

**Vascular Emergency Surgery: Simulated Exercises for Limb Salvage (VESSELS) -
Development of a simulation model and hybrid curriculum for the military general surgeon**

By:

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Title of Culminating Project: "Vascular Emergency Surgery: Simulated Exercises for Limb Salvage (VESSELS) - Development of a simulation model and hybrid curriculum for the military general surgeon"

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Dedication:

I would like to dedicate this project to my friends and family. Without their tremendous understanding and encouragement in the past few years, it would be impossible for me to complete my residency and this study.

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Abstract:*Purpose:*

Military surgeons have the unique responsibility of maintaining a broad set of surgical skills to care for combat-related injuries during times of peace. Lower and upper limb amputations are life-altering combat injuries sustained by our military personnel. Salvage of a limb saves someone from impaired mobility, abnormal physiology, and social effects of amputation and requires the knowledge and technical proficiency to diagnose and treat vascular traumatic injuries.

Methods:

A needs assessment of deployable military surgeons was performed, demonstrating a need for additional training to diagnose and treat vascular emergencies. Our institution's mixed material layering 3D medical applications center developed a novel low-cost arterial model for simulation skills training. A focused simulation curriculum was developed, which included both didactic and technical skills training for vascular trauma emergencies. Learners were assessed using a pre-and post-test design to evaluate efficacy.

Results:

A realistic vascular model was developed using 3D printed technologies and was used for traumatic vascular emergency skills training. Implementing the VESSELS course using in-person and online asynchronous formats demonstrated significant increases in knowledge and confidence in diagnosing and managing limb-threatening injuries.

Conclusions:

Vascular surgery is a low-volume and high-complexity specialty, where a comprehensive assessment of technical skills is essential. This novel, low-cost simulation model and curriculum increases understanding of vascular surgical techniques and emergency procedures. The medical education community will directly benefit from this new simulation learning resource that can be utilized by various learners, from medical students to practicing physicians. Broader effects would include improved quality of vascular emergencies managed by deployed military surgeons and rural and community centers without vascular subspecialty support.

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Chapter 1: Introduction

Background:

During general surgery residency training, the Accreditation Council for Graduate Medical Education (ACGME) requires major surgical cases for residents to graduate from an accredited program. Fifty of the 850 needed cases are vascular surgery (with ten central access and ten anastomoses/repair/endarterectomy). These minimums are consistently met through general training over the five years of general surgery residency. Therefore, fifty vascular cases over five years is a low volume compared to general cases. This is reflected in general surgery practice, with vascular surgery being a low volume, high complexity subspecialty of surgery, and many general practitioners do not regularly diagnose or manage these patients. Additionally, reservist subspecialties (i.e., colorectal, pediatric, plastic reconstruction, etc.) do not regularly use vascular surgical techniques in their daily practice.

Continuing medical education (CME) for the surgical community includes clinical knowledge and surgical techniques and operative instruments. Additionally, our military surgeons are responsible for maintaining a broad set of surgical skills during times of peace to care for combat-related injuries. Regarding vascular surgery, there is a current course, Advanced Surgical Skills for Exposure in Trauma (ASSET), that uses human cadavers to teach surgical exposure to anatomic structures that may pose a threat to life or limb when injured. It is available for surgeons to complete before deployment. It is designed for mid/senior surgical residents, trauma and acute care surgical fellows, or any surgeon who wishes to review the anatomy. However, there are few vascular surgery simulation events/resources at our institutions to include a high fidelity model on which to practice outside of the ASSET course. Current options for

vascular simulation training include arterial models for carotid repair and anastomosis, which are available for public purchase and do not include instructional resources. Other programs have created low-cost simulation models for vascular access [18,19], regular and transplant anastomosis [20,21], and neurosurgical vascular techniques [22,23]. However, there are few to no vascular trauma simulation curricula available.

Despite the low volume of vascular trauma seen by a general practitioner in the peacetime and civilian realms, these injuries are encountered in deployed environments. Lower and upper limb amputations are one of the most life-altering combat injuries sustained by our military personnel. From January 2001 through October 2017, 1,705 service members suffered deployment-related amputations. These men and women were 21-29 years old with 1,914 lower and 302 upper limb amputations [1]. Salvage of a limb saves someone from impaired mobility, abnormal physiology, and social effects of amputation and is, therefore, a valuable skill to the deployed surgeon.

We believed a curriculum and simulation model to teach basic skills would be more accessible and transferable. These resources would help junior practitioners learn and practice vascular surgery techniques and be comfortable with the instruments and materials if created. Additionally, practicing surgeons can enroll in the course in preparation for deployment. We completed a formal needs assessment and found that most of those surveyed had completed the ASSET course, encountered traumatic vascular injuries while deployed, and did not have access to a vascular subspecialist for help. Staff surgeons also expressed wishes for more opportunities to train and continue education/practice in vascular subspecialty skills. (This is discussed further in Chapter 2.)

Instructional Design Guided by Educational Theory:

There are many instructional strategies to facilitate active learning and skills acquisition, including case-based learning (CBL), problem-based learning (PBL), team-based learning (TBL), and simulation-based mastery learning (SBML). A simulation was chosen because of its value as an adjunct to medical education and the hands-on nature of the skill to be learned. Most learners (93%) favor simulators for their training due to the combined realism and ability to practice [3]. It provides a standardized and safe environment to learn and practice. SBML also builds on CBL and PBL strategies where learners are guided by instructors who provide real-time assessment and feedback. By mastering technical skills through simulation, learners can also increase their confidence in their knowledge, clinical reasoning, and skills.

Following didactic instruction, learners engage in a hands-on practice informed by simulation-based learning and experiential learning theories [16,17]. Having the simulation following a lecture supports learning of content with short interval application of learned material. This actively engages the learning process and has the student utilize a higher level of thinking and reasoning to reflect on their learning. With the goal of mastery learning, we used a competency-based education platform that required all learners to acquire essential knowledge and skills measured through multiple-choice knowledge questions, Likert scale confidence intervals, and skill competency assessments. This was completed using Kolb's Experiential Learning Theory to realize that individual learners may vary in expertise and require different times and levels of instruction to achieve mastery [17]. The simulation can also be repeated until mastery is achieved.

Curriculum Design:

Kern's 6-step approach for curriculum development was applied to support the successful integration of VESSELS in graduate and continuing medical education [5]. Upon completing the course, the learner is expected to demonstrate the knowledge, clinical and technical skills, and decision-making capabilities pertinent to managing patients with limb-threatening lower and upper extremity vascular injuries. Data from multiple sources were triangulated to generate learning objectives and define the standard care of vascular injuries and required technical skills. Medical educators that practice vascular surgery were consulted to assist in creating and executing the curriculum.

Learning objectives include:

Upon completion of the VESSELS course, the learner will be able to:

- *Define vascular anatomy in the upper and lower extremity*
- *Recognize limb-threatening vascular injury and assess with appropriate diagnostic imaging,*

As assessed by a short answer and multiple-choice examination.

As well as:

- *Display proper vascular surgical technique (i.e., tissue handling, instrument use, suture)*
- *Choose and demonstrate the appropriate management of a vascular injury with ligation, primary repair, anastomosis, or temporary shunt placement.*

As assessed by direct observation of technical skills during the simulation.

First, learners engage in didactic instruction that reviews the anatomy, appropriate diagnostic strategies, required supplies and instrumentation, and procedural steps to treat vascular injuries. The didactic portion of the course was informed by the cognitive theory of multimedia learning with the material presented in text, graphic, and audio form to deepen the

learning experience [15]. After an in-person pilot course, the curriculum was also developed into an online format to make it more accessible. Additional online resources were made available to all learners after pre-testing and prior to in-person instruction. All lecture presentations were digitally converted and implemented using an online open education resource (GoogleClassroom™), Google LLC, Menlo Park, California). VESSELS courses can utilize either format based on program preference, location, and available resources.

This curriculum would affect medical students hoping to learn basic skills, residents with a goal to practice technique, and staff surgeons who need to review and practice. Residency programs have competencies to meet accreditation, and practicing physicians have continuing medical education requirements - this course can help fulfill those needs. Indirectly this will also involve future patients who experience vascular trauma and are treated by those who learn from the course.

Chapter 2:

Vascular Emergency Surgery: Simulated Exercises for Limb Salvage (VESSELS) - Development of a curriculum and simulation model for general surgeon training

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Abstract:*Purpose:*

Military surgeons have the unique responsibility of maintaining a broad set of surgical skills to care for combat-related injuries during times of peace. Lower and upper limb amputations are life-altering combat injuries sustained by our military personnel. Salvage of a limb saves someone from impaired mobility, abnormal physiology, and social effects of amputation and requires the knowledge and technical proficiency to diagnose and treat vascular traumatic injuries.

Methods:

A needs assessment of deployable military surgeons was performed which demonstrated a need for additional training to diagnose and treat vascular emergencies. For simulation skills training, a novel low-cost arterial model was developed by our institution's mixed material layering 3D medical applications center. A focused simulation curriculum was developed which included both didactic and technical skills training for vascular trauma emergencies. Learners were assessed using a pre-, post-test design to evaluate efficacy.

Results:

A realistic vascular model was developed using 3D printed technologies and was used for traumatic vascular emergency skills training. Implementation of the VESSELS course using both in-person and online asynchronous formats demonstrated significant increases in knowledge and confidence in diagnosing and managing limb-threatening injuries.

Conclusions:

Vascular surgery is a low-volume and high-complexity specialty, where a comprehensive assessment of technical skills is essential. This novel, low-cost simulation model and curriculum increases understanding of vascular surgical techniques and emergency procedures. The medical education community will directly benefit from this new simulation learning resource that can be utilized by various learners, from medical students to practicing physicians. Broader effects would include improved quality of vascular emergencies managed by deployed military surgeons and rural and community centers without vascular subspecialty support.

Key Words: simulation, vascular surgery, limb salvage, vascular trauma, trauma

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Introduction

Vascular injuries in trauma are rare but real injuries that can lead to limb loss and death when inappropriately addressed. Lower and upper limb amputations are one of the most life-altering combat injuries sustained by our military personnel, and from January 2001 through October 2017, 1,705 service members suffered deployment-related amputations. These men and women were 21-29 years old with 1,914 lower and 302 upper limb amputations [1,2]. Salvage of a limb saves someone from impaired mobility, abnormal physiology, and social effects of amputation. Therefore, a valuable skill to the deployed or rural surgeons in remote locations.

Unfortunately, many of the skills required to address vascular injuries appropriately are rarely encountered in the regular practice of non-fellowship-trained surgeons. This issue is amplified for rural surgeons or military surgeons who deploy to locations without ready access to vascular or trauma surgeons. These surgeons are often in austere locations where they are independently required to diagnose and manage vascular injuries.

Simulation training has been heavily utilized as a valuable adjunct as it provides a standardized and safe environment to learn and practice skills. Most learners (93%) favor simulators for their training due to the combined realism and ability to practice [3]. Advanced Surgical Skills for Exposure in Trauma (ASSET) was developed to train surgeons to expose and isolate major vascular structures throughout the body [4]. This cadaver-based continuing medical education course aims to increase learner knowledge, ability, and confidence. However, the ASSET curriculum focuses on vascular exposures, and to a lesser degree, on the basic skills required to manage these injuries. Few simulation curricula address these basic vascular skills, particularly in the trauma setting.

A targeted needs assessment of military general and subspecialty surgeons was performed using Kern's 6-step model for curriculum development [5]. A survey was used to identify vascular emergencies and procedures faced while deployed or without access to a vascular surgeon. Thirteen general and subspecialty surgeons were surveyed, including six junior (less than ten years of practice) and seven senior surgeons. Deployments without immediate access to a vascular surgeon ranged from one to ten deployments, with one surgeon who has yet to deploy.

Only one surgeon manages vascular emergencies in their current practice without assistance from a vascular subspecialist. While the majority (61.5%) participated in the cadaveric ASSET course, vascular procedures while deployed are uncommon. The surveyed surgeons reported injuries such as deep laceration to the antecubital fossa, shell blast to the carotid artery, right femoral vein injury requiring iliac control, and transactions to the subclavian, brachial, radial, and femoral arteries secondary to blast injuries. Management of these injuries included ligation, interposition graft repair using the greater saphenous vein, or temporary vascular shunt placement and transfer to a higher level of care. A need for further vascular surgical technical training, including vascular control, shunt placement, and vessel repair with or without anastomosis, was identified.

Currently, few vascular-specific simulation curricula focus on basic skills required to manage vascular trauma. Previous studies have focused on vascular access, anastomotic and open aortic stimulation, ultrasound, and endovascular simulation learning platforms [6-10]. This study aimed to improve the knowledge and basic technical skill required to manage vascular injuries. Thus, this study aimed to develop and implement and evaluate a simulation curriculum

that would focus on the diagnosis and management of vascular trauma. This curriculum could then be adapted to fulfill the needs of other training programs needing further vascular trauma skills training. Finally, we sought to create a suitable and more cost-effective vascular model that could be used to practice the technical skills within the curriculum.

Methods:

Vascular Model Development:

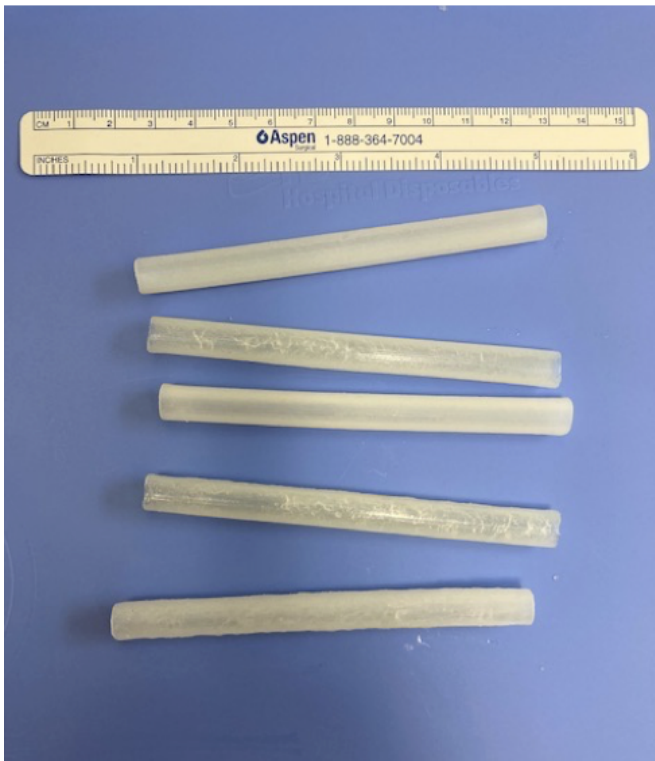
A simulation model was created based on ultrasound measured average dimensions of adult in vivo brachial and femoral arteries [11-14]. The upper-arm brachial artery measured 3.9 ± 0.5 mm in diameter, and the common femoral artery measured 6.6 mm in diameter (3.9 – 8.9 mm) and 4 cm in length. Arterial wall thickness in patients without peripheral arterial disease is 1.3 ± 0.5 mm, with intimal layer thickness at 0.3 ± 0.1 mm. Our institution's mixed material layering 3D medical applications center used these dimensions to create multiple different models for qualitative testing.

Cylinders for vessels were designed in SolidWorks[©](Dassault Systèmes SolidWorks Corporation, Waltham, Massachusetts). The vessels were designed with two concentric tubes sharing the surface of the outer wall of the external tube and the internal wall of the outer tube. The inner and outer diameters of the external tube were 7.0 and 8.6mm, respectively. The inner and outer diameters of the internal tube were 6.6 and 7mm, respectively. These two solid bodies were saved as separate STL files. The STL files were imported into GrabCAD [©](STRATASYS solution, Eden Prairie, Minnesota) Print software as an assembly to prepare for manufacturing. This software processed models for 3D printing on a Stratasys J750 DAP. Material sections for

the external tube were: Family- Structural Heart, Element- Myocardium, Stiffness- Stiffened. Material selection of the internal tube was: Family: Blood Vessel, Element- Vessel Wall, Compliance- Slightly Compliant. Multiple vessels were printed on one build tray. Vessels were cleaned of support material by hand with cotton swabs cleaning solution (CleanMor 706^(c)(Omegasonics, Simi Valley, California) and allowed to air dry.

Vessels were tested and refined based on feedback from three vascular and two trauma board-certified surgeons. Feedback was elicited through semi-structured interviews. Each model was compared to actual vascular tissue in the following characteristics: handling, cutting, suturing, and shunt placement. After the qualitative assessments, modifications to the model were incorporated into the final high-fidelity model (Figure 1).

Fig.1: Photograph of 3D printed vascular model.



Curriculum Development:

Kern's 6-step approach for curriculum development was applied to support the successful integration of Vascular Emergency Surgery: Simulated Exercises for Limb Salvage (VESSELS) in graduate and continuing medical education [5]. Initially, learners engage in didactic instruction that covers the basics of vascular trauma. This session includes an overview of vascular anatomy, appropriate diagnostic strategies, required supplies and instrumentation, and procedural steps to treat vascular injuries. The didactic portion of the course was informed by the cognitive theory of multimedia learning with the material presented in text, graphic, and audio form to deepen the learning experience [15]. Additional online resources were made available to all learners after pre-testing and prior to in-person instruction.

The didactic sessions utilized a lecture presentation and corresponding summary reference handouts. Initially, all didactics were held in person and were led by either a board-certified trauma or vascular surgeon. Didactics were later transitioned to an online and asynchronous format. All lecture presentations were digitally converted into a narrated format and then implemented using an online open education resource (GoogleClassroom[™], Google LLC, Menlo Park, California). VESSELS courses can utilize either format based on program preference.

Following the didactic instruction, learners engage in a hands-on practice informed by simulation-based learning and experiential learning theories [16,17]. All skills utilize the vascular model developed for this course, and a complete setup of required instruments and materials is depicted in Figure 2. Specific procedures practiced included vessel isolation and

Assessment:

We utilized a pretest-posttest design to measure the knowledge and confidence impact of the educational intervention. Learners completed a precourse assessment consisting of demographic knowledge questions and the level of confidence in emergency vascular procedures (Supplementary Appendix 1). Confidence was measured on a 5-point Likert scale (1—very not confident, 2—not confident, 3—somewhat confident, 4— confident, and 5—very confident). Participants also completed a knowledge assessment consisting of 13 multiple-choice, single-best answer questions on vascular anatomy and physiology, key features of recognizing and diagnosing limb-threatening vascular injuries, and proper procedural techniques. The authors developed confidence and knowledge assessments (C.H., M. C., B.R.F., and W.B.S.), later reviewed by board-certified vascular and trauma surgeons from our institutions who served as subject matter experts. Competency checklists for repairable injury identification, proper technique, correct primary repair, and successful placement of a temporary vascular shunt were utilized to ensure learners practiced all demonstrable skills during the simulation (see Supplementary Appendix 3 for checklist).

Subjects:

General surgery trainees who had not previously participated in a dedicated adult vascular emergencies training course from Walter Reed National Military Medical Center (WRNMMC) and Naval Medical Center Portsmouth (NMCP) were voluntarily recruited for participation in VESSELS. This project was granted education exemption by both institutional review boards.

Statistical Analysis:

All scores were compared using paired Student's *t*-tests. P values less than .05 were considered statistically significant. Values are reported as means +/- standard deviation unless otherwise noted. All statistical analysis was conducted using SPSS version 27 (IBM, Chicago, IL). The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Results:

Seventeen residents from WRNMMC participated in the in-person didactic lecture and ten residents from NMCP in the online didactic modules prior to simulation skills training. Demographics of the learners are listed in Table 1. All residents completed the pre-assessment and engaged in simulation skills training for vessel isolation and control, temporary shunt placement, vascular anastomosis, and arteriotomy with patch repair.

Table 1: Demographics of learner groups.

	In-person (n=17)	Online Hybrid (n=6)
Location	WRNMMC	NMPC
PGY-1	6	7
PGY-2	2	2
PGY-3	5	1
PGY-4	0	0
PGY-5	4	0
Male Female	11 6	6 4
Handedness (R L)	16 1	10 0

Residents' reactions to the course have been positive. Specific positive comments from learners focused on the self-paced learning with directed faculty feedback in a low-stakes simulation environment, which helped them practice and learn the VESSELS material. Eliciting feedback from the online group of learners at NMCP showed that they used the additional resources provided in the module, including additional readings, videos showing anastomotic techniques, and a podcast, all obtained from online open educational resources more than the in-person didactic group from WRNMMC.

Analysis of assessment data showed a significant difference in knowledge and confidence after completing the in-person (Table 2) and hybrid online (Table 3) VESSELS course. The in-person cohort originally included seventeen residents; however, only 14 were able to complete the simulation training and post-assessment due to clinical duties of three residents.

Table 2: Comparison of in-person pre and post-assessments.

	Mean	Std. Deviation	95% Confidence Interval		Sig. (2-tailed)
			Lower	Upper	
Knowledge multiple choice questions	-0.089	0.128	-0.167	-0.011	0.029*
Anatomy	-1.000	0.707	-1.427	-0.573	<0.001*
Recognizing vascular injuries	-0.538	0.776	-1.008	-0.069	0.028*
Assessing vascular injuries	-0.692	0.947	-1.265	-0.120	0.022*
Vascular surgical technique	-1.076	0.954	-1.653	-0.500	0.002*
Ligation of vessel	-0.692	1.031	-1.316	-0.690	0.032*
Primary repair of vascular injury	-1.153	0.987	-1.750	-0.557	0.001*
Performing vascular anastomosis	-1.153	0.898	-1.697	-0.611	<0.001*
Placing temporary vascular shunt	-1.846	0.987	-2.443	-1.250	<0.001*

*statistically significant

Table 3: Comparison of hybrid online course pre and post-assessments.

	Mean	Std. Deviation	95% Confidence Interval		Sig. (2-tailed)
			Lower	Upper	
Knowledge multiple choice questions	-0.382	0.176	-0.545	-0.220	0.001*
Anatomy	-1.428	0.786	-2.156	-0.701	0.003*
Recognizing vascular injuries	-1.857	1.069	-2.845	-0.868	0.004*
Assessing vascular injuries	-2.571	1.133	-3.620	-1.523	<0.001*
Vascular surgical technique	-1.714	0.951	-2.593	-0.835	0.003*
Ligation of vessel	-1.857	1.069	-2.845	-0.868	0.004*
Primary repair of vascular injury	-2.000	0.577	-2.533	-1.466	<0.001*
Performing vascular anastomosis	-2.000	0.577	-2.533	-1.466	<0.001*
Placing temporary vascular shunt	-2.000	0.816	-2.755	-1.245	<0.001*

*statistically significant

Discussion:

Vascular trauma is a low-volume and high-complexity discipline, where a comprehensive assessment of technical skills is essential. The traditional surgical learning model of "learning by doing" only modestly suffices during general surgery training. Upon graduation, non-fellowship trained surgeons rarely, if ever, interact with vascular trauma nor perform vascular procedures. This training gap is amplified for rural and military surgeons responsible for diagnosing and managing traumatic vascular injuries.

Current options for vascular simulation training include arterial models for carotid repair and anastomosis, which are available for public purchase (i.e., LifeLike Bio Tissue Inc., London, Ontario; 3-Dmed, Franklin, OH) for \$30 to \$40. Other programs have created low-cost simulation models for vascular access [18,19], regular and transplant anastomosis [20,21], and

neurosurgical vascular techniques [22,23]. The total cost for a single unit of our VESSELS model is \$11.50, with \$9.38 for the vessel material and \$2.04 for the support material. A comparison of current simulated vascular models can be found in Table 4.

Table 4: Cost comparison of current simulated vascular models.

Model	Simulation Skill	Material	Total Cost
Morrow, et al., 2015 ²⁶	Vascular Access	Gelatin and latex	\$22.83
Tan, et al., 2021 ²⁷		3D printed	\$120
Sarmiento, et al., 2018 ²⁸	Anastomosis	Latex balloons and frame	\$152
Melkonian, et al., 2020 ²⁹	Transplant anastomosis	Penrose drains and frame	\$20.20
McGuire, et al., 2021 ³⁰	Neurosurgical	3D printed	\$624.83
	VESSELS model	3D printed	\$11.50

Cadaver-based training like the ASSET course teaches advanced vascular exposures for life or limb-threatening injuries. It is designed for mid/senior surgical residents, trauma and acute care surgical fellows, or any surgeon who desires further training. The ASSET course can be held at the learner’s institution, but more often requires travel to a host location. Material is studied beforehand, and the class runs over one day. Totals to run this course include individual costs for the system including the manual, registration, and lodging which can range from \$500-990 - the course fees are set by the hosting institution plus travel expenses [24]. Additionally, each human cadaver is between \$1500 and \$2000 based on a 2014 evaluation of cadaveric-based medical school anatomy courses [25]. There is also additional overhead for cadaver facilities which can cost up to \$50,000.

More cost-effective options include individual cadaveric leg models. This allows for focused training using the femoral artery with each leg costing about \$250. This option also requires facility costs that are often prohibitive for many institutions. In addition to these direct costs, they also require regulatory body oversight, personnel and administrative investments. The VESSELS curriculum focuses on important vascular technical knowledge and skill all while avoiding these financial and logistic hurdles.

There were limitations to this study performed at two military training facilities. The post-course assessments of knowledge and confidence were completed within 24 to 72 hours following the course, and score improvements may be due to recency bias versus durable improvements. Additionally, all participants were surgical residents whose improvements in confidence may be falsely inflated due to less experience. To address these limitations, we plan to conduct the course annually and compare future assessments to previous performance. The VESSELS curriculum is also being advertised to other military locations with surgical residencies to increase the number of learners and better determine the immediate and long-term efficacy of the vascular model and curriculum.

Future directions include expansion of VESSELS for different levels of learning. Specifically, this model can be used for simulation to teach medical students basic surgical techniques, surgical residents to practice skills and prepare for operative cases, or fellows and vascular subspecialists to practice advanced anastomosis and angioplasty. The VESSELS course has been implemented into the general surgery academic schedule and will be available to other programs who are interested. This course is also an option for the military reservist population who rarely if ever encounter vascular emergencies, and are called to deploy with minimal

additional training. Finally, future plans include expansion of the model to include branches of the common femoral artery (current model) and creation of a brachial artery model with bifurcation into radial and ulnar arteries for more advanced skills training.

Conclusion

After surveying military general surgeons about the need for additional limb-salvage skills training, we created a novel low-cost arterial model and curriculum for an emergency vascular surgery training course dedicated to limb salvage. This curriculum provides training for rural and military surgeons and is a needed component for general surgeons who rarely treat vascular trauma, and in particular for surgeons in the pre-deployment setting. The VESSELS course is a viable option for all general surgery residency training programs who desire further vascular simulation training.

Chapter 3: Discussion

Limb salvage techniques in the setting of traumatic vascular injuries are a valuable skill for a surgeon without access to subspecialty help. Temporary vascular shunt placement is a fairly straightforward procedure that can be performed to temporize an injury and possibly save someone from amputation. Due to limited clinical exposure during graduate medical education and general practice, many surgeons lack the knowledge and skill required to manage vascular injuries. This thesis evaluated a novel, low-cost simulation model and curriculum (VESSELS) with surgical residents.

After completing the VESSELS curriculum, we saw a statistically significant improvement in knowledge and confidence regarding traumatic vascular injuries and limb-salvage techniques. Residents scored higher on written multiple-choice question tests, which evaluated their knowledge of vascular anatomy and recognition, identification, and management of vascular injuries. Each learner practiced skills on a 3D printed model until mastery was achieved using a skills assessment checklist (Supplementary Appendix 2).

During both iterations of the course, several trends were noted among the levels of learners. When reviewing the pre- and post- assessments, the overall change in knowledge score and confidence was inversely related to experience level. Junior residents (PGY 1-2) had a larger increase in knowledge and confidence, while senior residents (PGY 3-5) started at a higher level of knowledge and experience and had a smaller increase in their post assessment scores. Junior residents with less surgical experience tended to have lower confidence in their technical skills but higher confidence in their knowledge. The reverse was seen in the senior residents, with higher scores seen in the technical skills aspect of knowledge questions and confidence intervals.

The more experienced learners also spontaneously assisted their more junior colleagues and helped facilitate the skills portion of the course at WRNMMC. This is consistent with how surgical residents are trained - more senior residents are expected to teach their peers and have operative teaching case requirements. During the course provided at NMCP the junior residents were intentionally paired with seniors to help demonstrate and facilitate the simulated learning experience.

Transferability was a goal of this curriculum in that it could be easily provided at any facility or personal practice. The online modules created easy access to both learners and instructors. Standardized resources and documents were created with a variety of learners, instructors, and facilities in mind. The assessments are available online or can be printed. Resources are available in multiple forms (i.e., print, video, audio) and the lecture portion of the class was recorded to be viewed by learners as didactics or instructors in preparation of the simulation. We hope that in the future, anyone can access this course and provide a fully synchronous or hybrid online course at their institution.

Implications & Future Research:

Surgical residents were chosen as a test group because of their early status in training and relative inexperience to determine if knowledge and performance would improve independent of previous experience. The successes of the curriculum and positive outcomes may suggest that this training could be incorporated into residency programs to allow for more practice in a relatively low volume subspecialty of surgery. Mastery of vascular techniques in a simulated environment could allow residents to improve operative and patient outcomes.

The VESSELS course was developed as part of a more extensive simulation program to provide needed training for the deploying surgeon. The overarching program aims to provide skills training and practice for common surgical procedures encountered while deployed. Implementation of the course will target the active duty and reservist populations for training in a safe learning environment. This low-stakes environment will impart the necessary knowledge and skills to manage vascular trauma and can be transferred to the deployed setting. Learners can create a deeper understanding, increase their confidence, and build strategies for managing vascular trauma's high stakes and stressful situations.

This program could also have civilian implications and provide training for surgical residents in various programs and surgeons practicing in rural areas. It requires minimal preparation and resources, involves a small amount of time, and can be completed anywhere with a few 3D printed vessels and surgical instruments available at most, if not all, hospitals. Moving forward, we plan to examine this curriculum with more significant numbers of trainees to include both residents and practicing surgeons. Additionally, future studies will be prospective to evaluate knowledge retention and skills over time. We will repeat the course at the inaugural institutions and compare pre-and post-assessment values. This project can also be expanded to include operating support staff and surgical teams to practice vascular cases and techniques. For example, training new surgical techs and assistants learning to use vascular surgical instruments.

Limitations:

There are several limitations to this study. Our sample sizes were small and dependent on residents' availability. Despite our small sample sizes, we did see statistically significant improvements in pre and post-assessments. Another limitation was the simulation fidelity - while our model vessel was reviewed and considered high-fidelity, it does not include arterial branching or surrounding tissues. Of note, some senior residents used an abdominal wall model previously created at our institution to simulate working inside an incision to increase the model's fidelity. Access to a 3D printer is needed to create this model. If one is not available, a program may need to reach out or partner with another institution to make the models.

Additionally, our checklist to assess skills mastery was developed to complete but not comprehensive. There are many details and intricacies of vascular surgical techniques, and vascular surgeons reviewed our skills sheet to ensure it included the necessities. However, it could be expanded to include the more detailed and nuanced intricacies of vascular techniques, especially if it is to be used for more advanced learners, such as vascular fellows. Finally, the VESSELS curriculum was not compared to a control or alternate curriculum.

Military Relevance:

It is vital to provide post-graduate medical education to resident physicians and continuing medical education to staff physicians to ensure medical force readiness. Military health educators' training, improvement, and sustainment determine the ability to meet these demands. During Operation Enduring Freedom, training programs have increased virtual reality and medical simulation utilization to rapidly train medical personnel while decreasing costs and maintaining the fidelity of the combat training experience [26]. The Combat Casualty Care

Course (C4) was created to fill the need for deployment medical training. It provides initial training but not sustained practice. Also, refresher training is not mandatory for service members to maintain those skills before deployment [27]. Learning from this experience, we created a course and model with resources available as needed. This curriculum provides continual training for medical providers to ensure that units are medically ready for limb-threatening vascular injuries. Plans include its incorporation into a more extensive simulation program to provide needed training for the deployed surgeon. As mentioned above, the overarching program aims to provide skills training and practice for common surgical procedures encountered while deployed, including anorectal, urological, gynecological, orthopedic, ENT, ophthalmologic, vascular, and veterinary medicine.

Conclusions:

A novel, low-cost simulation model and curriculum for vascular emergency surgery and limb salvage was created with promising results upon application with a group of novice surgical trainees. We demonstrated improvement in knowledge and skills needed to manage traumatic vascular injuries. This curriculum was developed to prepare to deploy military surgeons and supplement surgical training. Future studies and implementations could consider further dissemination and development of the training model.

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Supplementary Appendix 1: Pre Assessment

Vascular Emergency Surgery: Simulated Exercises for Limb Salvage (VESSELS) PRE-ASSESSMENT

Learner: _____

Date: _____

SCORE: _____ /13

- Which of the following is not a branch of the axillary artery?
 - internal thoracic artery
 - subscapular artery
 - superior thoracic artery
 - thoracoacromial artery
- Which of the following correctly describes the brachial artery?
 - Closely associated with the ulnar nerve
 - Gives off the anterior and posterior circumflex humeral arteries
 - Originates where the coracobrachialis muscle attaches to the humerus
 - Terminates after bifurcating into the ulnar and radial arteries
- Lower extremity arterial anatomy includes which of the following:
 - Femoral artery becomes the popliteal artery after passing through the adductor hiatus
 - Femoral nerve is medial to the artery
 - Popliteal artery terminates after bifurcating into the anterior tibial and tibioperoneal trunk
 - Superficial femoral artery is on the lateral aspect of the thigh
- Which of the following is a soft sign of vascular injury?
 - ABI of 0.9
 - Hypotension
 - Expanding hematoma
 - History of significant bleeding.
- Ideally, a significant vascular injury will be identified and treated within how many hours to minimize ischemic nerve and muscle damage?
 - 2
 - 4
 - 6
 - 8
- A 26 year old male presents with a stab wound to the left medial thigh. After primary and secondary assessment in the trauma bay no other injuries are found and the patient remains hemodynamically normal. There is a 3 cm, clean wound to the mid-medial thigh with no active bleeding. Sensation and motor function are intact. Distal pulses are diminished and an ABI is measured at 0.8. What is the next best step?
 - Apply a tourniquet to the affected limb
 - Obtain CT angiography to assess for vascular injury
 - Obtain Duplex ultrasound to assess for vascular injury
 - Proceed to operating room for wound exploration and possible vascular injury repair
- When clamping an artery it is important to remember that atherosclerotic plaques are typically found where within the vessel?
 - dorsally
 - laterally
 - medially
 - ventrally

8. When suturing artery what layer should always be included to prevent flap dissection?
- Tunica intima
 - Tunica media
 - Tunica externa
 - It does not matter if you take partial thickness bites
9. You are completing a patch angioplasty repair to an injured femoral artery. What suture do you ask for?
- 4-0 PDS
 - 5-0 Prolene
 - 6-0 Vicryl
 - 7-0 Core-Tex
10. A 42 year old female sustained a gunshot wound to the right lower extremity with an associated fibular fracture. During the operation you find injuries to both the popliteal and peroneal arteries. While your colleague gains access to the popliteal artery, you get proximal control of the bleeding peroneal artery but cannot locate the distal end of the injured vessel. Your colleague is having trouble controlling bleeding from behind the knee. How should you proceed?
- Continue to try and obtain distal control of the peroneal artery
 - Debride edge of proximal peroneal artery in preparation for primary repair
 - Ligate the peroneal artery and turn attention to the popliteal injury
 - Use intra-operative angiography to assess for perfusion distal to the injured vessels
11. You are in the operating room repairing a brachial artery that was injured in a motorcycle accident. The wound is open and contaminated with dirt and debris from the scene. A conduit is needed to bridge the gap of the injured vessel. Which conduit is preferred in this scenario?
- autogenous cephalic vein
 - autogenous saphenous vein
 - prosthetic polyethylene terephthalate
 - prosthetic expanded polytetrafluoroethylene
12. Which of the following is the correct sequence to place a temporary vascular shunt?
- obtain proximal and distal control, clean edges of injured vessel, Fogarty catheter thrombectomy to ensure back bleeding, select shunt of smaller diameter to vessel, insert shunt 5-10 mm, water-tight fixation with two heavy-gauge ligatures
 - obtain proximal and distal control, clean edges of injured vessel, Fogarty catheter thrombectomy to ensure back bleeding, select shunt of similar diameter to vessel, insert shunt 15-20 mm, water-tight fixation with two heavy-gauge ligatures
 - obtain proximal and distal control, Fogarty catheter thrombectomy to ensure back bleeding, clean edges of injured vessel, select shunt of similar diameter to vessel, insert shunt 5-10 mm, water-tight fixation with two heavy-gauge ligatures
 - obtain proximal and distal control, Fogarty catheter thrombectomy to ensure back bleeding, clean edges of injured vessel, select shunt of smaller diameter to vessel, insert shunt 15-20 mm, water-tight fixation with two heavy-gauge ligatures
13. After prolonged ischemia time for a lower extremity injury you opt to perform a fasciotomy. Which of the follow is true regarding the technique?
- Medial incision is used to open the anterior compartment
 - Lateral incision is used to open the posterior compartments
 - The intermuscular septum separates the superficial and deep posterior compartments
 - The most commonly missed compartment is the anterior

Learner: _____ [circle one] medical student | resident | practicing surgeon

1) What year did/will you complete general surgery residency? _____

2) If applicable, what is your subspecialty? _____

If you are subspecialty trained, what year did you complete fellowship? _____

3) If applicable, what are common vascular procedures you perform? (Examples: vascular anastomoses, suture repair of a vascular injury, embolectomy, etc.)

4) Which is your dominant hand?

[circle one] L R

5) How confident do you feel about upper and lower extremity vascular anatomy?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
----------------	-----------	--------------------	---------------	--------------------

6) How confident do you feel about recognizing limb threatening vascular injuries?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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7) How confident do you feel about assessing vascular injuries?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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8) How confident do you feel with vascular surgical technique?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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9) How confident do you feel about completing a vascular ligation?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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10) How confident do you feel about completing a vascular primary repair?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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11) How confident do you feel about completing a vascular anastomosis?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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12) How confident do you feel about placing a temporary vascular shunt?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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Supplementary Appendix 2: Skills Assessment

Vascular Emergency Surgery: Simulated Exercises for Limb Salvage (VESSELS) SKILLS ASSESSMENT

Instructions to Learner:

Using the model common femoral artery, place a temporary vascular shunt then remove and perform an end-to-end anastomosis. Using the brachial artery, make a longitudinal arteriotomy and repair with patch angioplasty.

ITEM	Not Done/ Incorrect	Done correctly
Control of Vessel		
Uses appropriate vascular clamp (*DeBakey available for the exam)	0	1
Achieves appropriate proximal and distal control using vessel loops	0	1
Shunt		
Clean transection of the artery in an uninjured area	0	1
Use systematic Fogarty catheter for thrombectomy (verbalize if no Fogarty available)	0	1
Placement of a TVS with a diameter close to that of the artery, inserted to a depth of 15–20 mm	0	1
Secure fixation of the shunt with two heavy-gauge ligatures	0	1
Anastomosis		
Selects appropriate suture (5-0 available for the exam) and vascular needle driver/forceps	0	1
Starts appropriately – two stay sutures opposite of one another	0	1
Places a rubber shod on anterior wall suture while suturing the posterior wall first	0	1
Performs bites inside to outside on artery and takes suture bites in two	0	1
Places bites consistently 2-3mm from one another and guides suture down to desired position following bites	0	1
Flushes graft with saline and allows for back bleeding prior to securing last knots	0	1
Has the two suture ends meet and ties with two hands (minimum of 6 throws) with no air knot	0	1
Avoids excessive trauma / handling of artery with instruments	0	1
Loads needle 1/2 to 2/3 from tip >80% of time	0	1
Uses correct needle angle >80% of time	0	1
Bites through artery and graft started at 90 degrees >80% of time	0	1
Follows curve of needle on entrance / exit >80% of time	0	1

SCORE: _____ /18

Learner: _____ [circle one] medical student | resident | practicing surgeon

Date: _____ Examiner: _____

Comments:

Supplementary Appendix 3: Post Assessment

Vascular Emergency Surgery: Simulated Exercises for Limb Salvage (VESSELS) POST-ASSESSMENT

Learner: _____

Date: _____

SCORE: _____ /13

- Which of the following is not a branch of the axillary artery?
 - internal thoracic artery
 - subscapular artery
 - superior thoracic artery
 - thoracoacromial artery
- Which of the following correctly describes the brachial artery?
 - Closely associated with the ulnar nerve
 - Gives off the anterior and posterior circumflex humeral arteries
 - Originates where the coracobrachialis muscle attaches to the humerus
 - Terminates after bifurcating into the ulnar and radial arteries
- Lower extremity arterial anatomy includes which of the following:
 - Femoral artery becomes the popliteal artery after passing through the adductor hiatus
 - Femoral nerve is medial to the artery
 - Popliteal artery terminates after bifurcating into the anterior tibial and tibioperoneal trunk
 - Superficial femoral artery is on the lateral aspect of the thigh
- Which of the following is a soft sign of vascular injury?
 - ABI of 0.9
 - Hypotension
 - Expanding hematoma
 - History of significant bleeding.
- Ideally, a significant vascular injury will be identified and treated within how many hours to minimize ischemic nerve and muscle damage?
 - 2
 - 4
 - 6
 - 8
- A 26 year old male presents with a stab wound to the left medial thigh. After primary and secondary assessment in the trauma bay no other injuries are found and the patient remains hemodynamically normal. There is a 3 cm, clean wound to the mid-medial thigh with no active bleeding. Sensation and motor function are intact. Distal pulses are diminished and an ABI is measured at 0.8. What is the next best step?
 - Apply a tourniquet to the affected limb
 - Obtain CT angiography to assess for vascular injury
 - Obtain Duplex ultrasound to assess for vascular injury
 - Proceed to operating room for wound exploration and possible vascular injury repair
- When clamping an artery it is important to remember that atherosclerotic plaques are typically found where within the vessel?
 - dorsally
 - laterally
 - medially
 - ventrally

Learner: _____ [circle one] medical student | resident | practicing surgeon

1) How confident do you feel about upper and lower extremity vascular anatomy?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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2) How confident do you feel about recognizing limb threatening vascular injuries?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
----------------	-----------	--------------------	---------------	--------------------

3) How confident do you feel about assessing vascular injuries?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
----------------	-----------	--------------------	---------------	--------------------

4) How confident do you feel with vascular surgical technique?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
----------------	-----------	--------------------	---------------	--------------------

5) How confident do you feel about completing a vascular ligation?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
----------------	-----------	--------------------	---------------	--------------------

6) How confident do you feel about completing a vascular primary repair?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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7) How confident do you feel about completing a vascular anastomosis?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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8) How confident do you feel about placing a temporary vascular shunt?

Very confident	Confident	Somewhat confident	Not confident	Very not confident
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9) The course gave me the confidence to do more advanced work in the sub

Strongly agree	Agree	Neither agree or disagree	Disagree	Strongly disagree
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10) The instructional materials increased my knowledge and skills in the subject matter.

Strongly agree	Agree	Neither agree or disagree	Disagree	Strongly disagree
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11) The lectures, tests, and simulation complemented each other.

Strongly agree	Agree	Neither agree or disagree	Disagree	Strongly disagree
----------------	-------	---------------------------	----------	-------------------

12) I received useful feedback on my performance.

Strongly agree	Agree	Neither agree or disagree	Disagree	Strongly disagree
----------------	-------	---------------------------	----------	-------------------

13) Do you have any other feedback?

8. When suturing artery what layer should always be included to prevent flap dissection?
- Tunica intima
 - Tunica media
 - Tunica externa
 - It does not matter if you take partial thickness bites
9. You are completing a patch angioplasty repair to an injured femoral artery. What suture do you ask for?
- 4-0 PDS
 - 5-0 Prolene
 - 6-0 Vicryl
 - 7-0 Core-Tex
10. A 42 year old female sustained a gunshot wound to the right lower extremity with an associated fibular fracture. During the operation you find injuries to both the popliteal and peroneal arteries. While your colleague gains access to the popliteal artery, you get proximal control of the bleeding peroneal artery but cannot locate the distal end of the injured vessel. Your colleague is having trouble controlling bleeding from behind the knee. How should you proceed?
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 - Ligate the peroneal artery and turn attention to the popliteal injury
 - Use intra-operative angiography to assess for perfusion distal to the injured vessels
11. You are in the operating room repairing a brachial artery that was injured in a motorcycle accident. The wound is open and contaminated with dirt and debris from the scene. A conduit is needed to bridge the gap of the injured vessel. Which conduit is preferred in this scenario?
- autogenous cephalic vein
 - autogenous saphenous vein
 - prosthetic polyethylene terephthalate
 - prosthetic expanded polytetrafluoroethylene
12. Which of the following is the correct sequence to place a temporary vascular shunt?
- obtain proximal and distal control, clean edges of injured vessel, Fogarty catheter thrombectomy to ensure back bleeding, select shunt of smaller diameter to vessel, insert shunt 5-10 mm, water-tight fixation with two heavy-gauge ligatures
 - obtain proximal and distal control, clean edges of injured vessel, Fogarty catheter thrombectomy to ensure back bleeding, select shunt of similar diameter to vessel, insert shunt 15-20 mm, water-tight fixation with two heavy-gauge ligatures
 - obtain proximal and distal control, Fogarty catheter thrombectomy to ensure back bleeding, clean edges of injured vessel, select shunt of similar diameter to vessel, insert shunt 5-10 mm, water-tight fixation with two heavy-gauge ligatures
 - obtain proximal and distal control, Fogarty catheter thrombectomy to ensure back bleeding, clean edges of injured vessel, select shunt of smaller diameter to vessel, insert shunt 15-20 mm, water-tight fixation with two heavy-gauge ligatures
13. After prolonged ischemia time for a lower extremity injury you opt to perform a fasciotomy. Which of the follow is true regarding the technique?
- Medial incision is used to open the anterior compartment
 - Lateral incision is used to open the posterior compartments
 - The intermuscular septum separates the superficial and deep posterior compartments
 - The most commonly missed compartment is the anterior