C5-C6 Range of Motion

Group		Axial rotation	Lateral bending	Flexion extension
1	Intact	7.6 ± 2	7.5 ± 3	10.7 ± 3
2	C5-6 CDA	8.8 ± 2	6.6 ± 2	14.1 ± 4 ⊥
3	C5-6 CDA with unilateral C5-6 foraminotomy	9.8 ± 4	7.4 ± 3	16.7 ± 2* ⊥
4	C5-6 CDA with bilateral C5-6 foraminotomy	9.5 ± 4	7.5 ± 3	17.2 ± 2* ⊥
5	C5-6 CDA with bilateral C5-6 foraminotomy + bilateral C4-5 foraminotomy	10.9 ± 4	7.9 ± 3	16.7 ± 3* ⊥
	α	$p > 0.3$	$p > 0.9$	$\mathbf{p < 0.007}$

*, significantly different compared to intact (control) state; ⊥, no significant difference between experimental groups

Table 2. C4-C5 Range of Motion

Group		Axial rotation	Lateral bending	Flexion extension
1	Intact	8.8 ± 5	8.5 ± 3	9.9 ± 3
2	C5-6 CDA	9.6 ± 5	8.3 ± 4	13.4 ± 7
3	C5-6 CDA with unilateral C5-6 foraminotomy	8.1 ± 3	9.4 ± 4	12.4 ± 7
4	C5-6 CDA with bilateral C5-6 foraminotomy	8.7 ± 4	9.7 ± 4	12.8 ± 6
5	C5-6 CDA with bilateral C5-6 foraminotomy + bilateral C4-5 foraminotomy	8.8 ± 4	10.8 ± 4	13.2 ± 7
	α	$p > 0.9$	$p > 0.6$	$p > 0.8$

Combined range of motion across all measured levels, reported as C4-7, did not significantly change across the tested groups. Both axial rotation and lateral bending ROM values remained relatively stable. Axial rotation increased from 23.5° in group 1 to 25.9° in group 2 ($p > 0.9$) and lateral bending increased from 24.3° in group 1 to 26.8° in group 5 ($p > 0.9$). In the flexion/extension plane there was a 7.5° increase from group 1 to 2 (31.4°→38.9°) and although the change was not significant, $p > 0.1$, it indicates that placement of the CDA at C56 had the greatest impact on motion in this plane.

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Table 3. C6-C7 Range of Motion				
Group		**Axial rotation**	**Lateral bending**	**Flexion extension**
1	Intact	7.1 ± 3	8.4 ± 4	10.7 ± 2
2	C5-6 CDA	5.9 ± 4	8.4 ± 4	11.3 ± 2
3	C5-6 CDA with unilateral C5-6 foraminotomy	5.3 ± 2	8.2 ± 4	11.2 ± 2
4	C5-6 CDA with bilateral C5-6 foraminotomy	5.8 ± 3	8.1 ± 4	11.9 ± 2
5	C5-6 CDA with bilateral C5-6 foraminotomy + bilateral C4-5 foraminotomy	6.2 ± 2	8.1 ± 3	12.1 ± 2
	α	$p > 0.8$	$p > 0.9$	$p > 0.7$

Table 4. C4-C7 Range of Motion				
Group		**Axial rotation**	**Lateral bending**	**Flexion extension**
1	Intact	23.5 ± 9	24.3 ± 9	31.4 ± 5
2	C5-6 CDA	22.9 ± 9	23.3 ± 7	38.9 ± 10
3	C5-6 CDA with unilateral C5-6 foraminotomy	23.1 ± 9	25.1 ± 9	40.4 ± 9
4	C5-6 CDA with bilateral C5-6 foraminotomy	24.0 ± 10	25.3 ± 9	41.8 ± 9
5	C5-6 CDA with bilateral C5-6 foraminotomy + bilateral C4-5 foraminotomy	25.9 ± 7	26.8 ± 9	41.9 ± 9
	α	p > 0.9	p > 0.9	p > 0.1

Flexion extension remained stable with minimal increase from group 2 to group 5 (38.5°→41.9°) (see Table 4).

DISCUSSION

The addition of a posterior foraminotomy to cervical spine specimens implanted with a CDA did not cause a statistically significant increase in segmental ROM. This finding held true in the setting of bilateral foraminotomies, and even when foraminotomies were added to a supra-adjacent level. The flexion/extension plane experienced the largest ROM changes and a significant increase was observed when comparing the intact specimens to those that had both foraminotomy and CDA. Lateral bending and axial rotation were minimally affected by either CDA or the addition of foraminotomies. Flexion and extension at the C56 level increased initially from the intact state following implantation of the artificial disc and again after the first foraminotomy, however, neither of these increases was significant. Subsequent foramintomies following the initial foraminotomy caused only a minimal change in segmental motion. This indicates that any destabilizing effect from the foraminotomy occurred after violation of the initial joint and was not affected by additional foraminotomies. The biomechanical results of this analysis illustrate that a posterior foraminotomy can be performed in the setting of a pre-existing CDA without causing a significant increase in segmental range of motion.

CDA has had clinical and biomechanical success in recent literature. In spite of this, recurrent/persistent symptoms following CDA, as in ACDF, are inevitable in some patients and are one of the more common reasons for surgical revision. The ideal approach to revision surgery in the setting of CDA is unknown. One option entails a repeat anterior approach with explant of the arthoplasty device and conversion to a traditional ACDF. The drawbacks of this approach include higher complications with the repeat approach[16,17] and loss of any advantages seen with preservation of segmental motion. A potentially more attractive alternative would be to perform the revision decompression from a posterior approach via laminoforaminotomy. This would obviate the need to dissect scar tissue in the anterior neck and allow preservation of the arthroplasty device. However, the safety of posterior foraminotomy in the setting of CDA is largely unknown.

The potentially destabilizing effects of posterior laminoforaminotomy have been known for decades. In the early 1990s, Zdeblick, et al.[18,19] published biomechanical results on the consequences of posterior foraminotomy, stating that greater than 50% resection of the facet joint and capsule created segmental instability. More recent studies have reported clinical data regarding iatrogenic instability resulting from posterior laminoforaminotomy. In 2009, Jaganathan, et al.[13] published loss of cervical lordosis in 20% and instability in 4.9% of foraminotomy patients. Additionally, Clarke, et al.[20] cited a 6.7% risk of adjacent segment disease at 10 years following posterior foraminotomy. While there are downsides, when performed correctly, the procedure is safe and highly effective for the treatment of cervical radiculopathy.[11,12]

There exists only limited data regarding the combination of CDA and posterior foraminotomy. A retrospective clinical series published by Sekhon, et al.[21] examined the results of CDA in patients who had undergone a prior posterior foramintomy. They reported favorable clinical outcomes with no cases of instability resulting from the addition of a CDA to a cervical spine with a foraminotomy. A biomechanical analysis by Roberto, et al.[22] in 2010 examined the effects of uncinate resection, posterior longitudinal ligament excision, foraminotomy, and laminectomy on cervical ROM and translation following ProDisc C implantation. The authors found some statistically significant increases in ROM from the intact specimens to the foraminotomy specimens, but concluded that the posterior decompressive procedures were safe in the setting of cervical disc arthroplasty. A subsequent biomechanical study in 2010 by Kikkawa, et al.[23] studied the effects of laminoplasty in combination with cervical disc arthroplasty. Similarly, the authors reported no significant ROM increases when laminoplasty was combined with CDA. This current study aimed to focus primarily on the effects of posterior foraminotomy in the setting of CDA and our results echo that of the previously mentioned biomechanic reports. The flexion/extension (sagittal motion) plane was most affected by posterior

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decompressive procedures, but the addition of a posterior foraminotomy did not significantly increase segmental ROM.

There are several limitations to this study. The specimens included for analysis are from elderly people who inevitably had some degeneration of their cervical spines. This fact makes the studied population different than the usual CDA candidates, namely younger patients with limited disc degeneration and radiculopathy. However, this can potentially be viewed as a strength of the study. Performing wide discectomies and decompressions in specimens with some degree of spondylosis likely causes more segmental destabilization than the same procedure would in a young, non-degenerative spine. Secondary to this, the ROM differences found in our analysis may be overestimated from what would be observed in younger patients who are more likely to undergo CDA. Another weakness is that this method of biomechanical testing allows for ROM analysis at only one point in time. Therefore, it is difficult to draw conclusions about the development of segmental instability over time.

A question that remains when applying this biomechanical data to clinical use is determining whether a statistically significant difference, or lack of, represents one that is clinically significant. The addition of a foraminotomy to spines with a preexisting CDA caused a 2.6° (18%) increase in sagittal plane (flexion/extension) motion. While this was not statistically significant, it is unknown whether this ROM increase would manifest clinically.

CAD, to date, has been clinically successful and offers several theoretical advantages over traditional fusion procedures. As the number of people living with a CDA continues to increase, so will the need for surgical revision. In the setting of recurrent/persistent radiculopathy, posterior foraminotomy obviates the need to re-expose the anterior spine and offers the advantage of being able to leave the CDA intact. Iatrogenically induced instability from this approach is a valid concern. However, the results of this cadaveric analysis indicate biomechanically that when less than 50% of the facet joint is removed, bilateral and even supra-adjacent level foraminotomies can be performed without significantly increasing segmental ROM.

REFERENCES

1. Phillips FM, Garfin SR. Cervical disc replacement. *Spine (Phila Pa 1976).* Sep 1 2005;30(17 Suppl):S27-S33.
2. Nesterenko SO, Riley LH 3rd, Skolasky RL. Anterior cervical discectomy and fusion versus cervical disc arthroplasty: current state and trends in treatment for cervical disc pathology. *Spine (Phila Pa 1976).* Aug 1 2012;37(17):1470-1474.
3. Burkus JK, Haid RW, Traynelis VC, Mummaneni PV. Long-term clinical and radiographic outcomes of cervical disc replacement with the Prestige disc: results from a prospective randomized controlled clinical trial. *J Neurosurg Spine.* Sep 2010;13(3):308-318.
4. Garrido BJ, Taha TA, Sasso RC. Clinical outcomes of Bryan cervical disc arthroplasty a prospective, randomized, controlled, single site trial with 48-month follow-up. *J Spinal Disord Tech.* Aug 2010;23(6):367-371.
5. Nabhan A, Ahlhelm F, Pitzen T, et al. Disc replacement using Pro-Disc C versus fusion: a prospective randomised and controlled radiographic and clinical study. *Eur Spine J.* Mar 2007;16(3):423-430.
6. Sasso RC, Smucker JD, Hacker RJ, Heller JG. Artificial disc versus fusion: a prospective, randomized study with 2-year follow-up on 99 patients. *Spine (Phila Pa 1976).* Dec 15 2007;32(26):2933-2940; discussion 2941-2932.
7. Coric D, Cassis J, Carew JD, Boltes MO. Prospective study of cervical arthroplasty in 98 patients involved in 1 of 3 separate investigational device exemption studies from a single investigational site with a minimum 2-year follow-up. Clinical article. *J Neurosurg Spine.* Dec 2010;13(6):715-721.
8. Zindrick M, Harris MB, Humphreys SC, et al. Cervical disc arthroplasty. *J Am Acad Orthop Surg.* Oct 2010;18(10):631-637.
9. Anderson PA, Sasso RC, Riew KD. Comparison of adverse events between the Bryan artificial cervical disc and anterior cervical arthrodesis. *Spine (Phila Pa 1976).* May 20 2008;33(12):1305-1312.
10. Heary RF, Ryken TC, Matz PG, et al. Cervical laminoforaminotomy for the treatment of cervical degenerative radiculopathy. *J Neurosurg Spine.* Aug 2009;11(2):198-202.
11. Henderson CM, Hennessy RG, Shuey HM Jr, Shackelford EG. Posterior-lateral foraminotomy as an exclusive operative technique for cervical radiculopathy: a review of 846 consecutively operated cases. *Neurosurgery.* Nov 1983;13(5):504-512.
12. Herkowitz HN, Kurz LT, Overholt DP. Surgical management of cervical soft disc herniation. A comparison between the anterior and posterior approach. *Spine (Phila Pa 1976).* Oct 1990;15(10):1026-1030.
13. Jagannathan J, Sherman JH, Szabo T, Shaffrey CI, Jane JA. The posterior cervical foraminotomy in the treatment of cervical disc/osteophyte disease: a single-surgeon experience with a minimum of 5 years' clinical and radiographic follow-up. *J Neurosurg Spine.* Apr 2009;10(4):347-356.
14. Finn MA, Brodke DS, Daubs M, Patel A, Bachus KN. Local and global subaxial cervical spine biomechanics after single-level fusion or cervical arthroplasty. *Eur Spine J.* Oct 2009;18(10):1520-1527.
15. Park DK, Lin EL, Phillips FM. Index and adjacent level kinematics after cervical disc replacement and anterior fusion: in vivo quantitative radiographic analysis. *Spine (Phila Pa 1976).* Apr 20 2011;36(9):721-730.
16. Coric D, Branch CL Jr, Jenkins JD. Revision of anterior cervical pseudoarthrosis with anterior allograft fusion and plating. *J Neurosurg.* Jun 1997;86(6):969-974.
17. Gok B, Sciubba DM, McLoughlin GS, et al. Revision surgery for cervical spondylotic myelopathy: surgical results and outcome. *Neurosurgery.* Aug 2008;63(2):292-298; discussion 298.
18. Zdeblick TA, Zou D, Warden KE, McCabe R, Kunz D, Vanderby R. Cervical stability after foraminotomy. A biomechanical in vitro analysis. *J Bone Joint Surg Am.* Jan 1992;74(1):22-27.
19. Zdeblick TA, Abitbol JJ, Kunz DN, McCabe RP, Garfin S. Cervical stability after sequential capsule resection. *Spine (Phila Pa 1976).* Oct 15 1993;18(14):2005-2008.
20. Clarke MJ, Ecker RD, Krauss WE, McClelland RL, Dekutoski MB. Same-segment and adjacent-segment disease following posterior cervical foraminotomy. *J Neurosurg Spine.* Jan 2007;6(1):5-9.
21. Sekhon LH, Sears W, Duggal N. Cervical arthroplasty after previous surgery: results of treating 24 discs in 15 patients. *J Neurosurg Spine.* Nov 2005;3(5):335-341.
22. Roberto RF, McDonald T, Curtiss S, Neu CP, Kim K, Pennings F. Kinematics of progressive circumferential ligament resection (decompression) in conjunction with cervical disc arthroplasty in a spondylotic spine model. *Spine (Phila Pa 1976).* Aug 15 2010;35(18):1676-1683.
23. Kikkawa J, Cunningham BW, Shirado O, Hu N, McAfee PC, Oda H. Multidirectional flexibility of the spine following posterior decompressive surgery after single-level cervical disc arthroplasty: an in vitro biomechanical investigation. *Spine (Phila Pa 1976).* Dec 1 2010;35(25):E1465-1471.

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Risk Factors for Infection and Amputation following Open, Combat-Related Calcaneus Fractures

MAJ Jonathan F. Dickens, MD, MC, USA; MAJ Kelly G. Kilcoyne, MD, MC, USA; CPT Matthew W. Kluk, MD, MC, USA; Lt Col Wade Gordon, MD, MC, USAF; LTC(P) Scott B. Shawen, MD, MC, USA; MAJ(P) Benjamin K. Potter, MD, MC, USA

INTRODUCTION

Open calcaneus fractures represent a severe and often disabling injury, occurring in less than 8.5% of all calcaneus fractures,[1] with subsequent complications occurring in up to 78% of cases.[1-5] The severity of the injury, soft tissue compromise, fracture displacement, and fracture comminution present unique challenges in the treatment of open calcaneus fractures. These injuries are often complicated by non-anatomic reduction, limited subtalar motion, wound necrosis, infection, guarded functional outcomes, injury to passing neurovascular and tendinous structures, and frequent eventual amputation.[1-9]

The natural history of open calcaneus fractures is poorly understood and the variables that allow for successful limb salvage have not been described. Likewise, few studies have assessed treatment and outcomes of open calcaneus fractures. The purpose of this study was to further characterize high-energy open calcaneus fractures by identifying risk factors that may predict infection, amputation, and poor outcomes. We hypothesized that more severe soft tissue injury, as measured by both the Gustilo and Anderson classification and the size and location of the wound(s),[4] would be the strongest predictor of infection and amputation.

METHODS

After institutional review board approval, all patients receiving treatment for an open calcaneus fracture sustained between March 2003 to August 2010 during Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) were identified from the Armed Forces Health Longitudinal Technology Application (AHLTA), the Joint Theater Trauma Registry (JTTR), and the local Surgical Scheduling System (S3). The JTTR is a database of medical treatment information on patients in a theater of combat operations treated at U.S. military medical facilities. AHLTA is the electronic medical record and coding system for the military healthcare system. The S3 is an electronic operative case log of all surgical procedures at our facility. All databases were queried to identify patients with an open or closed calcaneus fracture (ICD-9 code 825.0, CPT codes 28400, 28415, 28420, 28406).

Inclusion criteria were U.S. service members who sustained an open calcaneus fracture while performing combat operations and who subsequently received treatment at a single tertiary referral hospital. Patients who received an immediate amputation within the first 24 hours of injury were excluded. Thus, all patients in this study population were deemed to have severe lower extremity trauma resulting in an open calcaneus fracture, but the injury did not require immediate amputation for a grossly unsalvageable limb or to preserve life.

Abstracted data included patient demographics, mechanism of injury, wound size and location, Gustilo and Anderson[10,11] and Sanders[12,13] fracture classifications, interval and definitive treatment procedures, adjunctive procedures (rotational or free tissue transfer, skin graft, and neurovascular procedures), as well as ipsilateral and contralateral orthopaedic injuries. The definitive treatment was defined as the procedure after injury which, after healing, would allow reduced fracture union and eventual weight bearing. The reported complications were documented for deep and superficial infection, need for late amputation, and type and timing of revision surgery. Functional outcomes were evaluated by visual analog pain scale and recreational status as assessed by Tegner activity level.[14]

RESULTS

From March 2003 to July 2010, 583 U.S. military personnel sustained a calcaneus fracture during OEF or OIF. Two hundred eighty-three individuals received treatment at one of our institutions for a combat-related calcaneus fracture and 122 patients sustained open fractures. Thirty-three patients were transferred to another hospital during their initial hospital admission and were thus excluded from the study population due to lack of in-patient data. Complete records were available for 89 patients who sustained 102 combat-related open calcaneus fractures and who were followed for a mean of four years (range, 5 to 92 months). The injury and treatment characteristics are presented in Table 1.

Limb Salvage versus Amputation

During the study period, 42% (43/102) of open calcaneus fractures were treated with an amputation (42 transtibial, 1 knee disarticulation). Extremities that failed limb salvage were more likely to have an associated ipsilateral forefoot fracture ($p < 0.0001$), talus fracture ($p < 0.0001$), plantar wound ($p < 0.0001$), and culture positive wound infection ($p < 0.0001$). Wound size was significantly associated with amputation ($p < 0.0001$; Table 2). The mean total size of salvaged open calcaneus fracture wounds was 15 cm^2 ± 13 cm^2 versus 51 cm^2 ± 58 cm^2 ($p < 0.0001$) in the amputation cohort. Gustilo and Anderson fracture type was significantly associated with amputation, with type I (0%), type II (8%), type IIIA (29%), type IIIB (55%), and type IIIC (100%) ($p < 0.0001$). Ipsilateral tibia fractures, spine fractures, and the absence of plantar sensation at presentation were not significantly associated with eventual amputation. In a multivariate Cox Proportional Hazards Survival model with amputation as the end point, blast mechanism of injury, location and larger size of open wound in cm^2, and escalating Sanders and Gustilo and Anderson classification types (all $p < 0.05$) were predictive of eventual amputation. At final follow-up, patients who

Department of Orthopaedics and Rehabilitation, Walter Reed National Military Medical Center, Bethesda, MD.

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Table 1. Demographic and Injury Characteristics of Open Calcaneus Fractures Treated at Walter Reed National Military Medical Center from 2003 - 2010

Characteristic	No. (range or %)
Total open calcaneus fractures	102
Median age (range) (yr)	26 (19-44)
Injury severity score (range)	18.6 (5-57)
Sex*	
Male	85 (96)
Female	4 (4)
Method of injury	
Improvised explosive device	75 (74)
Gun shot	8 (8)
Rocket-propelled grenade	16 (16)
Fall from height	1 (1)
Vehicular accident	2 (2)
Associated major ipsilateral lower extremity fractures	
Femur	7(7)
Tibia	44 (43)
Talus	49 (48)
Method of definitive fixation	
Plate-and-screw fixation	27 (26)
Circular external fixation	11 (11)
Pin or screw fixation	16 (16)
Nonoperative	14 (14)
Subtalar arthrodesis	12 (12)
Amputation before fixation attempt	22 (22)
Wound location	
Plantar	55 (54)
Medial	9 (9)
Lateral	10(10)
Dorsal	16 (16)
Posterior	12 (12)
Wound size (cm2) (mean 30 cm^2)	
≤ 20	65 (64)
21 to 39	19 (19)
≥ 40	18 (18)
Gustillo and Anderson classification	
I	3 (3)
II	12 (12)
IIIA	31 (30)
IIIB	49 (48)
IIIC	6 (6)
Plantar Sensation	
Intact	36 (35)
Diminished	55 954)
Absent	11 (11)
Common culture positive deep infections (n = 47)	47 (46)
Acinetobacter	21 (45)
Stapholocaucus	12 (26)
Pseudomonas	7 (15)
Enterococcus	11 (23)
Klebsiella	6 (13)
Mold species	2 (4)
Enterobacter	3 (6)
Other	2 (4)
Mulitple organisms	17 (36)
Soft tissue reconstruction (n = 28)	
Skin graft	22 (22)
Free tissue transfer	6 (6)
Total procedures	13.7 (2-47)
Total procedures after definitive treatment	3.3 (0-14)
Amputation (n = 43)	
Time from injury to amputation (days)	120 (1-647)
Transtibial	42 (98)
Through knee	1 (2)
Outcomes (n = 100)	
Return to duty (n = 100)	38 (38)
Medical board	62 (62)
Visual analog scale pain	3.2 (0-7)
Tenger activity level	4.3 (0-7)

* The values are given as the number and the percentage or range in parentheses.

had undergone amputation had lower visual analogue scale scores for pain (2.1 versus 4.0, $p < 0.0001$) and higher Tegner activity levels (5.4 versus 3.5, $p < 0.0001$) than limb salvage patients.

Complications following limb salvage and amputation were common. Compared to extremities that received early amputation, the group that received a delayed amputation required more total operative procedures during the study period (17 versus 11, $p = 0.001$). Sixty-six percent (29/43) of patients with an amputation required a re-operation and/or revision procedure. The most common revision procedures for those who underwent amputation were irrigation and debridement (63%; 27/43), revision wound closure (49%; 21/43), and hardware removal (19%; 8/43). Comparatively, 83% (49/59) of patients who continued limb salvage treatment required a revision surgery. The most common revision procedures in the limb salvage group were implant removal (42%; 25/59), exostectomy (37%, 22/59), and revision wound closures (34%; 20/59).

Early versus Delayed Amputation

A late amputation (> 12 weeks from injury) was performed in 15% (15/102) of open calcaneus fractures compared to 27% (28/102) undergoing early amputation (24 hours to 12 weeks from injury). The mean time to early amputation was 19 days (range, 1 to 53) versus 312 days (range, 84 to 647) in the delayed amputation group. All patients in the late amputation cohort received a transtibial amputation; one knee disarticulation was performed in the early period. Patients receiving delayed or late amputation did not demonstrate significantly different injury severity score, Gustilo and Anderson fracture severity, wound size, wound location, presence of plantar sensation, need for tissue transfer, associated fracture patterns, or final Tegner activity level. Patients receiving a late amputation underwent statistically more revision surgeries (7.2 versus 1.9, $p < 0.001$) and were more likely to receive definitive fracture treatment in a circular external fixator ($p < 0.001$).

DISCUSSION

Open calcaneus fractures account for 8.5% of all calcaneus fractures in the civilian trauma setting.[1] Presently, 43% of wounded warriors with calcaneus fractures present to our institution more than 24 hours from injury with a combat-related open calcaneus fracture and a salvaged lower extremity. Open calcaneus fractures are burdened by high infection rates, compromised soft tissues, high malunion and nonunion rates, substantial patient morbidity, and high rates of concomitant inju-

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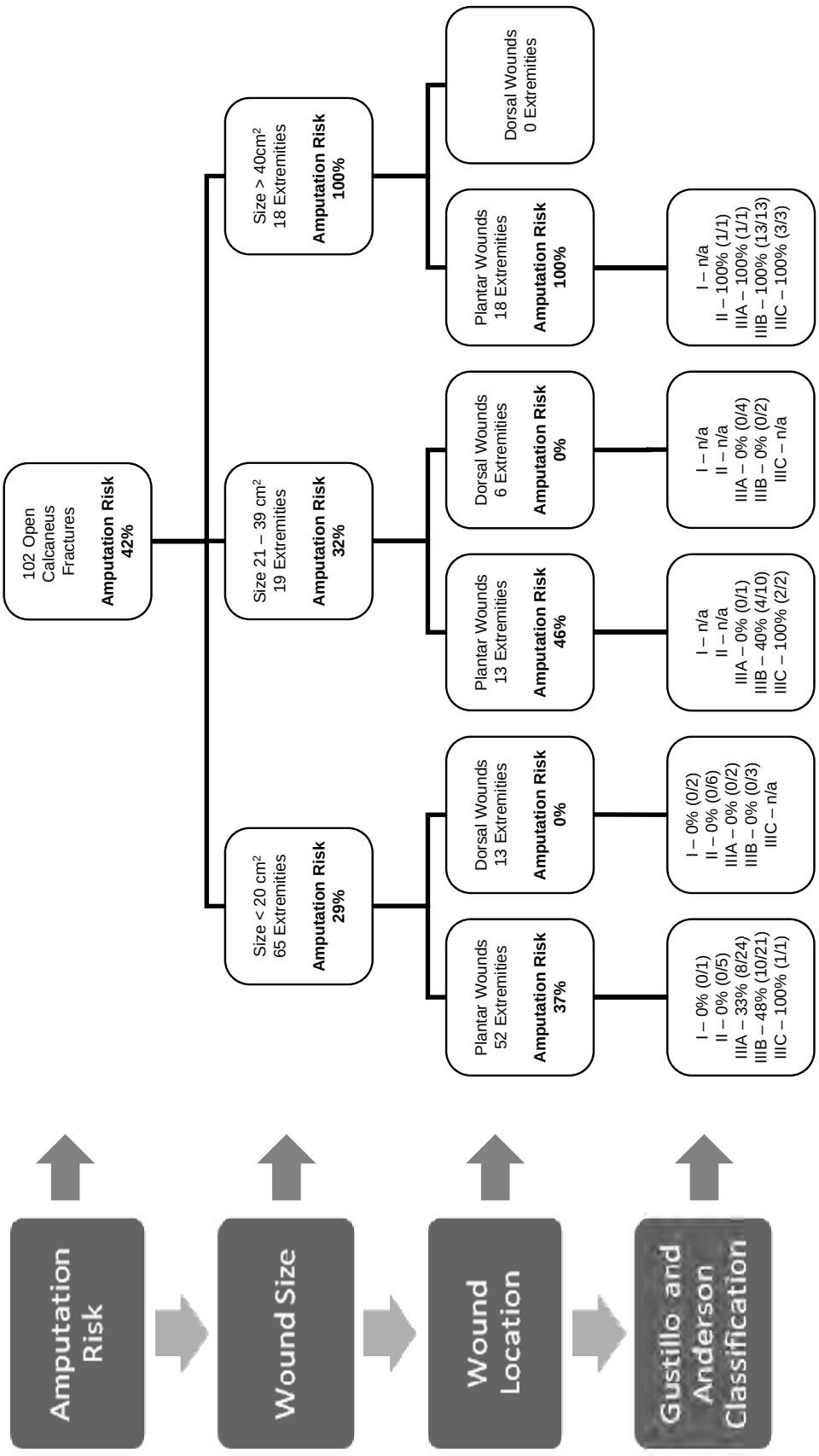

Figure 1. Risk factors for amputation follow open calcaneus fractures. Overall, 42% of patients with an open calcaneus fracture required amputation. All Gustilo and Anderson IIIC fractures required amputation. Gustillo and Anderson IIIB fractures with plantar wounds required amputation in 61% of extremities, regardless of the size of the wound.

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Table 2. Risk Factors for Amputation and Infection following Open Calcaneus Fracture

Characteristic	No.	Amputation (%)	Likelihood ratio	*p* value	Infection	Likelihood ratio	*p* value
Wound size (cm^2) (mean 30 cm^2)							
≤ 20	65	19 (29%)			28 (43%)		
21 to 39	19	6 (32%)			10 (52%)		
≥ 40	18	18 (100%)	36.6	< 0.0001	9 (50%)		0.107
Ipsilateral lower extremity fractures							
Femur	7	5 (71%)		0.104	4 (57%)		0.543
Tibia	44	23 (53%)		0.072	23 (53%)		0.274
Talus	50	29 (58%)	10.3	0.001	30 (60%)	7.7	0.006
Forefoot	67	37 (55%)	14.7	< 0.0001	37 (55%)	6.7	0.01
Method of definitive fixation							
Plate-and-screw fixation	27	4 (15%)			9 (33%)		
Circular external fixation	11	5 (45%)			6 (55%)		
Pin or screw fixation	16	6 (38%)			9 (56%)		
Nonoperative	14	--			3 (21%)		
Subtalar arthrodesis	12	6 (50%)		0.086	6 (50%)		
Amputation before fixation attempt	22	--			14 (64%)	9.3	0.11
Wound location							
Dorsal	19	0 (0%)			5 (26%)		
Plantar	83	43 (52%)	23.9	< 0.0001	42 (51%)	3.8	0.055
Gustillo and Anderson classification							
I	3	0 (0%)			1 (33%)		
II	12	1 (8%)			3 (25%)		
IIIA	32	9 (28%)			10 (31%)		
IIIB	49	27 (55%)			29 (59%)		
IIIC	6	6 (100%)	27.2	< 0.0001	4 (67%)	12.2	0.042
Plantar sensation							
Intact	36	11 (31%)			14		
Diminished	55	25 (45%)			27		
Absent	11	7 (64%)	4.4	0.116	6	1.27	0.531
Culture positive deep infection	47	28 (60%)	11.1	0.001	--	--	--

Amputation was significantly associated with wounds ≥ 40 cm, ipsilateral talus and forefoot fractures, initial definitive fixation using subtalar arthrodesis, plantar wounds, and culture positive deep wound infections. Number of patients are documented with percentage in parentheses. Likelihood ratios are provided for significant variables.

ries, often necessitating multiple revision surgeries or delayed amputation. To date, small series have reported complications following open calcaneus fractures in up to 78% of injuries.[1-5,7] These studies report soft tissue complications in 44% of open calcaneus fractures[4], deep tissue infection in 10% to 39%,[1-4] and eventual amputation in 0 to 14%.[1-4,9] The factors that predict infection, amputation, and poor outcomes remain ill-defined. The purpose of this study was to characterize high-energy open calcaneus fractures by identifying risk factors that may predict infection and amputation. We hypothesized that more severe soft tissue injury, as measured by the Gustilo and Anderson classification and size of the wound[4] would be the strongest predictor of infection and amputation.

The incidence of amputation and risk factors that predict amputation following open calcaneus fractures had not been previously identified.[1-4,15] No prior study has demonstrated a significant correlation between Gustilo and Anderson fracture type and amputation following an open calcaneus fracture.[1-5,8,16] Heir, et al.[1] found that a subset of patients with Gustilo and Anderson type IIIB fractures and wounds in a non-medial location were more likely to require amputation. To our knowledge there have been a total of 78 type III open calcaneus fractures reported in the English literature, with a 22% incidence of amputation following an initial period of limb salvage in this population (n = 17; range, 0 to 33%).[1-5,8,9,16] Our study demonstrated that increasing Gustilo and Anderson fracture type is an independent risk factor for amputation following open calcaneus fractures, irrespective of the location of the predominant wound. We note an amputation rate of 47% in 87 patients with type III open calcaneus fractures, which is notably higher than previously reported series.[1-5,8,16] The larger soft tissue deficits and more frequent associated injury patterns that result from blast trauma likely contribute to the higher amputation rate in this study.

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The characterization of injuries leading to early versus delayed amputation is infrequently reported[17-23] and there are no studies which specifically evaluate the impact of open calcaneus fractures on the timing of amputation. Additionally, given the infrequent nature of open calcaneus fractures and the limited series evaluating the natural history of this injury, inconsistency exists regarding the definition of amputation timing (early or late) and the rate of amputation. In our series, the overall amputation rate was 42%, with 15% of open calcaneus fractures eventually requiring a late amputation more than 12 weeks after injury. These findings are consistent with a recent evaluation of amputations in the current military conflicts, in which the overall late amputation rate for all amputees was 15%.[17] This is in contradistinction to the lower extremity assessment project (LEAP) study group, which found that after a two-year follow-up, late amputations, defined as occurring after the initial hospitalization, occurred in 3.9% of cases.[17] It is possible that the more severe soft tissue injuries and multiple associated fractures may account for this difference. It is also conceivable that in our military practice environment, in an open access healthcare system with a sophisticated amputee rehabilitation center, it is more socially acceptable and functionally practicable for an injured young service member to pursue amputation.

Outcomes following open calcaneus fractures have demonstrated poor functional outcomes in Gustilo and Anderson type III fractures,[4] while more satisfactory results have been reported in less severe open fracture wounds,[1,3,9] wounds in a medial location,[3,16] and after staged treatment that first addresses the soft tissue wound.[1,4,8,16] In this series of severe open calcaneus fractures, patients who pursued limb salvage were able to perform light labor and had significantly higher amounts of pain compared to patients who received eventual amputation. After two-year[15] and seven-year[6] follow-up, the LEAP study group found no difference in functional outcomes between those patients who underwent limb salvage or amputation using the Sickness Impact Profile. Functional outcomes were poor in both groups, worse after longer follow-up, and not affected by the severity of the fracture or soft tissue injury. Our results demonstrate significantly greater Tegner activity levels and lower pain scores in patients who received an amputation. These differences may be attributed to the younger age, centralized rehabilitation, and increased amputee resources available for our patient population. Long-term outcomes of amputation in our young patient population are not known; while early outcomes demonstrate improved function, we believe that amputation should not be performed without careful deliberation with the patient and on an individualized basis. Additionally, we found no difference in activity level or pain in amputations performed in the early versus the late period. This is in contrast to a recent LEAP study, which reported more complications in patients undergoing late amputation for any lower extremity trauma.[23] The initial pursuit of limb salvage followed by late amputation, while requiring additional procedures and a longer treatment course in our study, does not appear to influence ultimate Tegner activity level or pain.

REFERENCES

1. Heier KA, Infante AF, Walling AK, Sanders RW. Open fractures of the calcaneus: soft-tissue injury determines outcome. *J Bone Joint Surg Am.* Dec 2003;85-A(12):2276-2282.
2. Aldridge JM 3rd, Easley M, Nunley JA. Open calcaneal fractures: results of operative treatment. *J Orthop Trauma.* Jan 2004;18(1):7-11.
3. Berry GK, Stevens DG, Kreder HJ, McKee M, Schemitsch E, Stephen DJ. Open fractures of the calcaneus: a review of treatment and outcome. *J Orthop Trauma.* Apr 2004;18(4):202-206.
4. Siebert CH, Hansen M, Wolter D. Follow-up evaluation of open intra-articular fractures of the calcaneus. *Arch Orthop Trauma Surg.* 1998;117(8):442-447.
5. Benirschke SK, Kramer PA. Wound healing complications in closed and open calcaneal fractures. *J Orthop Trauma.* Jan 2004;18(1):1-6.
6. Bosse MJ, MacKenzie EJ, Kellam JF, et al. An analysis of outcomes of reconstruction or amputation after leg-threatening injuries. *N Engl J Med.* Dec 12 2002;347(24):1924-1931.
7. Lawrence SJ. Open calcaneal fractures. *Orthopedics.* Jul 2004;27(7):737-741; quiz 742-733.
8. Lawrence SJ, Grau GF. Evaluation and treatment of open calcaneal fractures: a retrospective analysis. *Orthopedics.* Jun 2003;26(6):621-626; discussion 626.
9. Mehta S, Mirza AJ, Dunbar RP, Barei DP, Benirschke SK. A staged treatment plan for the management of type II and type IIIA open calcaneus fractures. *J Orthop Trauma.* Mar 2010;24(3):142-147.
10. Gustilo RB, Anderson JT. Prevention of infection in the treatment of one thousand and twenty-five open fractures of long bones: retrospective and prospective analyses. *J Bone Joint Surg Am.* Jun 1976;58(4):453-458.
11. Gustilo RB, Mendoza RM, Williams DN. Problems in the management of type III (severe) open fractures: a new classification of type III open fractures. *J Trauma.* Aug 1984;24(8):742-746.
12. Romash MM. Calcaneal fractures: three-dimensional treatment. *Foot Ankle.* Feb 1988;8(4):180-197.
13. Sanders R, Fortin P, DiPasquale T, Walling A. Operative treatment in 120 displaced intraarticular calcaneal fractures. Results using a prognostic computed tomography scan classification. *Clin Orthop Relat Res.* May 1993(290):87-95.
14. Tegner Y, Lysholm J. Rating systems in the evaluation of knee ligament injuries. *Clin Orthop Relat Res.* Sep 1985(198):43-49.
15. MacKenzie EJ, Bosse MJ, Kellam JF, et al. Factors influencing the decision to amputate or reconstruct after high-energy lower extremity trauma. *J Trauma.* Apr 2002;52(4):641-649.
16. Thornton SJ, Cheleuitte D, Ptaszek AJ, Early JS. Treatment of open intra-articular calcaneal fractures: evaluation of a treatment protocol based on wound location and size. *Foot Ankle Int.* May 2006;27(5):317-323.
17. Stinner DJ, Burns TC, Kirk KL, Scoville CR, Ficke JR, Hsu JR. Prevalence of late amputations during the current conflicts in Afghanistan and Iraq. *Mil Med.* Dec 2010;175(12):1027-1029.
18. Bondurant FJ, Cotler HB, Buckle R, Miller-Crotchett P, Browner BD. The medical and economic impact of severely injured lower extremities. *J Trauma.* Aug 1988;28(8):1270-1273.
19. Caudle RJ, Stern PJ. Severe open fractures of the tibia. *J Bone Joint Surg Am.* Jul 1987;69(6):801-807.
20. Fairhurst MJ. The function of below-knee amputee versus the patient with salvaged grade III tibial fracture. *Clin Orthop Relat Res.* Apr 1994(301):227-232.
21. Stansbury LG, Lalliss SJ, Branstetter JG, Bagg MR, Holcomb JB. Amputations in U.S. military personnel in the current conflicts in Afghanistan and Iraq. *J Orthop Trauma.* Jan 2008;22(1):43-46.
22. Thiagarajan P. Delayed amputation in lower limb trauma: an analysis of factors leading to delayed amputation. *Ann Acad Med Singapore.* Mar 1999;28(2):227-230.
23. Harris AM, Althausen PL, Kellam J, Bosse MJ, Castillo R. Complications following limb-threatening lower extremity trauma. *J Orthop Trauma.* Jan 2009;23(1):1-6.

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The Ventral Lamina and Superior Facet Rule: a Morphometric Analysis for Ideal Thoracic Pedicle Screw Starting Point

[1]CPT Daniel G. Kang, MD; [1]LTC Ronald A. Lehman, Jr., MD; [2]Lawrence G. Lenke, MD; [1]Rachel Gaume, BS; [1]MAJ Haines Paik, MD

INTRODUCTION

Pedicle screw instrumentation has become increasingly popular for fixation of the thoracic spine for degenerative, deformity, tumor, and trauma pathologies. Given the inherent dangers associated with pedicle screw placement, the topographic anatomy has been extensively detailed and described in the literature.[1-7] This has allowed surgeons to carefully find the appropriate anatomic starting point, as well as to determine the optimal screw length and trajectory. Despite the recent plethora of literature detailing the anatomic starting points, the safety and efficacy of screw insertion, and the expanding scope of practice utilizing thoracic pedicle screws, there are no objective, definable landmarks to assist with free-hand insertion of pedicle screws. The slightest misunderstanding or error can lead to an unwanted cortical breach, resulting in potential neurologic complication, and the risk of iatrogenic injury from an erroneously placed screw is more catastrophic in the thoracic spine versus the lumbar spine.

With our own increasing surgical experience, we have noted a reproducible and unique anatomic structure known as the "ventral lamina." The ventral lamina is formed by the roof of the spinal canal and is confluent laterally with the medial pedicle wall (Figure 1). An increased understanding of its three-dimensional structure and relationships has significantly improved our ability to place screws safely in pedicles previously thought impossible to instrument (*i.e.*, hypoplastic, deformed, or those with small cancellous channels). This cadaveric study is designed to test the hypothesis that the lateral border of the ventral lamina, where it is contiguous with the medial pedicle wall, occurs medial to the midline of the superior articular facet, thereby serving as a reproducible anatomic guide for pedicle screw instrumentation of the thoracic spine. We set out to 1) determine the true morphometry of the ventral lamina, and 2) to establish a reproducible, ideal medial-lateral thoracic pedicle screw starting point based on the anatomic relationship of the ventral lamina and pedicle with the superior articular facet (SAF), which we term the "superior facet rule."

METHODS

One-hundred fifteen thoracic spine vertebral levels were individually disarticulated and divested of all soft tissue, ensuring the osseous surface of each SAF, lamina, pedicle, and spinous process were clearly visualized. Each individual level was then prepared by removing the vertebral body with a coronal saw cut at the junction of the pedicle and body. Kirschner wires were then placed in a retrograde fashion along the four boundaries of the pedicle canal (medial, lateral, caudad, and cephalad) (Figure 2). Using digital calipers, the following distances were measured in millimeters (mm):

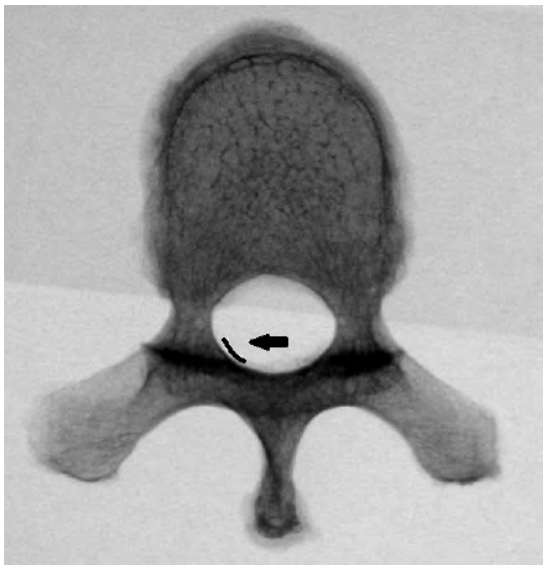

Figure 1. Axial radiograph of thoracic vertebra, demonstrates the ventral lamina (arrow) and its confluence with the medial pedicle wall.

1) width of the SAF at longitudinal mid-point

2) medial border of SAF to medial pedicle wall (MPW)

3) midline of vertebra (cephalad ridge of spinous process) to MPW

4) lateral border of SAF to lateral pedicle wall

5) pedicle diameter at the isthmus

Measurements were analyzed to calculate the anatomic relationship of the ventral lamina and center of the pedicle (COP) to the midline of the SAF. Data analysis was performed using mean ± standard deviation and 95% confidence interval. This study was performed using intramural institutional funding; there are no potential conflicts of interest directly related to this study.

[1]Department of Orthopaedic Surgery and Rehabilitation, Walter Reed National Military Medical Center, Bethesda, MD; [2]Department of Orthopaedic Surgery, Washington University School of Medicine, St. Louis, MO. Address correspondence to: Daniel G. Kang, MD, daniel.g.kang@gmail.com.

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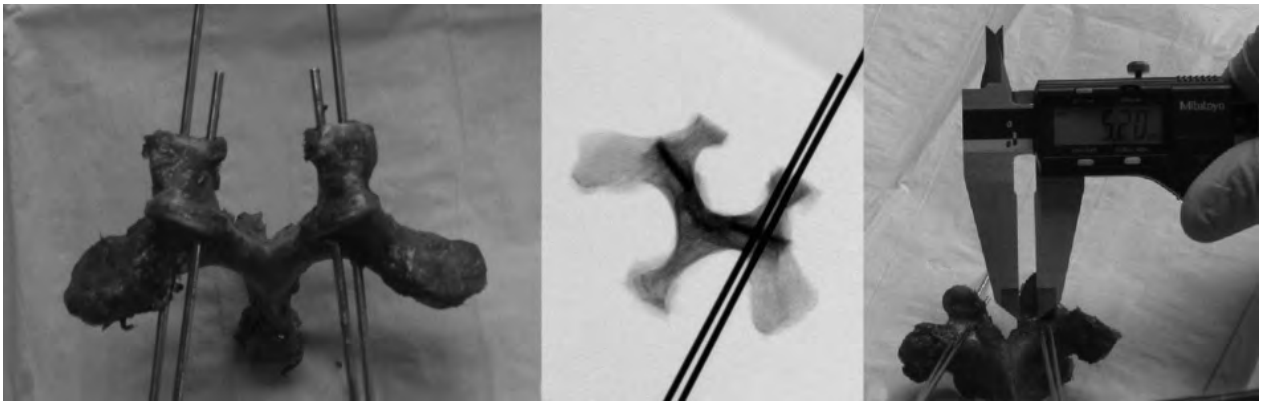

Figure 2. Image of test specimen with vertebral body removed, and K-wires placed along medial and lateral boundaries of pedicle (**A**); axial radiograph of test specimens with K-wires placed (**B**); image of digital caliper measurement (**C**).

RESULTS

Two hundred twenty-nine pedicles were measured. One pedicle was excluded due to fracture of the SAF during disarticulation. The ventral lamina was clearly identifiable at all levels, and in every specimen, forming the roof of the spinal canal and confluent with the medial pedicle wall. The smallest average pedicle width measurements occurred at the T3 to T7 levels (range, 5.45 mm to 6.27 mm), with the largest average measurements occurring at T11 and T12 (range, 8.94 mm to 9.19 mm). This is similar to previous studies evaluating pedicle morphometry, which showed the smallest pedicle isthmic diameters occurring in the mid-thoracic region between T4 and T7.[8] The average pedicle width for all pedicles was 7.06 mm ± 1.86 mm (CI = 6.82 mm to 7.30 mm) (Chart 1, Table 1).

The mean distance from the midline of the SAF to the ventral lamina was 1.36 mm ± 1.23 mm medial (CI = 1.19 to 1.52). The ventral lamina was lateral to the midline of the SAF in 34 (14.85%) pedicles, with a mean distance of only 0.52 ± 0.51 mm lateral (CI = 0.35 to 0.69). There was only 1 (0.43%) ventral lamina that was > 2 mm lateral, and it was found to be 2.18 mm lateral (Chart 2, Table 2).

The mean distance from the midline of the SAF to the center of the pedicle (COP) was 2.17 mm ± 1.38 mm lateral (CI = 1.99 to

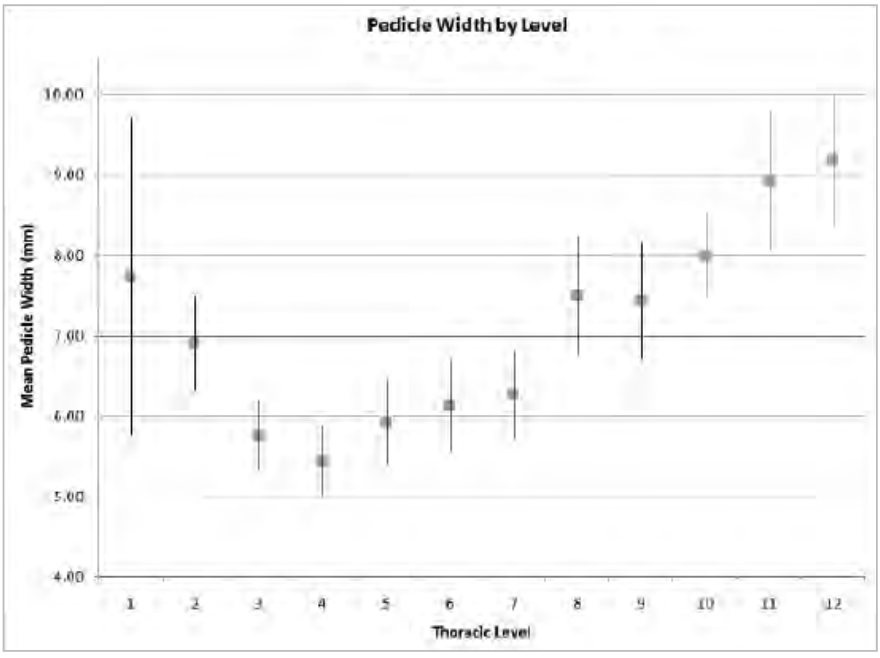

Chart 1. Mean pedicle width by level (mm).

Table 1. Average Pedicle Width per Level (mm)

	N =	Mean	Standard deviation	CI
T1	9	7.73	3.03	1.98
T2	14	6.91	1.11	0.58
T3	24	5.77	1.08	0.43
T4	20	5.45	1.00	0.44
T5	20	5.94	1.20	0.53
T6	20	6.13	1.30	0.57
T7	20	6.27	1.25	0.55
T8	20	7.51	1.67	0.73
T9	22	7.44	1.67	0.73
T10	20	8.01	1.24	0.54
T11	20	8.94	2.02	0.88
T12	20	9.19	1.86	0.82
TOTAL	**229**	**7.06**	**1.86**	**0.24**

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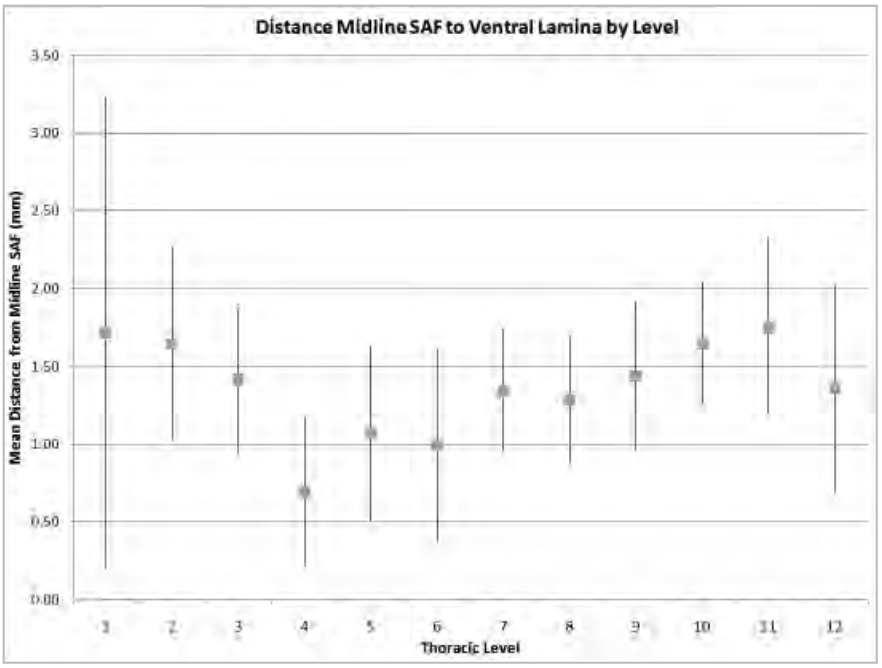

Chart 2. Mean distance midline SAF to ventral lamina by level (mm).

Table 2. Mean Distance from Midline Superior Articular Facet to Ventral Lamina (mm)

	N =	Mean	Standard deviation	CI
T1	9	1.72	2.32	1.52
T2	14	1.65	1.17	0.62
T3	24	1.42	1.20	0.48
T4	20	0.70	1.10	0.48
T5	20	1.08	1.28	0.56
T6	20	0.99	1.42	0.62
T7	20	1.34	0.90	0.39
T8	20	1.29	0.95	0.42
T9	22	1.44	1.08	0.47
T10	20	1.65	0.89	0.39
T11	20	1.75	1.33	0.58
T12	20	1.36	1.51	0.66
TOTAL	**229**	**1.36**	**1.23**	**0.16**

2.35). The COP was medial to the midline of the SAF in 11 (4.80%) pedicles, with a mean distance of only 0.76 mm ± 0.76 mm medial. The most medial COP was 2.32 mm medial to the midline of the SAF (Chart 3, Table 3). We also found the COP to be 13.17 mm ± 2.47 mm caudad (CI = 12.85 to 13.49) to the superior border of the SAF.

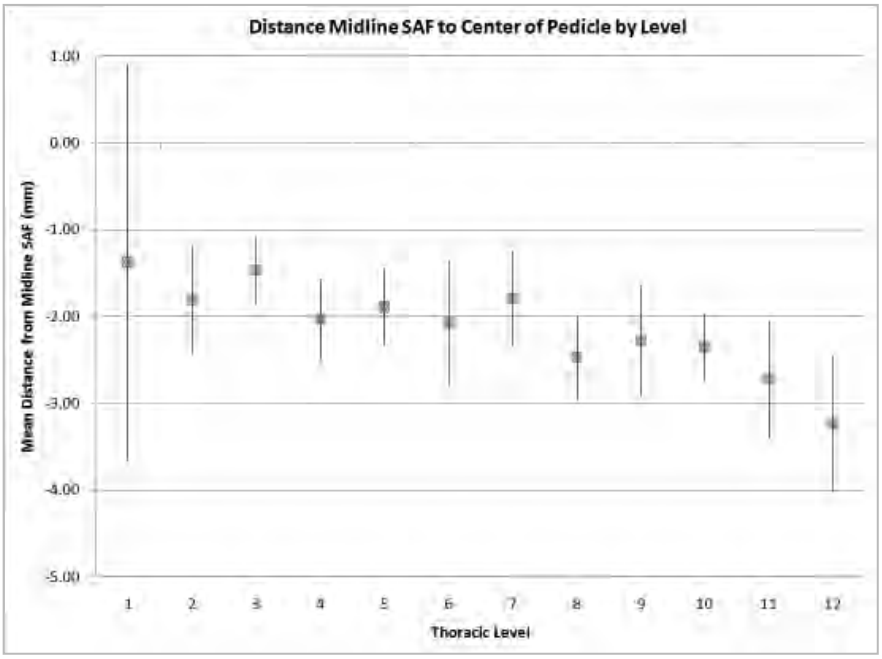

Chart 3. Mean distance midline SAF to center of pedicle by level (mm).

Table 3. Mean Distance from Midline Superior Articular Facet to Center of Pedicle (mm)

	N =	Mean	Standard deviation	CI
T1	9	-1.37	3.50	2.29
T2	14	-1.81	1.18	0.62
T3	24	-1.47	0.97	0.39
T4	20	-2.03	1.06	0.47
T5	20	-1.89	1.03	0.45
T6	20	-2.07	1.64	0.72
T7	20	-1.79	1.24	0.54
T8	20	-2.47	1.11	0.49
T9	22	-2.28	1.47	0.64
T10	20	-2.35	0.88	0.39
T11	20	-2.72	1.54	0.68
T12	20	-3.23	1.79	0.78
TOTAL	**229**	**-2.17**	**1.38**	**0.18**

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In addition, we evaluated all calculated distances, irrespective of vertebral level, of the ventral lamina and the COP (Figure 4) in relation to the midline SAF ordered in increasing distance from the midline SAF. We found a parabolic relationship (Figure 4**)** and this was used to determine the ideal anatomic starting point approximately 2 mm to 3 mm lateral to the midline SAF.

DISCUSSION

Given the individual variability in pedicle anatomy, as well as differences in surgeon training/experience with thoracic pedicle screw placement, the primary purpose of this study was to verify our observation regarding the presence of the ventral lamina as a reproducible, anatomic structure that can serve as an anatomic "map" for the ideal medial-lateral placement of thoracic pedicle screws. In 85% of our studied specimens, the ventral lamina was found to be medial to the midline of the SAF. In the remaining 15%, the ventral lamina was lateral to the midline of the SAF by a mean distance of 0.52 mm, and only one (0.43%) ventral lamina was > 2 mm lateral to the midline of the SAF. This statistic alone further solidifies the tenet that if the surgeon begins the starting point 2 mm lateral to the midline of the SAF, there is a 0.43% chance the starting point will be medial to the pedicle or into the spinal canal. The center of the pedicle was also found to be a mean distance of 2.17 mm lateral to the midline of the SAF, and was lateral to midline in 95% of pedicles. Therefore, results from our morphometric study suggest the ideal starting point for thoracic pedicle screw insertion should be 2 mm to 3 mm lateral to the midline of the SAF. We term this reproducible, anatomic landmark the "superior facet rule" (Figure 3). This consistent anatomic relationship can be used as a reliable guide for thoracic pedicle screw insertion in the center of the pedicle, and to avoid penetration into the spinal canal without having to adjust the starting point depending on the thoracic vertebral level being instrumented. The surgeon should also take into consideration the fact that the medial pedicle wall is two to three times thicker than the lateral pedicle wall.[1] The medial pedicle wall can be envisioned as a "buttress," serving as a boundary for a "funnel," or path, for the trajectory of the pedicle screw.

Previous studies have recommended various anatomic landmarks for appropriate pedicle screw placement; however, no standard, objective anatomic landmark for thoracic pedicle screw insertion exists.[9-14] Cinotti, et al.[9] also used the superior facet as an anatomic landmark for thoracic pedicle screw insertion and found the pedicle axis intersecting the middle of the SAF in 15% of specimens, lateral two-thirds of the SAF in 62%, and lateral border of the SAF in 23%. The authors found the COP to be at or lateral to the midline SAF in 100% of specimens, which is similar to our findings (95%) concerning the lateral relationship of the COP to the midline SAF. In the same study, an entry point at the midline SAF resulted in a 10% rate of pedicle cortex violation, compared to no pedicle cortex violation using the entry point along the lateral two-thirds of the SAF.[9] Therefore, the authors recommended a starting point at the intersection between the superior border of the transverse process and the lateral two-thirds of the SAF.

Recently, Yang, et al.[14] described the utility of the nutrient foramen of the lamina as a guide to placement of pedicle screws in the thoracic spine. However, the nutrient foramen was not found uniformly at all thoracic levels, and was found in only 63% of specimens. This lack of reproducibility may make pedicle screw insertion difficult if one relies on this anatomic landmark alone.[14] This is in comparison to our current study, which found the superior facet rule to be 95% reproducible and consistent at nearly all thoracic levels. In another study, Kim, et al.[15] describe the ideal pedicle screw starting point in the thoracic spine. However, the authors describe a dynamic and changing starting point depending on the thoracic level. For the lower thoracic regions, the starting point is described as the junction of the bisected transverse process and the lamina at, or just medial to, the lateral aspect of the pars. As instrumentation progresses cephalad to the apical mid-thoracic region, the starting point trends toward a more medial and cephalad starting point. At T7 to T9, the anatomic starting point is described as the confluence of the transverse process, lamina, and the superior articular facet. Finally, at the most cephalad levels, the starting point then changes again to progress more lateral and caudad, described as the junction of the bisected transverse process and the lamina at the lateral pars. Using this technique, the authors reported only a 1.7% incidence of medial cortical breach with no neurologic complications in a total of 577 screws.[15] Despite the safety profile highlighted by use of the free-hand technique as described by Kim, et al.,[15] of particular mention is the fact that the success of the free-hand technique used in this study was achieved by a surgeon with clinical experience in placing over 30,000 pedicle screws.

The difference between the thoracic and lumbar spine pedicle anatomy cannot be over emphasized, and makes the task of placing pedicle screws much more challenging in thoracic vertebrae. This is especially true within the mid-thoracic spine (between T4 and T7), where previous morphologic studies have found pedicles become significantly smaller.[7,9,16] This finding was also demonstrated in our study where the pedicles were found to be much smaller between T3 and T7, compared to those at the most caudad levels (T10-T12) (Chart 1). Also, when evaluating the mean distance of the ventral lamina from the midline SAF, we found the T4 to T6 ventral laminae were closest to the midline SAF (Chart 2). However, when evaluating the mean distance of the COP from the midline SAF, the COP trended more lateral with more caudad thoracic levels (Chart 3). Interestingly, the T4 to T6 center of pedicle measurements were not the most lateral, despite having ventral laminae closest to the midline SAF, and this relationship may contribute to the mid-thoracic pedicles being the most difficult to instrument. These factors can make complete containment

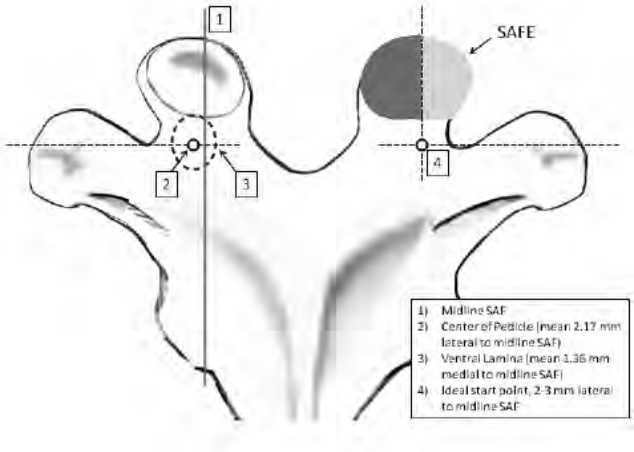

Figure 3. Illustration of superior facet rule, with relationship of midline SAF (solid line) to ideal starting point (small circle), 2 mm to 3 mm lateral to midline SAF.

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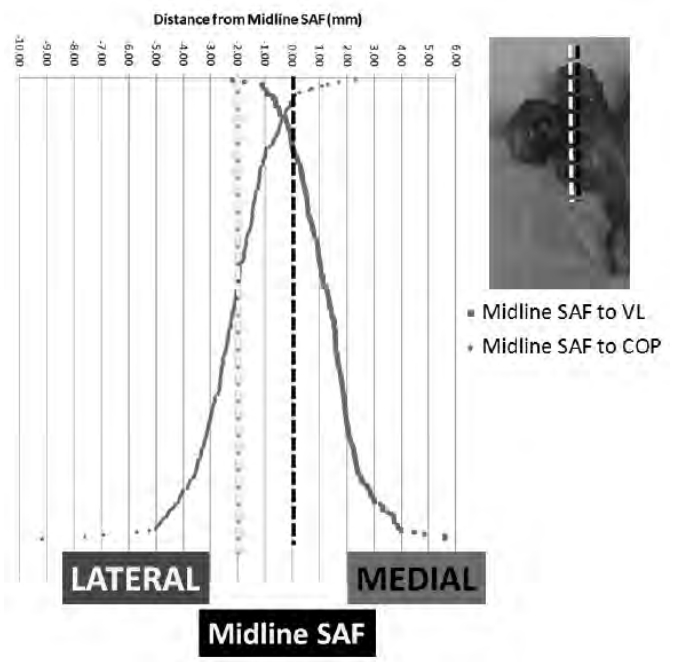

Chart 4. Combined measurements of all specimens, ordered in increasing distance from the midline SAF (black dashed line) irrespective of specimen or vertebral level, for the ventral lamina (squares) and center of pedicle (diamonds) (mm); the ideal medial-lateral starting point (2 mm lateral; light gray dashed line) is also depicted.

of pedicle screws extremely challenging, or sometimes even impossible in the mid-thoracic spine or at an apical thoracic vertebrae during deformity surgery, and misplaced screws or cortical breaches may be unavoidable. Some studies have suggested thoracic pedicles from T4 to T8 may not be wide enough for safe pedicle screw fixation.[9,16] However, these studies were performed with early generation instrumentation systems with the smallest available pedicle screw diameter of 5.5 mm. Our study demonstrated a mean inner pedicle isthmus diameter of 7.06 mm ± 1.86 mm (CI = 6.82 to 7.30), and the smallest measured pedicle isthmus was 5.45 mm. Medial cortical breach is of particular concern, given the proximity of the spinal cord to the medial cortical wall and the increased rate of neurologic injury reported with this error.[7] Despite the recognition of confounding residual imaging artifact (on post-operative computed tomography) as well as hypothesized "safe zones" for acceptable cortical violation, many situations still preclude the safe placement of pedicle screws.[15,17-19]

Several authors have demonstrated safety of free-hand pedicle screw placement in vivo, using only surface topography to guide screw placement.[15,17,20-24] Kim, et al.[15] demonstrated the free-hand placement of pedicle screws to be safe and effective, even in the setting of revision surgery;[23] however, misplaced screws still occur, and the resulting neurologic complications can be devastating.[24] Therefore, other authors have recommended the use of intra-operative fluoroscopy or image guidance techniques, which have been espoused to improve accuracy with screw insertion.[18,19,25-30] The accuracy rate of image-guided systems has been widely variable and very few in vivo studies actually exist. Several cadaveric studies have demonstrated an accuracy rate from as low as 80% to 99%.[27-30] A recent meta-analysis by Tian, et al.[31] of image-guided versus free-hand pedicle screw insertion found a total of 43 studies in the literature and reported a statistically significant lower incidence of pedicle violation with computed tomography-based navigation versus conventional insertion technique. This reduced screw deviation rate was also found in the two-dimensional and three-dimensional fluoroscopy-based navigation techniques. The authors concluded that the navigated approaches had a statistically significant higher accuracy in the placement of pedicle screws compared with conventional techniques.[31] In a prospective study by Laine,[25] 139 of 174 pedicle screws were placed with computer assistance versus free-hand technique, and reported a misplacement rate of 4.3% with computer assistance compared to a rate of 14.3% using conventional methods. In contrast, Hart, et al.[32] in a cadaveric study, found no significant difference in the overall thoracic pedicle screw misplacement rate between stereotactic image guidance versus manual fluoroscopic technique. Mirza, et al.[26] performed a similar cadaveric study evaluating the use of conventional fluoroscopy versus multiple image-guided programs. They found that accuracy was increased with the computed tomography-based image guidance, but increased procedure time by six-fold and resulted in a 20-fold increase in radiation exposure to the patient. Therefore, significantly increased operative time and radiation exposure continue to be substantial deterrents to these image-guided techniques. For these reasons, as well as several large series demonstrating minimal complications without image guidance, the free-hand technique has been espoused to be an effective and safe technique for instrumentation.[15,24]

During our surgical approach to thoracic spine instrumentation and fusion, we perform a wide and complete facetectomy of the inferior articular facet (IAF) bilaterally at every level. This allows for 1) complete visualization of the entire facet for morphometric confirmation of the anatomy for employment of the free-hand technique, 2) additional local bone graft material, 3) improved mobility/flexibililty of the spine for deformity correction, and 4) proper preparation/decortication of the facet fusion bed. Exposing the entire SAF to its medial aspect, where the confluence of the ligamentum flavum attaches, allows the surgeon to measure accurately the width of the facet in the medial to lateral direction. From our study, if the facet measures 12 mm in width, the starting point should start 4 mm from the lateral aspect of the facet (or 2 mm lateral from the midline of the facet). The ideal cephalo-caudad starting point and sagittal inclination remains unknown and changes based on the use of a straight-forward or anatomic trajectory. We use the straight-forward trajectory, with screw placement in a position perpendicular to the superior endplate in the proximal and mid-thoracic spine and perpendicular to the lamina in the lower thoracic spine, which has been found in a cadaveric study to improve pedicle screw fixation strength.[33] The cephalo-caudad starting point for the straight forward trajectory as described by Kim, et al.,[15] changes based on the vertebral level, and is at the bisected transverse process for the first and twelfth thoracic vertebrae, trending towards a more cephalad starting point in relation to the transverse process as one proceeds towards the mid-thoracic region (T7 to T9), which has a cephalo-caudad starting point at the proximal edge of the transverse process (Table 4).

Once the starting point is determined, we use a high speed burr to create a dorsal cortical pilot hole. The pedicle probe is then inserted into the pilot hole. We prefer to use an angled pedicle probe with a tapered tip that is 2 mm in width (Figure 4). This bevel is started with the concavity oriented in the lateral direction. This should result in safe insertion of the probe. If the probe does not pass easily, the probe should

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Table 4. Cephalo-Caudad Starting Point for Straight-Forward Trajectory (Kim, et al.)[15]

Thoracic level	Cephalo-caudad starting point	Medial-lateral starting point
T1	Bisected transverse process	**"Superior facet rule"** 2 mm to 3 mm lateral to midline of the superior articular facet
T2-T4	Proximal 1/3 transverse process	
T7-T9	Proximal Edge transverse process	
T10-T11	Proximal 1/3 transverse process	
T12	Bisected transverse process	

be extracted from the pilot hole, flipped to orient the bevel medially, and then the ventral lamina can be palpated medially with the use of the pedicle probe. With proper palpation of the ventral lamina, the surgeon can feel and hear the thickened cortex at the confluence of the spinal canal and medial pedicle wall, which is two to three times thicker than the lateral pedicle wall. Therefore, taking advantage of the fact that the medial cortical wall is thicker than the lateral wall, after palpating the ventral lamina, the surgeon can then "scrape" laterally along the ventral lamina and "fall" into the pedicle along the appropriate axial trajectory. The axial pedicle trajectory is nearly parallel to the sagittal plane at the twelfth thoracic vertebra and changes progressively towards a more medial trajectory with more cephalad levels. However, once the ventral lamina is palpated, and as long as the insertion of the probe stays lateral to this structure, the spinal canal should not be breached.

Our study has one obvious weakness, in that the cadaveric specimens evaluated did not include those with deformity. However, the majority of surgeons do not perform major deformity corrections, so the applicability of this technique and anatomic reference point applies to all surgical cases in the thoracic spine. Pedicle screw instrumentation plays a large role in deformity correction surgery, and our findings do not specifically address whether the ventral lamina can be used as an anatomic guide in those patients with scoliosis or other pre-existing congenital deformities. While the free-hand technique has been shown to be effective even in curves > 90 degrees, it would be difficult to interpret whether the anatomic relationships associated with the ventral lamina are reproducible in the spine with deformity.[22] This may be of particular utility, however, as instrumenting spines with acquired or congenital deformity can be especially challenging, as pedicles may be absent, obscured, or altogether obliterated. Having stated this, the senior author (LGL) has found that the ventral lamina is a reproducible structure that aids in extremely complex deformity cases and placement of pedicle screws at the apices of curves, serving to enhance curve correction. The realization of this structure during complex deformity surgery led to initiation of the current investigation in a cadaveric model. However, the importance of the "superior facet rule" and an understanding of the ventral lamina morphometry may be particularly important for residents/fellows or an inexperienced spine surgeon, to prevent confusion and catastrophic neurologic injury, and less so for the experienced and perspicacious spine surgeon who possesses the exquisite tactile feedback to avoid intracanal violation. Therefore, given the reproducibility of the ventral lamina and "superior facet rule" at all levels in the thoracic spine, we hope our findings can be easily teachable to the training spine surgeon and will help prevent confusion and catastrophic neurologic injury compared to a more complex description, an inconsistent anatomic landmark, or a changing pedicle screw starting point based on the vertebral level.

CONCLUSION

We have described the ventral lamina as the portion of the roof of the spinal canal that becomes confluent with the medial wall of the pedicle. Given the consistent anatomic relationship that exists between the ventral lamina and the superior articular facet at all thoracic levels, the ventral lamina can be used as a reliable guide for the medial-lateral starting point in thoracic pedicle screw placement. We recommend that the ideal medial-lateral starting point for the placement of thoracic pedicle screws start 2 mm to 3 mm lateral to the midline of the superior articular facet to avoid spinal canal violation during insertion.

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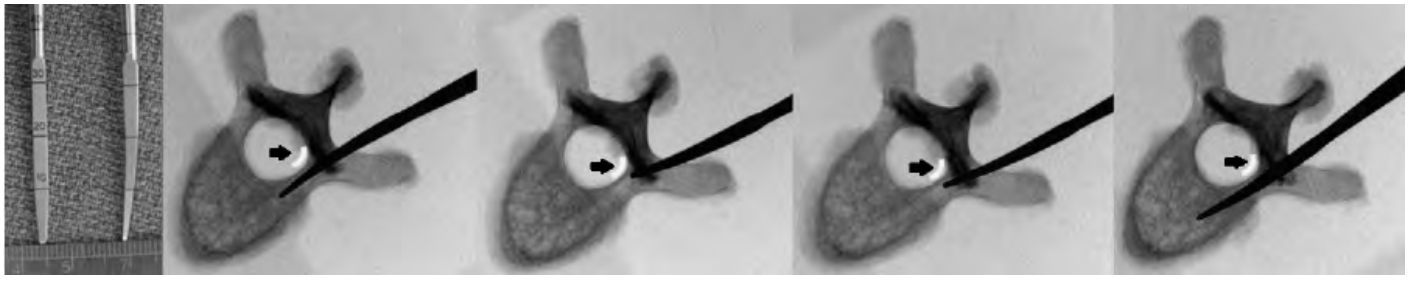

Figure 4. Axial radiographs of thoracic vertebrae, using an angled pedicle probe with tapered 2-mm tip, with tip pointed lateral, then re-inserted with tip pointed medial to palpate and scrape laterally along the ventral lamina (arrow) to fall into the pedicle.

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REFERENCES

1. Kothe R, O'Holleran JD, Liu W, Panjabi MM. Internal architecture of the thoracic pedicle. An anatomic study. *Spine (Phila Pa 1976).* Feb 1 1996;21(3):264-270.
2. Berry JL, Moran JM, Berg WS, Steffee AD. A morphometric study of human lumbar and selected thoracic vertebrae. *Spine (Phila Pa 1976).* May 1987;12(4):362-367.
3. Ebraheim NA, Xu R, Ahmad M, Yeasting RA. Projection of the thoracic pedicle and its morphometric analysis. *Spine (Phila Pa 1976).* 1 Feb 1997;22(3):233-238.
4. Krag MH, Weaver DL, Beynnon BD, Haugh LD. Morphometry of the thoracic and lumbar spine related to transpedicular screw placement for surgical spinal fixation. *Spine (Phila Pa 1976).* Jan 1988;13(1):27-32.
5. Panjabi MM, Takata K, Goel V, et al. Thoracic human vertebrae. Quantitative three-dimensional anatomy. *Spine (Phila Pa 1976).* Aug 1991;16(8):888-901.
6. O'Brien MF, Lenke LG, Mardjetko S, et al. Pedicle morphology in thoracic adolescent idiopathic scoliosis: is pedicle fixation an anatomically viable technique? *Spine (Phila Pa 1976).* 15 Sep 2000;25(18):2285-2293.
7. Vaccaro AR, Rizzolo SJ, Balderston RA, et al. Placement of pedicle screws in the thoracic spine. Part II: An anatomical and radiographic assessment. *J Bone Joint Surg Am.* Aug 1995;77(8):1200-1206.
8. Vaccaro AR, Rizzolo SJ, Allardyce TJ, et al. Placement of pedicle screws in the thoracic spine. Part I: Morphometric analysis of the thoracic vertebrae. *J Bone Joint Surg Am.* Aug 1995;77(8):1193-1199.
9. Cinotti G, Gumina S, Ripani M, Postacchini F. Pedicle instrumentation in the thoracic spine. A morphometric and cadaveric study for placement of screws. *Spine (Phila Pa 1976).* 15Jan 1999;24(2):114-119.
10. Roy-Camille R, Saillant G, Mazel C. Internal fixation of the lumbar spine with pedicle screw plating. *Clin Orthop Relat Res.* Feb 1986(203):7-17.
11. Magerl FP. Stabilization of the lower thoracic and lumbar spine with external skeletal fixation. *Clin Orthop Relat Res.* Oct 1984(189):125-141.
12. Su BW, Kim PD, Cha TD, et al. An anatomical study of the mid-lateral pars relative to the pedicle footprint in the lower lumbar spine. *Spine (Phila Pa 1976).* 1 Jun 2009;34(13):1355-1362.
13. Husted DS, Yue JJ, Fairchild TA, Haims AH. An extrapedicular approach to the placement of screws in the thoracic spine: an anatomic and radiographic assessment. *Spine (Phila Pa 1976).* 15 Oct 2003;28(20):2324-2330.
14. Yang JY, Lenke LG. Usefulness of the nutrient foramen of lamina for insertion of thoracic pedicle screws. *J Spinal Disord Tech.* May 2008;21(3):205-208.
15. Kim YJ, Lenke LG, Bridwell KH, Cho YS, Riew KD. Free hand pedicle screw placement in the thoracic spine: is it safe? *Spine (Phila Pa 1976).* 1 Feb 2004;29(3):333-342; discussion 342.
16. McLain RF, Ferrara L, Kabins M. Pedicle morphometry in the upper thoracic spine: limits to safe screw placement in older patients. *Spine (Phila Pa 1976).* 15 Nov 2002;27(22):2467-2471.
17. Belmont PJ, Jr., Klemme WR, Dhawan A, Polly DW, Jr. In vivo accuracy of thoracic pedicle screws. *Spine (Phila Pa 1976).* 1 Nov 2001;26(21):2340-2346.
18. Yoo JU, Ghanayem A, Petersilge C, Lewin J. Accuracy of using computed tomography to identify pedicle screw placement in cadaveric human lumbar spine. *Spine (Phila Pa 1976).* 15 Nov 1997;22(22):2668-2671.
19. Rao G, Brodke DS, Rondina M, Dailey AT. Comparison of computerized tomography and direct visualization in thoracic pedicle screw placement. *J Neurosurg.* Sep 2002;97(2 Suppl):223-226.
20. Gertzbein SD, Robbins SE. Accuracy of pedicular screw placement in vivo. *Spine (Phila Pa 1976).* Jan 1990;15(1):11-14.
21. Karapinar L, Erel N, Ozturk H, Altay T, Kaya A. Pedicle screw placement with a free hand technique in thoracolumbar spine: is it safe? *J Spinal Disord Tech.* Feb 2008;21(1):63-67.
22. Kuklo TR, Lenke LG, O'Brien MF, Lehman RA Jr., Polly DW Jr., Schroeder TM. Accuracy and efficacy of thoracic pedicle screws in curves more than 90 degrees. *Spine (Phila Pa 1976).* Jan 15 2005;30(2):222-226.
23. Kim YW, Lenke LG, Kim YJ, Bridwell KH, Kim YB, Watanabe K. Freehand pedicle screw placement during revision spinal surgery: analysis of 552 screws. *Spine (Phila Pa 1976).* 1 May 2008;33(10):1141-1148.
24. Lehman RA Jr., Lenke LG, Keeler KA, Kim YJ, Cheh G. Computed tomography evaluation of pedicle screws placed in the pediatric deformed spine over an 8-year period. *Spine (Phila Pa 1976).* 15 Nov 2007;32(24):2679-2684.
25. Laine T, Schlenzka D, Makitalo K, Tallroth K, Nolte LP, Visarius H. Improved accuracy of pedicle screw insertion with computer-assisted surgery. A prospective clinical trial of 30 patients. *Spine (Phila Pa 1976).* 1 Jun 1997;22(11):1254-1258.
26. Mirza SK, Wiggins GC, Kuntz CT, et al. Accuracy of thoracic vertebral body screw placement using standard fluoroscopy, fluoroscopic image guidance, and computed tomographic image guidance: a cadaver study. *Spine (Phila Pa 1976).* 15 Feb 2003;28(4):402-413.
27. Glossop ND, Hu RW, Randle JA. Computer-aided pedicle screw place ment using frameless stereotaxis. *Spine (Phila Pa 1976).* 1 Sep 1996;21(17):2026-2034.
28. Choi WW, Green BA, Levi AD. Computer-assisted fluoroscopic targeting system for pedicle screw insertion. *Neurosurgery.* Oct 2000;47(4):872-878.
29. Kim KD, Patrick Johnson J, Bloch BO, Masciopinto JE. Computer-assisted thoracic pedicle screw placement: an in vitro feasibility study. *Spine (Phila Pa 1976).* 15 Feb 2001;26(4):360-364.
30. Schwend RM, Dewire PJ, Kowalski TM. Accuracy of fluoroscopically assisted laser targeting of the cadaveric thoracic and lumbar spine to place transpedicular screws. *J Spinal Disord.* Oct 2000;13(5):412-418.
31. Tian NF, Huang QS, Zhou P, et al. Pedicle screw insertion accuracy with different assisted methods: a systematic review and meta-analysis of comparative studies. *Eur Spine J.* Jun 2011;20(6):846-859.
32. Hart RA, Hansen BL, Shea M, Hsu F, Anderson GJ. Pedicle screw placement in the thoracic spine: a comparison of image-guided and manual techniques in cadavers. *Spine (Phila Pa 1976).* 15 Jun 2005;30(12):E326-E331.
33. Lehman RA, Jr., Kuklo TR. Use of the anatomic trajectory for thoracic pedicle screw salvage after failure/violation using the straight-forward technique: a biomechanical analysis. *Spine (Phila Pa 1976).* 15 Sep 2003;28(18):2072-2077.

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