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Critical errors in infrequently performed trauma procedures after training

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ABSTRACT

Background: Critical errors increase postoperative morbidity and mortality. A trauma readiness index was used to evaluate critical errors in 4 trauma procedures. In comparison to practicing and expert surgeon benchmarks, we hypothesized that pretraining trauma readiness index including both vascular and nonvascular trauma surgical procedures can identify residents who will make critical errors.
Methods: In a prospective study, trained evaluators used a standardized script to evaluate performance of brachial, axillary, and femoral artery exposure and proximal control and lower-extremity fasciotomy on unpreserved cadavers. Forty residents were evaluated before and immediately after Advanced Surgical Skills for Exposure in Trauma training, and 38 were re-evaluated 14 months later. Residents were compared to 34 practicing surgeons evaluated once 30 months after training, and 10 experts.
Results: Resident trauma readiness index increased with training ($P < .001$), remained unchanged 14 month later and was higher, with lower variance than practicing surgeons ($P < .05$). Expert trauma readiness index was higher than residents ($P < .004$) and practicing surgeons ($P < .001$). Resident training decreased critical errors when evaluated immediately and 14 months after Advanced Surgical Skills for Exposure in Trauma training. Practicing surgeons had more critical errors and performance variability than residents or experts. Experts had 5 to 7 times better error recovery than practicing surgeons or residents. Trauma readiness index area under the receiver operating curve with Youden Index <0.60 or <6 decile in their cohort, predicts a surgeon will make a critical error.
Conclusion: Low trauma readiness index was associated with critical errors occurring in all surgeon cohorts and can identify surgeons in need of remedial intervention.

Introduction

Medical errors are a focus topic of patient safety and have recently been reported as the third leading cause of death in the United States.[1] Surgical errors in particular can have severe consequences, including preventable deaths.[2] In the 1991 Harvard Medical Practice study,[3] 53% of adverse events were associated with an operation. Of these 26% were operative technical adverse events and 10% were due to failure to achieve surgical goals; among 697 performance errors, technical errors accounted for 76%. Similarly, 28 hospitals in Colorado and Utah reported 9 years later that operative adverse events were about half of the adverse events, and most operative adverse events were attributed to surgeons (46%), with 22% identified as negligent and 17% resulting in permanent disability.[4] Efforts in surgery to reduce errors include the World Health Organization safety checklist,[5] The Joint Commission National Patient Safety Goals,[6,7] and initiatives to address disclosure

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and management of surgical errors.[8] However, few studies have focused on errors among individual surgeons. Trauma surgery is a core skill for general surgeons,[9] yet operative trauma experience during general surgery training is often limited. However, general surgeons in rural practice in particular need to be competent to provide the first level of surgical stabilization for trauma patients because this may be necessary on an infrequent basis.[10] In addition, the military faces ongoing challenges in maintaining a ready corps of general surgeons for deployment.[11] For these reasons, the American College of Surgeons developed the Advanced Surgical Skills for Exposure in Trauma (ASSET) Course (a 1-day human cadaver-based skills course that systematically reviews all of the major vascular exposures in the body).[12]

We have previously reported on performance of technical and nontechnical skills of surgeons performing vascular and nonvascular ASSET procedures before and after participation in the training course. Participants were evaluated using an Individual Procedure Score[13–16] developed for each procedure. The Trauma Readiness Index (TRI)[15] was the sum of the Individual Procedure Score for each of the 4 vascular and nonvascular procedures and is the single overall metric of individual surgeon performance. We found that anatomy and technical skills were key to error-free performance. In these new analyses of the previous dataset, in comparison to practicing and expert surgeon benchmarks, we hypothesized that pretraining TRI can identify residents who make critical errors in subsequent standardized interval evaluations.

Methods

The study was conducted at the Maryland State Anatomy Board cadaver laboratories situated at the University of Maryland School of Medicine. The University of Maryland School of Medicine Institutional Review Board and US Army Medical Research and Material Command Office of Research Protection approved the recruitment and consent process. Cadaver use was approved by the Maryland State Anatomy Board and the US Army. Enrolled surgeons received training in the ASSET course.[12] For the study, after informed consent was obtained, participants were presented with 4 case-based scenarios involving representative ASSET procedures (4 of the 59 procedures taught during the course).

As previously described, a standardized script was used for each procedure and performance was evaluated by 2 co-located trained evaluators. Study participants responded to questions relating to initial trauma resuscitation, diagnosis, management, anatomy and procedural steps, and were asked, without any feedback or instruction, to perform 4 procedures related to the cases: vascular exposure with proximal control of the axillary (AA), brachial (BA), and femoral (FA) artery (including individual control of common, superficial and profunda femoral arteries) and lower extremity (LE) fasciotomy with 2-incision, 4-compartment decompression (FAS) in fresh cadavers. After the completion of all 4 procedures, the evaluators debriefed the surgeons regarding their performance.[13–16] Resident participants were recruited by mailing letters to Program Directors. In addition, to benchmark resident performance the same evaluations were made of practicing and expert surgeons. Practicing board-certified surgeons from 25 different North American regions, who had received ASSET training between 2 to 4 years prior, were recruited by e-mail from American College of Surgeons listings of ASSET participants. These surgeons had a broad spectrum of subspecialization as previously described; none were ASSET instructors.[16] All the experts were attendings at level 1 trauma centers and both operating surgeons and practicing traumatologists, but 2 of the experts (one 25 years full time and the other 33 years full time in a level 1 trauma center) had not taken the ASSET Course nor were they ASSET instructors. The remaining 8 experts had taken the ASSET course and were ASSET instructors.

Critical technical errors and critical management errors that were potentially life-threatening were recorded for each procedure (Table I). TRI divided overall surgical technical and non-technical skill into 5 components: trauma patient knowledge, anatomy (landmarks, incision and structures), patient management, procedural steps, and technical skill.[13–16] TRI included time to complete the procedure, technical skills (uses instruments properly, handles tissues well, exposes artery on anterior surface, manipulates by grasping adventitia, no unnecessary dissection, communicates clearly etc) and evaluation of expert discriminators (operate using full incision, has a logical operating sequence, effective use of blunt dissection, uses sharp dissection confidently etc) as identified in previous publications.[13–16] Errors per surgeon and error recovery per surgeon among residents tested at intervals before, immediately after, and 12 to 18 months after the ASSET course were compared to errors and error recovery per surgeon among the practicing and expert surgeon cohorts. Error recovery process occurred in 3 stages: initial failure to detect an error, indicate the error to the evaluator, and then correction of the error.[17] Performance data were entered into a touch-screen mobile Android tablet application in real-time, and all procedures were video recorded.[13–16] The experience levels for each surgeon cohort were categorized as high, medium, and low (by tertiles of the enrolled cohort experience) for each procedure.[16]

Statistical analyses

Linear mixed modeling was used for TRI comparisons among residents, practicing, and expert surgeons and general linear modeling for identifying the effects of months and interval experience on making critical errors. The models included the following differences between the surgeon cohorts: time since ASSET training, interval experience (numbers of trauma patient evaluations, numbers of upper extremity [UE] and LE procedures), cadaver body habitus (obese, average, or thin), and relationship to components of TRI including knowledge, anatomy, patient management, procedural steps, technical skills. Tukey-Kramer adjusted P values were used for multiple TRI comparisons with critical errors as the primary outcome. The average of the squared differences from the mean TRI values among the surgeon cohorts was used to measure individual surgeon variance. Additional analyses of errors were performed beyond those previously reported. Using the pretraining TRI, we calculated the area under receiver operating curves (AUROC) for predicting resident critical errors at 14-month evaluations. We used the Youden index[18] to calculate the optimal sensitivity and specificity cut-off, identifying the value below, which a participant resident would make ≥ 1 critical technical errors for TRI and each of the 4 procedures. Because we had previously recognized anatomy, technical skills, and procedural steps score components of TRI as factors in error occurrence,[13–16] we calculated AUROC's for all technical evaluations (includes all anatomy and all technical); technical (includes technical and all the expert discriminators); and all anatomy (structures injured, landmarks, procedural steps, pitfalls) inputs to predict critical errors. Statistical Analysis Systems (SAS) version 9.3 (SAS Institute, Inc, Cary, NC) was used for analyses. A priori sample size calculation required 36 of 40 (90%) originally enrolled residents to be followed-up for re-evaluation to detect changes in skill, including errors, to detect 5% type I errors of 0.82 standard deviation with 90% power using a 2-tailed t test.

Table I
Specific CTE, CME, and error recovery (ER) for axillary, brachial, and FA and lower extremity fasciotomy

Axillary artery	Brachial artery	Femoral artery	Lower extremity fasciotomy
CME: Inappropriate use of CT or angiogram	CME: Inappropriate use of CT or angiogram	CME: Inappropriate use of CT or angiogram	CTE: Incorrectly identifies the intermuscular septum; does not recognize or correct error
CME: Delay in going to the operating room	CME: Delay in going to the operating room	Delay in going to the operating room	CTE: Fails to decompress anterior compartment; does not recognize or correct error
CME: Fails to obtain chest x-ray			CTE: Fails to open any of 4 compartments along entire length; does not recognize or correct error
CTE: Incorrectly identifies or fails to identify the axillary artery; does not recognize or correct error	CTE: Incorrectly identifies or fails to identify the brachial artery; does not recognize or correct error	CTE: Incorrectly identifies or fails to identify the CFA; does not recognize or correct error	ER: Incorrectly identifies the intermuscular septum, but is able to recognize and correct
CTE: Failure to loop the artery proximal to injury within 20 minutes	CTE: Failure to loop the artery proximal to injury within 20 minutes	CTE: Incorrectly identifies the SFA, and does not recognize or correct error	ER: Incorrectly identifies the anterior compartment but is able to recognize and correct
ER: Incorrectly identifies the axillary artery, but is able to recognize and correct	ER: Incorrectly identifies the brachial artery, but is able to recognize and correct	CTE: Incorrectly identifies the PFA and does not recognize or correct error	ER: Incorrectly identifies the deep posterior compartment but is able to recognize and correct
		CTE: Failure to loop artery proximal to injury within 20 minutes	ER: Incorrectly identifies the lateral compartment, but is able to recognize and correct
		ER: Incorrectly identifies CFA, SFA, or PFA, but is able to recognize and correct	ER: Incorrectly identifies the superficial compartment but is able to recognize and correct

Each error subtracts 2 points and error with recovery one point from the individual procedure score.
CFA, common femoral artery; *CME*, critical management errors; *SFA*, superficial femoral artery; *PFA*, profunda femoral artery.

Results

Eighty-four surgeons participated in the study, but 2 residents did not complete follow-up skill retention evaluations.[13,14] Enrolled participants included 40 post-graduate year 3 to 6 general surgery residents evaluated before they received ASSET training with follow-up within 1 month and 38 of 40 residents returned again 14 ± 2.7 (mean ± standard deviation [SD]) months after ASSET training for skill retention evaluation. Other participants included 34 practicing surgeons evaluated 30 ± 12.8 months after ASSET training, and 10 experts. The interval experience between ASSET training and participation in the study showed large variability[16] with some surgeons, including experts, in each cohort having performed none of these upper or lower extremity vascular procedures or FAS since ASSET training, while all except the lowest tertile of practicing surgeons had evaluated some trauma patients.

TRI among residents, practicing surgeons, and expert surgeons

TRI was significantly higher ($P < .004$), with lower variance (TRI 0.8, SD 0.04) for experts compared to residents pretraining (TRI 0.53, SD 0.07), 1 month posttraining (TRI 0.67, SD 0.07) and 12 to 18 months (mean 14 months) posttraining (TRI 0.67, SD 0.07; $P < .02$). Practicing surgeons (TRI 0.66, SD 0.08) had lower TRI ($P < .05$) and higher variance than experts and residents after training (Fig 1). When all participant surgeons were stratified into performance deciles based on overall TRI scores, the frequency of errors versus the performance decile showed that 98% of surgeons in the lowest decile made a critical technical error (Fig 2) and that below the sixth decile of all cohorts critical errors increased.

Prediction of errors among residents using area under receiver operating curves (AUROC)

Pretraining resident TRI (using all evaluation scores) predicted critical technical errors (CTE) and critical management errors (CME) immediately after training with AUROC 0.76 (confidence interval [CI] 0.57–0.95 with P value .006) and Youden Index of 0.54, and TRI at 14 month evaluations with AUROC of 0.62 (95% CI, 0.42–0.8; P value .15) and Youden index of 0.48, below which residents made a critical error. The AUROC's and Youden indices prediction of resident CTE at mean 14 months are shown in Tables II and III for each of the 4 procedures using only components of the total TRI evaluation as inputs, Youden index cut-offs for all technical evaluation (includes technical and expert discriminators) used to predict CTE varied between 0.49 (for FAS) to 0.60 (for FA and BA), technical (includes only landmarks and procedural steps). All anatomy includes structures injured, landmarks, procedural steps, and pitfalls. Similar to the data from deciles of TRI scores (mentioned earlier) the AUROC and Youden Index show a cut-off value below which residents made a critical error of 0.6.

Resident pre- and posttraining critical errors versus practicing and expert surgeons

The number of critical errors (critical technical errors and critical management errors) by the residents pre-ASSET training (3.4 critical errors per resident) were higher ($P < .0001$) than all the same resident posttraining evaluations and higher than practicing surgeons (2.8 critical errors per practicing surgeon; $P < .05$) and experts (1.4 errors per expert; $P < .0001$). Resident critical errors decreased ($P < .01$) to 3.0 per resident immediately after training and 1.6 per resident ($P < .0001$) at mean 14 months posttraining retention evaluations among 38 of 40 of the same resident surgeons. Significantly ($P < .0001$) fewer critical errors were made by experts than residents evaluated immediately after training. After 14 months there was no difference between residents and experts in critical errors while practicing surgeons had significantly greater number of critical errors ($P < .0001$; Fig 3 and Table IV). Error recovery[17] per unit critical error per surgeon (to account for the differing numbers of potential errors, multiple procedures and surgeons in each cohort) for experts (2.1) was about 7 times that of pretrained residents (0.26) and practicing surgeons (0.33) and

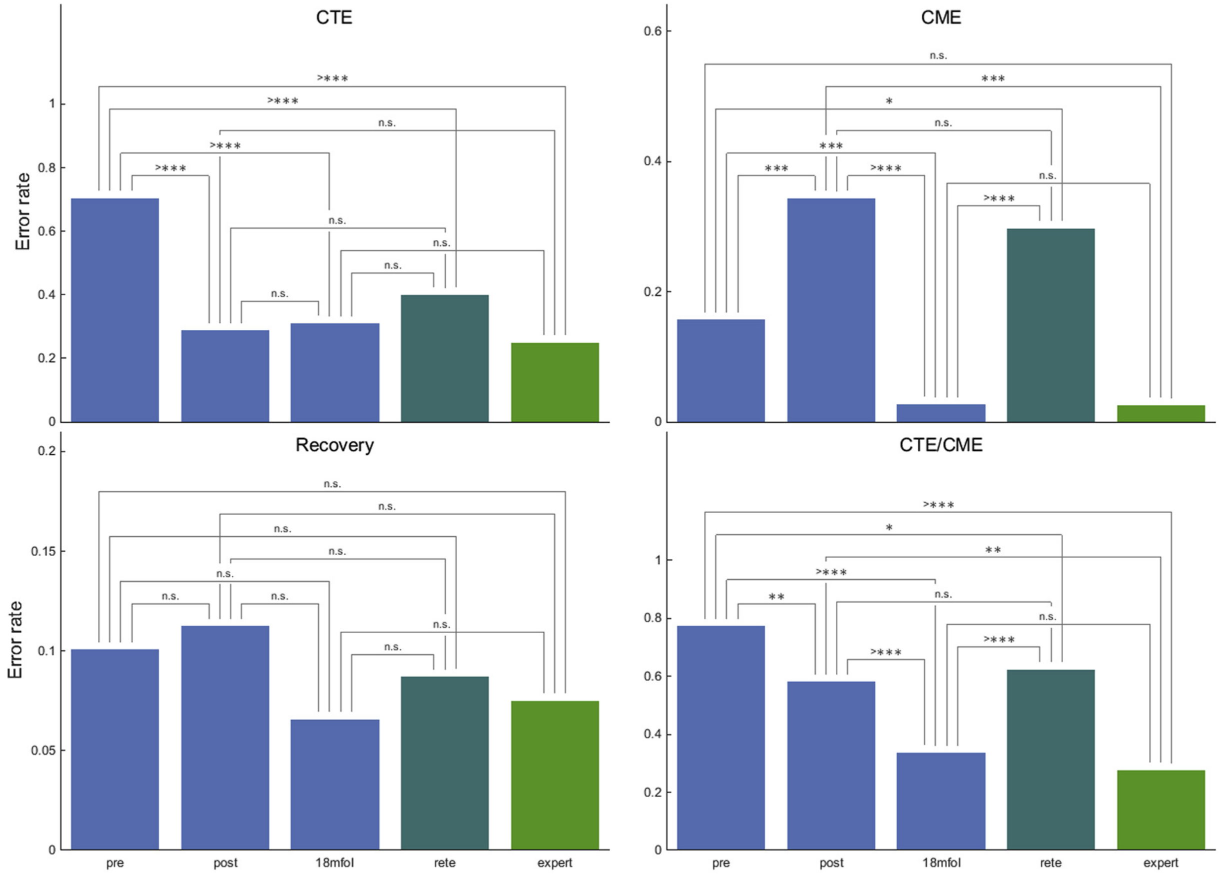

Fig 1. *Panel top left*: Differences between cohorts in critical technical errors (CTE) rates. *Panel top right*: critical management errors (CME). *Panel bottom left*: error recovery. *Panel bottom right*: total critical technical and management errors. Figure shows differences between cohorts of residents before, immediately after, and up to 18 months after training and errors among practicing surgeons (ret) and expert cohorts. ***$P < .0001$; **$P = .0001$ to 0.001; *$P = 0.01$ to 0.05. *N.S.*, no significant difference between cohorts in critical errors, although experts had five times the error recovery.

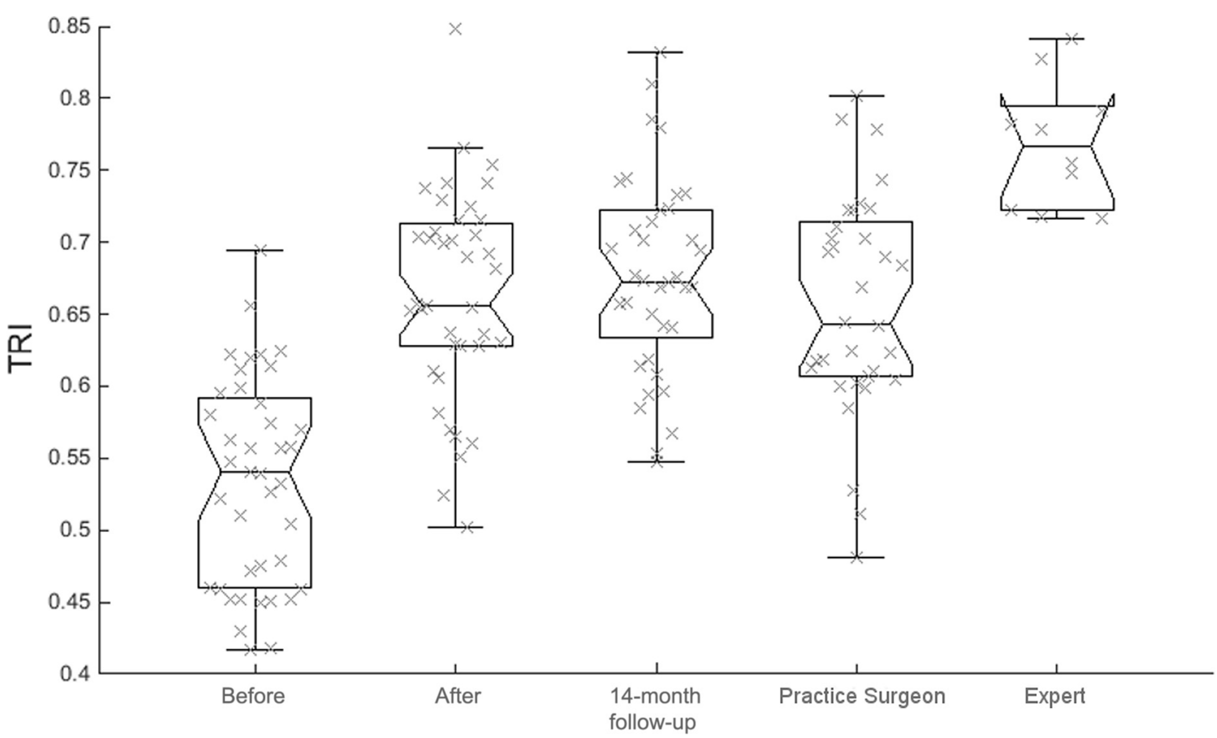

Fig 2. Mean ± standard deviation, confidence intervals, and individual surgeons' trauma. readiness indexes (TRIs) among all participant cohorts. Residents data are given for before, immediately after, and at 14-month follow-up (see text for absolute values of TRI and differences between cohorts).

Table II
AUROC, CI, *P* value, and YI for optimal sensitivity and specificity cut-off, identifying the point below which a participant resident at the 14 month interval evaluation made ≥1 critical technical errors during performance of AA, BA, FA artery, and lower extremity FAS procedures

AUROC (95% CI) for CTE 14 months follow-up	% Mean value and confidence interval YI technical anatomy	*P* value	% Mean value and confidence interval YI all anatomy	*P* value	% Mean value and confidence interval YI all technical	*P* value	Technical	All anatomy	All technical
AA	0.63 (0.34–0.92) YI = 0.16	.21	0.58 (0.26–0.89) YI = 0.56	.31	0.67 (0.41–0.93) YI = 0.58	.14	0.16	0.56	0.58
BA	0.59 (0.38–0.80) YI = 0.54	.20	0.62 (0.42–0.82) YI = 0.49	.15	0.57 (0.36–0.77) YI = 0.60	.27	0.54	0.49	0.60
FA	0.65 (0.42–0.89) YI = 0.17	.09	0.66 (0.43–0.88) YI = 0.37	.08	0.63 (0.42–0.84) YI = 0.60	.12	0.17	0.37	0.60
FAS	0.57 (0.36–0.78) YI = 0.5	.25	0.55 (0.34–0.75) YI = 0.59	.32	0.56 (0.35–0.77) YI = 0.49	.27	0.5	0.59	0.49

AUROC's and Youden indices are shown for technical (includes only landmarks and procedural steps); all anatomy (includes structures injured, landmarks, procedural steps, pitfalls); and all technical evaluations (includes technical and expert discriminators).
YI, Youden index.

Table III
Youden index for optimal sensitivity and specificity cut-off, identifying the point below which a participant resident at the 14 month interval evaluation made ≥1 critical technical errors during performance of AA, BA, FA artery, and lower extremity FAS procedures

Youden Index for CTE 14 months follow-up	Technical anatomy percent mean	All anatomy percent mean	All technical percent mean
AA	0.16	0.56	0.58
BA	0.55	0.49	0.60
FA	0.17	0.37	0.60
FAS	0.50	0.58	0.49

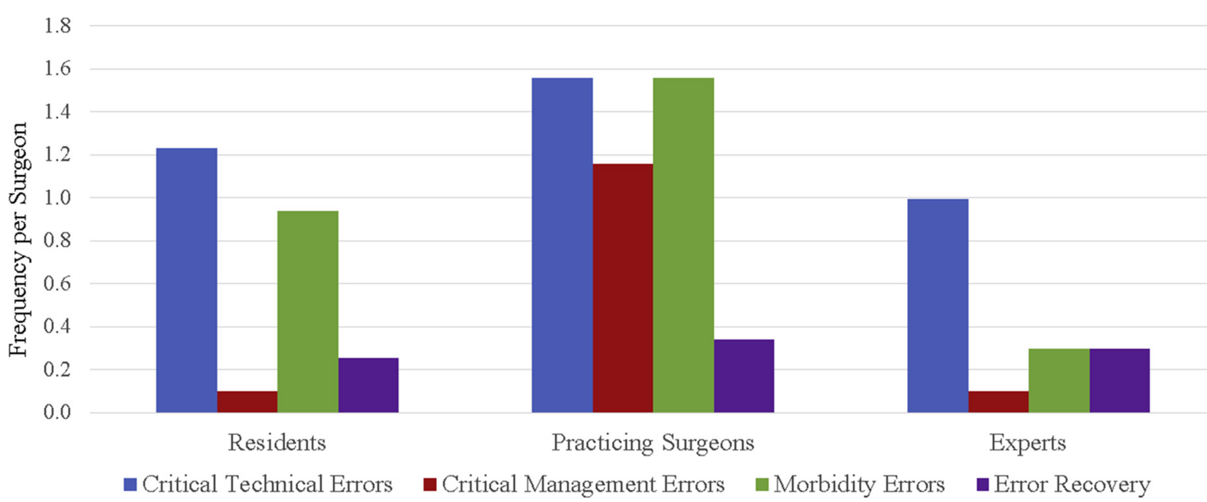

Fig 3. Critical technical and morbidity errors and error recovery per surgeon among resident, practicing, and expert surgeon cohorts.

about 5 times that of residents after training (0.38) and at their 14 month evaluation (0.43; Table V). Because the error recovery rate was low in all cohorts, none of these differences were statistically different.

Multiple critical technical errors

Among 40 residents, no resident performed the 4 procedures before ASSET training without making a critical technical error (CTE). Multiple CTEs at all evaluations among all cohorts of participants are shown in Table V. Immediately after training, 11 residents (27.5%) made no CTEs. At a mean 14 months after ASSET training, 8 made no critical technical errors (21%). Among 34 practicing surgeons evaluated once, mean 30 months after ASSET training, 11 in the upper tertile of TRI made no critical technical error (32%). Among the 10 experts, 2 made no critical technical errors (20%). Four residents made the same errors before and after training, including failure to identify a specific artery or failure to decompress a specific compartment of the leg. For the vascular procedures, 10 residents failed to expose the same one or more arteries at each of the 3 evaluations. For the fasciotomy procedure, 38 residents completed the evaluation at 3 separate intervals, the same 5 residents did not decompress the anterior compartment on any of the 3 evaluations, 4 did not decompress the lateral compartment, 5 did not decompress the superficial posterior compartment, and 16 did not decompress the deep posterior compartment. One resident surgeon did not decompress any of the 4 compartments on any of the 3 evaluations, and 6 residents failed to decompress ≥1 compartment at each evaluation.

Table IV
CTE, CME, and error recovery (ER) during interval evaluation of residents before, after, and 12 to 18 month retention after skills training in comparison to practicing and expert surgeons

	Residents: Before n = 40	Residents: After n = 40	Residents: Retention n = 38	Practicing n = 34	Experts n = 10
CTE/surgeon (no. of errors)	2.8 (112)	1.2 (46)	1.2 (47)	1.6 (55)	1.0 (10)
CME/surgeon (no. of errors)	0.6 (25)	1.4 (55)	0.1 (4)	1.2 (41)	0.1 (0.1)
(CTE + CME + ER)/surgeon	3.8	3.0	1.6	2.8	1.4
No. of ER	16	18	10	12	3
ER as % CTE + CME + ER	10.5%	15.1%	16.4%	11.1%	21.4%
ER/surgeon (*n*)	0.26	0.38	0.43	0.33	2.1

CME, critical management errors.

Table V
CTE, error recovery, and multiple CTE among resident (pretraining, posttraining, and retention evaluations), practicing, and expert surgeons during performance of AA, BA, FA, and lower extremity FAS procedures

Procedures	Total participants	Total CTE	Error recovery	1 Error	2 Errors	3 Errors	4 Errors
AA, BA, FA, FAS	pre *n* = 40	112	16	5	9	15	11
	post *n* = 40	46	18	18	6	4	1
	retention *n* = 38	47	10	16	11	3	0
	practicing *n* = 34	55	12	11	11	6	1
	expert *n* = 10	10	3	6	2	0	0

Common technical errors for individual procedures

For AA, the commonest error was incorrect identification of landmarks and placement of the skin incision too lateral (multiple residents before ASSET training made their incision in the axilla). Surgeons not completing the short BA procedure in the allowed 20 minutes, failed to palpate the neurovascular bundle, between biceps and triceps, against the humerus, so initial skin incisions revealed tissues inferior to triceps with no easily defined unique characteristics. A second common critical technical error in the pulseless cadaver, was mistaking the median nerve for BA. For FA, failure to extend the skin incision 4 to 5 cm above the inguinal ligament meant that errors related to proximal control of FA were all caused by inadequate proximal dissection and mistaking superficial femoral artery for common femoral artery owing to a failure to correctly identify profunda femoral artery. LE FAS technical errors all related to incorrect skin marking of incisions, including a failure to extend the proximal skin incisions to within 2 to 3 fingers breadth of the tibial plateau and the distal incisions to within 2 to 3 fingers breadth of the malleoli. For the lateral incision landmarks, skin incisions were not placed 2 to 3 fingers breadth in front of the fibula, but more lateral so that the intramuscular septum between anterior and lateral compartments was missed and the anterior compartment was not decompressed. For the medial incision, placement of skin markings more than one thumb width lateral to the tibial edge was the cause of critical errors in finding the deep posterior compartment and confirmation of entry by exposing the neurovascular bundle.

Discussion

Using an overall TRI skill evaluation of vascular and nonvascular open surgical procedures benchmarked by practicing surgeons and expert trauma surgeons, this study demonstrated that an intensive 1-day trauma exposure training course was associated with a reduction in critical errors among the resident cohort evaluated 14 months after training, no different to error occurrence found among experts. Total errors, including specific critical technical and management errors and repeated errors representing life- and limb-threatening failures, were higher among practicing surgeons who took the ASSET course an average of 2.5 years before the evaluations. A majority of the practicing surgeons had limited interval exposure to the 4 trauma exposures.[16] For critical technical errors there was little difference between the groups in that the majority of all cohorts made technical errors and the causes of common technical errors were identified. Only 21% of residents (evaluated at 14 months), 32% of practicing surgeons, and 20% of experts completed all 4 procedures without making a single technical error. The critical technical error rate for fasciotomy, representing incomplete decompression of at least one compartment, was high among all 3 surgeon cohorts evaluated. The ability to recognize and treat compartment syndrome, including lower extremity fasciotomy, has been recognized as a core skill for trauma surgeons.[19] Military surgeons, in particular, may be called on to perform fasciotomy in austere settings without subspecialty support. Poorly performed fasciotomy is a source of significant morbidity, with revision for incomplete fasciotomy required in 17% of military casualties in one study.[20]

What intervention should be made if a surgeon makes a critical error?

It is recognized that making errors is part of normal human behavior[21] and does not necessarily mean a surgeon is incompetent. Surgical competency involves a combination of good decision-making (preoperatively, operatively, and postoperatively), team performance and communication (with surgical, anesthetic, nursing, and other essential staff members), and technical skill. These skills, coupled with a high patient and operative volume, tend to achieve a reduced patient mortality and morbidity.[22,23] It is unlikely that no errors occur throughout this process, even for the simplest of cases.[23] We have previously noted that individual surgeon performance and errors could not be predicted based on time since training among residents.[16] In this study, we found a large TRI (Fig 2) and error (Table IV) variability among the 3 surgeon cohorts, with the least variability seen in experts and most in practicing surgeons. For individual residents, TRI predicted future critical errors, low TRI was associated with critical errors occurring in all surgeon cohorts and can identify surgeons in need of remedial intervention.

Practicing surgeons in the uppermost TRI tertile performed a greater number of error-free procedures than experts or residents. This finding suggests that errors were more frequent in the lower tertile of practicing surgeons and TRI could be used to identify residents, practicing surgeons, and experts in need of remedial interventions. The critical management errors among practicing surgeons as a cohort, were 10 times those of residents at their skill retention evaluation, and this may reflect the low interval trauma experience of many practicing surgeons since ASSET training. These management errors could be evaluated with knowledge assessment.

TRI inflection point for critical technical error remediation

Simple solutions potentially exist to minimize common technical errors for the 4 procedures we tested by teaching correct landmarks for each procedure, skin-marking of incisions, and learning the key procedural steps. Retraining could occur within an ASSET course for focal deficiency or a longer period in a trauma training partnership could be used for global issues. Those residents performing below the TRI AUROC cut-off value of 0.6 on the initial pretraining evaluation continued to make errors, including critical technical errors, and the same errors on the same procedures during repeat evaluations. Conversely, residents performing at the highest TRI level maintained a low error rate throughout the re-evaluation period. Most residents showed an overall improvement in TRI after the training intervention. Our findings indicate residents could be identified by a pretraining AUROC Youden index of 0.49 to 0.60 for any of the 4 procedures and this metric could be used to identify surgeons in need of remediation interventions to prevent critical errors when operating independently (without prompting or performance feedback). However, there is still a need to refine the TRI score because an AUROC of 0.6 is not high performing; TRI AUROC is a start for identifying surgeons who need remediation. Alternatively, TRI of the surgeon cohorts (Fig 2) showed increased critical errors when TRI was below the sixth decile. This would be simpler to calculate than AUROC and Youden index and could be benchmarked were more surgeons similarly evaluated and added to this historic cohort.

Error recovery

Experts had about 7 times better error recovery by recognizing their critical technical and management errors than the practicing surgeon cohort or residents before training. At resident skill retention evaluation, experts still had about 5 times the skill for error recovery after critical technical and management errors. The primary type of error recovery observed was related to initial misidentification of anatomic structures, followed by realization of the mistake and correct identification. Therefore, increased familiarity with the specific surgical anatomy would be expected to result in more frequent and quicker error recovery. The cadaver especially tests anatomic skills for the vascular procedures because there are no pulses to act as landmarks. The lowest error recovery rate was observed in practicing surgeons a mean of 2.5 years after ASSET training, whereas the highest rate was observed in expert surgeons. In all groups, however, the majority of errors were not recognized or corrected. This improvement in error recovery with training and the high error recovery seen in experts confirms the utility of error recovery as a performance metric for surgery.[24]

Previous studies of technical errors in open and vascular surgical training

A claims surgical malpractice analysis of 133 case studies found 140 discrete errors with attending surgeons responsible for 69% and 27% involving attending surgeons and trainees.[25] Remediation interventions suggested included restricting high-complexity operations to experienced surgeons, additional training for inexperienced surgeons, stricter supervision of trainees, and improving decision-making and performance in routine operations for complex patients and circumstances. Two comprehensive systematic reviews have examined the impact of training in open and vascular surgery skills on outcomes. Jelovsek et al[26] reviewed metrics to assess surgical psychomotor skills in medical trainees in live patients and found 30 tools. Twenty-four tools showed association between scores and training level. A systematic review assessing skill acquisition and operative competency in vascular surgical training[27] found 29 articles evaluating open vascular skills, 19 of which described endovascular skills, 6 non-technical skills, and 1 teamwork skills. No assessment tools were applicable to all study scenarios and procedures. Skills assessments included 611 surgeons and 43 medical students. Less than 19% of the studies included evaluations of expert (attending or consultant level) surgeons.

Practical aspects of implementation of ASSET training

Relative to making a single critical error in a real patient, the $500 to $2,000 cost[28] and the 1-day time commitment of taking the ASSET course has a favorable cost-to-benefit ratio, when the skill retention outcome mean 14 months after ASSET training shows residents reduced critical errors to levels made by traumatology attendings. ASSET training is important for military surgeons. We would propose the ASSET Course and evaluation of some of the procedures using TRI should be included as formative assessment for all second- or third-year surgery residency training programs. Simple screening tests could identify those in need of remediation interventions (screen with multiple choice questions, including case scenarios followed by multiple choice questions to identify what structures could be injured; incision landmarks; procedural steps and common pitfalls) every 2 years for general surgeons in rural areas, military surgeons, and residents before completion of training. Individual skill training, a term we have referred to as precision training, should allow individual residents, practicing surgeons and experts to identify their training needs and focus training accordingly.[13] This would be a departure from currently available training designed with a one-size-fits-all model.

Future studies

Robustly designed studies are needed to determine the most effective training methods, models for open trauma surgery, and the ideal training interval. The ability to detect improved performance of individual surgeons in a training environment is a challenge because the effects of team versus individual surgeon performance and other nontechnical factors, such as communication and leadership skills, may also affect patient outcomes. Future research designs should include both technical and nontechnical skill performance metrics that allow standardized evaluation (including use of validated standardized patients), before and after training and follow-up, to determine whether performance gains realized from training can be shown in the operating room. Reducing the variance seen in performance of resident and non-trauma surgeons after ASSET training would be a key objective of future studies.

Limitations

There may have been bias in the TRI scores because evaluators unavoidably knew who the experts were and when resident evaluations occurred in relation to pre-, post- and skill retention assessments after training. We rotated the resident evaluators so that wherever possible they did not evaluate the same residents. Just as the residents and practicing surgeons, the experts were equally unaware about what skills would be evaluated in this study. The evaluations scripts and metrics were identical for all surgeons. Fewer critical errors per resident surgeon seen 12 to 18 months after training, compared with evaluations immediately after training, may have resulted from repeated debriefings or owing to the follow-up loss of 2 surgeons who had both made repeated errors at the pre- and posttraining evaluations.[13]

An additional limitation in this study is that the practicing surgeons and experts evaluated in this study were not evaluated at baseline, so it is impossible to know if their performance was an improvement or a decrement from pretraining performance. It is also difficult to draw conclusions as to the differences in performance between the residents and the practicing surgeons as the interval from initial ASSET course training was more than twice as long (30 vs 14 months) and practicing surgeons interval experience was more varied.[16] Although we recommend remedial intervention for these residents based on TRI, we do not currently have evidence additional training will improve technical performance for those who score poorly after initial training, nor are there data to support or disprove that TRI improves outcomes in trauma patients, because to prove this link would require further prospective study.

Conclusions

Critical errors among residents decreased significantly after ASSET training. Critical errors were observed in all of the study groups including experts. Missed FAS compartment decompression is common among resident, practicing, and expert surgeons. A single pretraining evaluation using TRI can predict that an individual resident will make a critical technical or management error that will be limb or life-threatening, when performing the emergency vascular exposure and control or fasciotomy trauma procedures evaluated 14 months after training. Individual skill training and repeated training is needed for all surgeons who rarely perform these trauma procedures. TRI is a tool to screen and focus such training accordingly to allow individual residents, practicing surgeons and experts to identify their training needs. This would be a departure from currently available training designed with a one-size-fits-all model.

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Conflict of interest/Disclosure

Publication is approved by all authors, none of whom have a conflict of interest to report.

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