Prospective Randomized Trial of Standard Left Anterolateral Thoracotomy Versus Modified Bilateral Clamshell Thoracotomy Performed by Emergency Physicians

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Study objective: Resuscitative thoracotomy is a time-sensitive, lifesaving procedure that may be performed by emergency physicians. The left anterolateral thoracotomy (LAT) is the standard technique commonly used in the United States to gain rapid access to critical intrathoracic structures. However, the smaller incision and subsequent limited exposure may not be optimal for the nonsurgical specialist to complete time-sensitive interventions. The modified bilateral anterior clamshell thoracotomy (MCT) developed by Barts Health NHS Trust clinicians at London's Air Ambulance overcomes these inherent difficulties, maximizes thoracic cavity visualization, and may be the ideal technique for the nonsurgical specialist. The aim of this study is to identify the optimal technique for the nonsurgical-specialist-performed resuscitative thoracotomy. Secondary aims of the study are to identify technical difficulties, procedural concerns, and physician preferences.

Methods: Emergency medicine staff and senior resident physicians were recruited from an academic Level I trauma center. Subjects underwent novel standardized didactic and skills-specific training on both the MCT and LAT techniques. Later, subjects were randomized to the order of intervention and performed both techniques on separate fresh, nonfrozen human cadaver specimens. Success was determined by a board-certified surgeon and defined as complete delivery of the heart from the pericardial sac and subsequent 100% occlusion of the descending thoracic aorta with a vascular clamp. The primary outcome was time to successful completion of the resuscitative thoracotomy technique. Secondary outcomes included successful exposure of the heart, successful descending thoracic aortic cross clamping, successful procedural completion, time to exposure of the heart, time to descending thoracic aortic cross-clamp placement, number and type of iatrogenic injuries, correct anatomic structure identification, and poststudy participant questionnaire.

Results: Sixteen emergency physicians were recruited; 15 met inclusion criteria. All participants were either emergency medicine resident (47%) or emergency medicine staff (53%). The median number of previously performed training LATs was 12 (interquartile range 6 to 15) and the median number of previously performed MCTs was 1 (interquartile range 1 to 1). The success rates of our study population for the MCT and LAT techniques were not statistically different (67% versus 40%; difference 27%; 95% confidence interval –61% to 8%). However, staff emergency physicians were significantly more successful with the MCT compared with the LAT (88% versus 25%; difference 63%; 95% CI 9% to 92%). Overall, the MCT also had a significantly higher proportion of injury-free trials compared with the LAT technique (33% versus 0%; difference 33%; 95% CI 57% to 9%). Physician procedure preference favored the MCT over the LAT (87% versus 13%; difference 74%; 95% CI 23% to 97%).

Conclusion: Resuscitative thoracotomy success rates were lower than expected in this capable subject population. Success rates and procedural time for the MCT and LAT were similar. However, the MCT had a higher success rate when performed by staff emergency physicians, resulted in less periprocedural iatrogenic injuries, and was the preferred technique by most subjects. The MCT is a potentially feasible alternative resuscitative thoracotomy technique that requires further investigation. [Ann Emerg Med. 2021;77:317-326.]

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Editor's Capsule Summary

What is already known on this topic

Resuscitative thoracotomy is an infrequently performed, time-critical, potentially lifesaving procedure for select trauma patients.

What question this study addressed

This study compared performance characteristics among 15 military emergency physicians who completed both left anterolateral thoracotomies (LATs) and modified bilateral anterior clamshell thoracotomies (MCTs) on fresh human cadavers.

What the study adds to our knowledge

Study subjects preferred the MCT technique to the left anterolateral thoracotomy (87% versus 13%). However, in this small study there were no statistical differences in time to procedure completion and success, defined as fully exposing the heart and completely occluding the descending aorta. Iatrogenic injury occurred in all left anterolateral thoracotomies and 67% of MCT procedures.

How this is relevant to clinical practice

The MCT procedure may be an option for emergency physician–performed resuscitative thoracotomy, and appropriate for further evaluation.

INTRODUCTION

In the United States, trauma is a leading cause of morbidity and mortality in people younger than 44 years.[1] Blunt and penetrating thoracic trauma represents 25% to 50% of all injuries and is a contributing factor in half of civilian trauma deaths.[2,3] Although most traumatic thoracic injuries are treated with nonoperative management, there remains a significant subgroup (10% to 15%) for which an emergency thoracotomy is lifesaving.[2] The execution of the resuscitative thoracotomy is critical because any delay in performance rapidly diminishes the chances for survival.[3,4] Several studies have demonstrated that prognosis depends on the time between loss of cardiac output and performance of the resuscitative thoracotomy.[5-11]

Resuscitative thoracotomy is typically performed by surgeons, but it can be completed by emergency physicians when a suitable surgeon is not immediately available or in austere civilian or military environments.[3,4,12-14] In the United States, the left anterolateral thoracotomy (LAT) is considered by many to be the standard technique because it provides rapid access to the heart and descending thoracic aorta.[3,15] However, the smaller incision and subsequently more limited exposure may not be optimal for the nonsurgical specialist to rapidly access critical intrathoracic structures while minimizing errors that may lead to a catastrophic delay in intervention, decreasing the chance of survival.[3,4,12,15] In comparison, the modified bilateral anterior clamshell thoracotomy (MCT) may overcome the inherent difficulties associated with the LAT for the nonsurgical specialist.

Several studies have suggested that the MCT technique may be the better option for nonsurgeons because it has demonstrated improved and timely access to critical structures and may offer an increased probability of neurologically intact survival.[3,13,15] In the United Kingdom, Barts Health NHS Trust clinicians at London's Air Ambulance developed an MCT that adopted a different approach to maximize visualization of the thoracic cavity by the nonsurgical specialist in addition to simplifying the instrument set.[4,7,12,14] London's Air Ambulance found the MCT to be simple and rapid, and to provide excellent exposure that is easily reproducible among nonsurgeons. The 2018 *Advanced Trauma Life Support Student Course Manual* update also now includes the clamshell in addition to the LAT for management of traumatic circulatory arrest.[16] The purpose of this study was to evaluate time to successful completion of the MCT compared with the LAT when performed by nonsurgical specialists.

MATERIALS AND METHODS

Study Design and Setting

We conducted a prospective, randomized, crossover study comparing outcomes among US emergency medicine resident and staff physicians, using 2 resuscitative thoracotomy techniques in a fresh human cadaver model: LAT and the MCT. The standards outlined in the CONSORT checklist (http://www.consort-statement.org) were adhered to. Subject matter expertise was provided by board-certified military surgeons and Barts Health NHS Trust clinicians at London's Air Ambulance. The primary outcome was time to successful completion of the resuscitative thoracotomy technique. This study was an international military-civilian collaboration between the US Army, US Air Force, and London's Air Ambulance (London, England). The study took place at the Centre for Emergency Health Sciences in Spring Branch, TX. Data collection occurred from January 2019 through March 2019. Study outcomes were determined by the same board-certified general surgeon who was present during all data collection to avoid an issue with interrater reliability.

This study was reviewed and approved by the Brooke Army Medical Center Department of Clinical Investigation Office of the Institutional Review Board. Informed consent was obtained from each participant before his or her inclusion in the study. This study was registered after completion of data collection and analysis. We believed registration was not initially necessary because the intervention was performed by Physicians on human cadaver specimens. The outcome was to examine the technical aspects of the technique and the effects on those providers instead of health-related outcomes of patients.

Selection of Participants

Emergency medicine resident and staff physicians assigned to the emergency department (ED) of the San Antonio Military Medical Center (SAMMC), Fort Sam Houston, TX, a Level I military trauma center, were eligible for study participation. Inclusion criteria included current US medical licensure, US emergency medicine residency trainee (second year or greater) or graduate, and provider privileges at SAMMC. The sole exclusion criterion was unwillingness to participate. All participants had previous resuscitative thoracotomy training in the LAT technique as part of US graduate medical education and various clinical experience performing the technique. Trainees at SAMMC emergency medicine residency programs perform monthly procedure laboratories that include this training. No participants had previous training or experience with the MCT technique.

We approached all SAMMC emergency medicine residents and staff physicians. A brief study overview was provided during SAMMC emergency medicine grand rounds and by mass e-mail. During the study period, approximately 32 emergency medicine residents (postgraduate years 2 and 3) and 50 staff emergency physicians were approached.

Interventions

Participants were randomized to the order of intervention, with all participants performing each technique on a separate fresh human cadaver. The 2 resuscitative thoracotomy techniques compared were the LAT and MCT. The LAT technique taught during individual training was as described in *Roberts and Hedge's Clinical Procedures in Emergency Medicine*.[1] The MCT technique taught was developed by clinicians at Barts Health NHS Trust London's Air Ambulance and described in London's Air Ambulance's Resuscitative Thoracotomy standard operating procedure, as well as *Emergency Thoracotomy: "How to Do It"* (Figure E1 and Video E1, available online at http://www.annemergmed.com).[4,17]

Participants received standardized training in the LAT and MCT techniques. A standardized teaching PowerPoint program introducing surgical instruments, a step-by-step outline of each technique, and review of pertinent anatomy was presented. After review of didactic material, subjects participated in a hands-on training session. Participants underwent surgical instrument- and technique-specific surgical tray familiarization (Figure E2, available online at http://www.annemergmed.com). Each technique was then performed on fresh and embalmed human cadavers. Participants returned to complete data collection at a nonstandardized later date in accordance with availability of the participant and cadaver specimens.

Randomization sequence was performed by investigators using electronic randomization software (http://www.randomization.com) during protocol development. Subjects were randomized to order of intervention. Cadavers were randomized to intervention in blocks of 2 in the order they were delivered to the Centre for Emergency Health Sciences. Blocks of 2 ensured that each cadaver pair for each subject was randomized to both interventions. Sequential subjects performed procedures on sequential cadaver pairs.

Cadavers were positioned supine in a simulated trauma bay with a draped thoracotomy tray standardized to the resuscitative thoracotomy technique to be performed. Bilateral finger thoracostomies at the fifth intercostal spaces were performed by investigators before participant arrival to ensure successful and standardized procedure completion. A standardized scenario was presented, and the participant was subsequently instructed to perform the assigned resuscitative thoracotomy technique. A study investigator performed the role of an assistant trained at the paramedic level and was able to provide assistance with retracting at the instruction of the participant. After completion of the assigned resuscitative thoracotomy technique, participants left the room while the surgeon inspected the specimen for anatomic variance, iatrogenic injuries, preexisting pathology, and vascular clamp placement. Participants returned and were verbally instructed to identify anatomic structures by using a pointer. All data were collected on a standardized data collection form (Appendix E1, available online at http://www.annemergmed.com). After completion of the assigned technique and anatomic identification, a brief 30-minute washout period occurred before the next study technique was started. After completion of both techniques, participants completed a survey (Appendix E2, available online at http://www.annemergmed.com). They were provided no feedback until the study protocol and survey were concluded.

Methods of Measurement

All subjects completed a prestudy questionnaire reporting demographics, training status, and years of practice. The number of previous training LATs and therapeutic LATs performed on actual patients for each participant was recorded. Finally, participants were queried on any previous experience with the MCT technique.

Demographic information for each cadaver specimen was recorded. Cadaver reports provided suspected cause of death. Height and weight were measured, and body mass index was calculated. After performance of the resuscitative thoracotomy, cadavers were examined by the surgeon for additional pathology. Significant adhesions, effusions, previous thoracic surgery, tumors, preexisting sternal and rib fractures, and other anatomic variances were noted.

During the study period, investigators measured the time required to successfully complete the resuscitative thoracotomy technique. After the standard scenario was read to the subject, time measurement started from the command "go." Subjects were not allowed to put their hands on equipment or the specimen before this point. Time to exposure of the heart was marked by the subject's verbalizing delivery of the heart from the pericardial sac. Time to descending thoracic aorta cross clamping was marked by the subject's verbalizing completion of aortic cross clamping.

Successful exposure of the heart was determined by the surgeon observing adequate exposure and visualization of all cardiac chambers and surfaces of the heart anteriorly and posteriorly. If the subject verbalized exposure but did not fully expose the heart, the surgeon would determine delivery of the heart as unsuccessful and the time to delivery would not be analyzed as a successful time to delivery. Successful cross clamping of the aorta was determined by the surgeon after trial completion and strictly defined as 100% occlusion of the descending thoracic aorta. Procedural success was defined as both successful exposure of the heart and successful cross clamping of the aorta. Postprocedure surgeon inspection identified the number and type of iatrogenic injuries, anatomic variance, and preexisting pathology. No feedback was provided to the subject during this time. There was no time limit on the study procedure and all time measurements were rounded to the nearest second.

Anatomic structure identification was confirmed by the study surgeon. Key structures to be identified included the phrenic nerve, right atrium, right ventricle, left atrium, left ventricle, pulmonary hilum, descending thoracic aorta, and esophagus. After completion of both techniques, participants completed a poststudy questionnaire, which evaluated procedural ease, quality of view obtained, physician comfort level with technique, and procedural preference.

Outcome Measures

The primary outcome was time to successful procedural completion and included times for successful trials only. Secondary outcomes included successful exposure of the heart, successful descending thoracic aortic cross-clamp placement, successful procedural completion, time to exposure of the heart, time to descending thoracic aortic cross-clamp placement, number and type of iatrogenic injuries, correct anatomic structure identification, and poststudy participant questionnaire. All outcomes were recorded on printed data collection forms and participant questionnaires (Appendixes E1 and E2, available online at http://www.annemergmed.com).

Primary Data Analysis

A priori power analysis indicated that a sample size of N=28 (14 pairs) would be sufficient to identify a 60-second difference in times (with a standard deviation of 75 seconds) in a paired *t* test with 80% power and α=.05. A sample size of 14 participants and 28 cadaveric specimens was chosen. This power calculation assumed all participants would be successful with both procedures. A total of 16 participants and 32 cadaveric specimens were recruited in case of dropout after initial enrollment and training.

We entered all data collection forms data into an Excel database (version 1907; Microsoft, Redmond, WA) and exported the data into SAS (version 9.4; SAS Institute, Inc., Cary, NC) for analysis. Data for all participants meeting inclusion criteria were analyzed. Physician and cadaver characteristics were evaluated and reported as frequencies (percentages), mean (SD), and median (interquartile range [IQR]). The number of previous thoracotomies performed, number of structures correctly identified, and number of injuries per trial were reported as median (IQR) and compared (LAT versus MCT) with exact conditional Poisson regression for paired count variables. The number of trials in which all structures were correctly identified, trials in which no iatrogenic injuries occurred, reasons for trial failure, and successful trials were reported as frequencies (percentages) and tested with McNemar's test for paired proportions, with the paired (marginal) risk differences and 95% confidence intervals (CIs) reported. An unplanned subgroup analysis comparing success with physician level (resident or staff) was performed. Because of imperfect pairing of data (ie, not all participants succeeded in both trials), we used Cox proportional hazards regression analyses for paired time-to-event data to compare techniques (LAT versus MCT) on time to heart exposure, time to cross clamping of the aorta, and time to completion of a successful trial. These analyses were censored by failure of each event, and hazard ratios (with 95% CIs) are given in lieu of mean differences. Survey results were reported as percentages and compared with McNemar's test and paired risk differences with 95% CIs.

We assumed that all participants would be successful in both trials and that the time to successful completion was the primary comparison for our power analysis. This assumption was based on the studies by Flaris et al[3] and Puchwein et al[13] on MCT. However, we used stricter criteria for success (eg, required 100% occlusion of the aorta) and at study completion it became clear that the original analysis could not proceed as planned. Conducting the original analysis (ie, paired *t* tests, which use listwise deletion) using only the successes would have left only 4 participants who succeeded at both and therefore had valid "success times" to compare. The Cox proportional hazards model allowed us to use all of the participants while censoring for failures, and a simple change to the code allowed us to use this model for paired data (eg, we modeled within-participant variance to account for the study design).

RESULTS

Sixteen participants using 2 cadavers each were recruited to ensure a 14-participant sample size for data collection. After enrollment and completion of data collection, one participant was found to not meet inclusion criteria (current US medical licensure), and these data were not included in the final analysis of 30 cadavers. Eight subjects were randomized to LAT first and 7 were randomized to MCT, with all attempting the alternative technique afterward (Figure).

There was no difference in demographic characteristics or experience level among subjects randomized to perform the LAT or MCT first. Mean age of participants was 34.5 years (SD 5.2 years) and 80% were men. All participants were either third-year emergency medicine residents (47%) or staff emergency physicians (53%). SAMMC emergency medicine residents are licensed at the beginning of their second year of training. The median years licensed for subjects was 4 (IQR 2.0 to 7.0 years) and median years posttraining for staff emergency physicians was 2.5 (IQR 1.5 to 5.5 years), representing a newer physician cohort. Subjects reported more experience performing a LAT, with a range of 3 to 15 simulated and 60% having participated in a therapeutic LAT (range 0 to 3) (Table 1). All participants performed at least 1 simulated MCT and 1 simulated LAT during the hands-on training session, with 2 participants performing 2 MCTs. No participant had experience with simulated or therapeutic MCT before the intervention-related training. There were no differences in age, sex, body mass index, thoracic pathology, or previous thoracic surgical interventions when cadavers used for the LAT and MCT techniques were compared.

There was no difference in time to success for each procedure (Table 2). MCT and LAT success was 67% and 40%, respectively (difference –27%; 95% CI –61% to 8%). This did not reach statistical significance. However, when the procedures were performed by emergency medicine staff, there was a 63% absolute difference (95% CI 9% to 92%) between the MCT (88%) and LAT (25%) success. Time to successful exposure of the heart and time to successful cross clamping of the aorta were similar for both procedures. The categories time to successful cross clamping of the aorta and time to success differ in that time to success included only data for procedures with successful exposure of the heart and successful aortic cross clamping. Success on the LAT did not significantly predict success on the MCT (odds ratio 1.00; 95% CI 0.11 to 8.95).

The ability to correctly identify anatomy did not differ between techniques. All structures were identified in 67% of MCT trials and 40% of LAT trials (Table 2). The techniques did differ in iatrogenic injuries. No LAT trial was without iatrogenic injury compared with 33% of MCT trials that produced no injuries. Injuries ranged from rib fractures to lacerations of the diaphragm, esophagus, lung, and heart (Table E1, available online at http://www.annemergmed.com).

Physician previous experience with the procedure was not associated with success for either technique. Individuals who succeeded at performing the LAT had a median number of 12 previous LATs (both simulated and therapeutic; IQR 6 to 13) compared with 13 previous LATs (IQR 10 to 15) for those who did not succeed in the LAT trial (median difference –1; IQR –7 to 3). The median number of previous MCTs was the same for individuals who did and did not successfully complete the MCT trial (median 1, IQR 1 to 1 for both groups; median difference 0, IQR 0 to 0). Additionally, success on the first procedure did not increase the odds of success on the second procedure (odds ratio 0.8; 95% CI 0.1 to 5.8). Time from training session to data collection was also not associated with success.

Likewise, procedural safety was not associated with success. Thirty percent (3/10) of successful MCT trials resulted in no iatrogenic injuries compared with 40% (2/5) of failed MCT trials (difference –10%; 95% CI –61% to 41%). When reasons for trial failure were evaluated, the most common

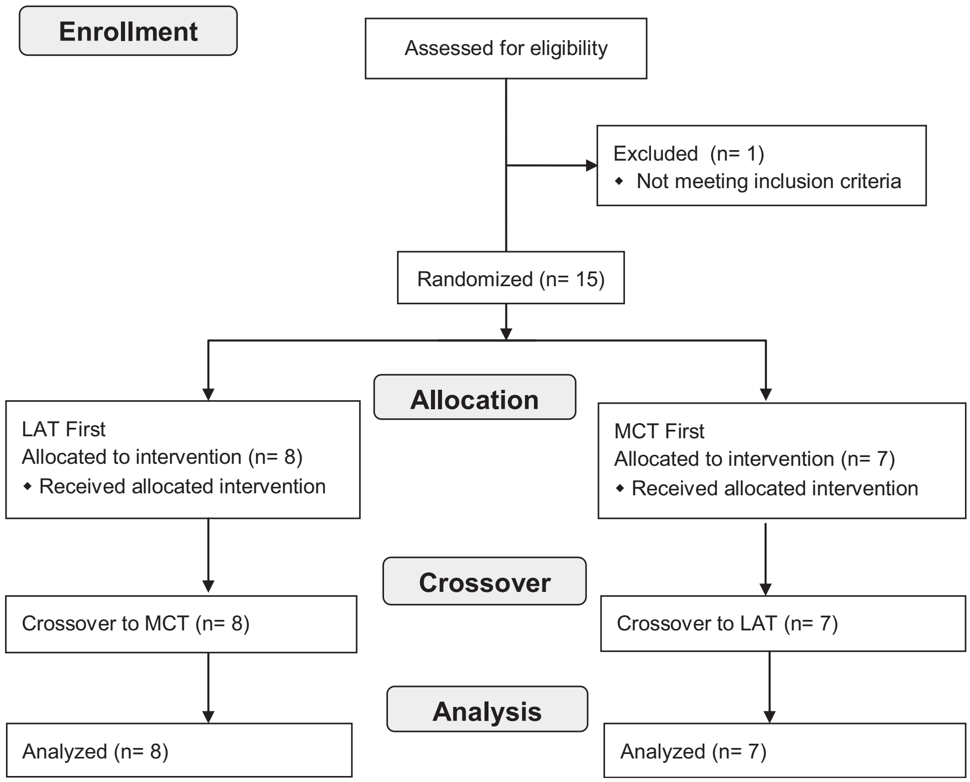

Figure. CONSORT flow diagram.

were partial aortic occlusion, failure to fully visualize the heart, and errors in clamp placement. The reasons for failure were not different for the LAT and MCT trials (Table 3).

There was no association with success and the number of days elapsed between standardized training and data collection. The median time between standardized training and data collection was 25 days (IQR 8 to 67 days). Participants who were successful on the LAT had a median of 34 days from training to performance (IQR 17 to 67 days); those who were not successful had a median of 21 days (IQR 8 to 46; median difference 9; 95% CI –29 to 46). Participants who were successful on the MCT had a median of 19 days from training to performance (IQR 6 to 46 days); those who were not successful had a median of 46 days (IQR 25 to 74; median difference 18; 95% CI –21 to 64).

On posttrial questionnaire, most subjects reported the MCT as their preferred procedural technique (87% versus 13%; difference 74%; 95% CI 23% to 97%). Most subjects rated the MCT as easy or very easy to perform (60%) compared with only 20% of subjects with the LAT (difference 40%; 95% CI 15% to 65%). Anatomic exposure was also reported as adequate or very adequate by 100% of subjects with the MCT compared with only 40% with the LAT (difference 60%; 95% CI 35% to 85%). Comfort with tray setup was greatest for the MCT, with 67% of subjects reporting being comfortable or very comfortable compared with only 7% with the LAT (difference 60%; 95% CI 35% to 85%). Comfort with performance of the procedure did not differ, with 60% of subjects rating the MCT as comfortable or very comfortable and 53% reporting the LAT as comfortable or very comfortable (difference 7%; 95% CI –15% to 29%).

Table 1. Number of previous thoracotomies by type.

	LAT	MCT	Difference (95% CI)
Median simulated (IQR)	10 (6–12)	1 (1–1)	9 (6–11)
Median therapeutic (IQR)	1 (0–2)	0 (0–0)	1 (0–2)
Median total (IQR)	12 (6–15)	1 (1–1)	11 (7–12)

Differences reported are median of paired differences (95% CI) calculated as LAT minus MCT for each subject.

LIMITATIONS

Our study has several limitations. First, our sample size was small and may be underpowered to detect a clinically

Table 2. Comparison of outcomes of LAT and MCT trials.

	Left anterolateral thoracotomy	Modified clamshell thoracotomy	Difference (95% CI), %	Hazard Ratio (95% CI)
Success, No. (%)	6/15 (40)	10/15 (67)	−27 (−61 to 8)	–
Mean time to success (SD), min:s	6:06 (2:34)	6:18 (2:15)	–	0.5 (0.2 to 1.4)
Exposure of heart, No. (%)	11/15 (73)	13/15 (87)	−14 (−45 to 18)	–
Mean time to heart (SD), min:s	4:09 (1:31)	4:35 (1:57)	–	1.0 (0.5 to 2.3)
Cross-clamp aorta, No. (%)	9/15 (60)	12/15 (80)	−20 (−47 to 7)	–
Mean time to aorta (SD), min:s	6:37 (2:13)	6:15 (2:02)	–	0.7 (0.4 to 1.1)
Trials with all structures identified, No. (%)	6/15 (40)	10/15 (67)	−27 (−56 to 2)	–
Median percentage of structures identified (IQR)	87.5 (87.5 to 100)	100 (87.5 to 100)	0 (−9.5 to 2.8)	–
Trials with no iatrogenic injuries, No. (%)	0	5 (33)	−33 (−57 to −9)	–
Median number of injuries per trial (IQR)	1 (1 to 4)	1 (0 to 3)	1 (0 to 1)	–

Times are given only for participants who successfully completed the respective task; success times are given only for those who completed all tasks. Differences are paired (marginal) risk differences (95% CI) or median of paired differences (95% CI), calculated as LAT minus MCT for each subject. Hazard ratios (95% CIs) are given for paired time-to-event data (LAT versus MCT) and censored for failure.

significant difference in success and times. This was further limited by the low number of successful procedures. This was a pilot study limited by cadaver specimen availability and cost. Second, similar to previous studies, we used a human cadaver model that did not provide the benefits of live-tissue physiology and hemorrhage control.[3,13,15] Our model allowed only evaluation of periprocedural complications and could not assess long-term complications associated with either procedure. Also, cadavers were older than typical trauma patients and had preexisting thoracic pathology, which potentially increased procedural difficulty. A larger proportion of cadavers in LAT trials had presence of pathology. However, this did not meet statistical significance and structural pathology was similar in both groups. Preexisting investigator-performed finger thoracostomies meant for standardization also provided the correct anatomic site for initial skin incision, potentially decreasing procedural time and improving likelihood of success.

The adjudicating surgeon and timekeeper were not blinded to the study hypothesis or procedure. Potential self-reporting bias for time to successful exposure of the heart and time to successful cross clamping of the aorta would have minimal influence on results. Participants verbalized exposure of the heart and cross clamping of the aorta nearl simultaneously with success determined by the surgeon. If the subject verbalized successful delivery but did not fully expose the heart, the adjudicating surgeon determined the exposure was unsuccessful and the trial would have been considered unsuccessful during data analysis. The subject questionnaire was also not pilot tested and validated.

Our subject population may not be a representative sample. The subjects were recruited from a single military trauma center with frequent trauma procedure training, potentially increasing the success of the LAT and MCT techniques. We also performed an unplanned subgroup analysis of success by physician training level, and these results should be interpreted cautiously. Despite these limitations, our results support those of previous studies that found no difference in procedural times as well as evaluated the success in resuscitative thoracotomies performed by nonsurgical specialists.

Table 3. Comparison of reasons for trial failure.

	Left anterolateral thoracotomy	Modified clamshell thoracotomy	Difference (95% CI), %
Partial (<100%) aortic occlusion	3 (20)	1 (7)	13 (−15 to 42)
Failure to fully visualize heart	4 (27)	2 (13)	13 (−22 to 49)
Failure to fully visualize aorta	2 (13)	1 (7)	6 (−8 to 21)
Clamp placement error	3 (20)	3 (20)	0 (−30 to 30)

Data are presented as No. (%). Denominators represent total number of trials (n=15). Participants may have more than one reason for trial failure.

DISCUSSION

We found that success and procedure times for the LAT and MCT techniques were similar when comparisons included both resident and staff emergency physicians. However, the staff emergency physician cohort was significantly more successful with the MCT technique compared with the LAT technique. Emergency medicine resident physicians regularly perform resuscitative thoracotomies during the emergency medicine residency program's monthly live tissue procedure laboratory, whereas staff physicians have little opportunity for procedural practice or performance in the clinical setting. Resident emergency physicians' monthly resuscitative thoracotomy procedural practice includes LAT with conversion to clamshell and may translate to improved success with either resuscitative thoracotomy technique. We theorize that emergency medicine staff physicians, having fewer opportunities to practice, may be less confident and competent, and therefore benefit from a more simplified approach. Among both staff and resident emergency physicians, the MCT also resulted in fewer iatrogenic injuries and was preferred by the majority of our subjects. Our findings suggest that the MCT may be a feasible alternative thoracotomy technique for emergency physicians.

If the patient survives the MCT, a significant disadvantage is the morbidity rendered in a bilateral thoracotomy incision with sternal division in comparison to the isolated singular thoracotomy. Potential complications of clamshell with sternal division reported during lung transplant include sternal wound dehiscence, sternal instability, wound infection, and pain.[18] A LAT may still require conversion to a clamshell if appropriate exposure cannot be obtained. This study focused on addressing which surgical technique affords the optimal approach for a nonsurgeon to improve survivability. The noted morbidity that coincides with the MCT is necessary if this engenders survival benefit. However, the reduction in periprocedural iatrogenic injury may be associated with additional long-term complications in surviving patients.

Numerous retrospective and prospective reviews of the LAT have been published. Survival is highest in patients with penetrating thoracic injuries, with reports ranging from 10% to 30%. Survival for resuscitative thoracotomy after blunt thoracic injury is significantly lower, reported as less than 5%.[19-22] One large systematic review published the overall survival of this procedure as 7.4%, ranging from 2.5% to 27.5%.[19] Similarly, an American College of Surgeons meta-analysis reported a similar overall survival rate of 7.8%.[20] Comparatively, a 15-year retrospective review (1993 to 2008) of the MCT performed by London's Air Ambulance reported an 18% (13/71) survival to hospital discharge for patients with penetrating thoracic injuries.[12] Investigators concluded that when resuscitative thoracotomy is performed for the subgroup of patients described, significant numbers of survivors with good neurologic outcomes can be expected.[12]

Surgeons are the most qualified physicians to perform resuscitative thoracotomies; however, emergency physicians have a high likelihood of encountering patients requiring one. Current US emergency medicine residency training programs expose emergency medicine residents to resuscitative thoracotomy, but US graduate medical education guidelines do not have a minimum requirement. Training is heterogenous, with different levels of exposure and training models such as simulation, cadaver laboratories, live-tissue laboratories, and trauma rotations with surgical services. Our participants' experience ranged from as few as 3 to as many as 15 simulated LATs and between 0 and 3 therapeutic LATs before our study. Our population was also unique in that we recruited from a large military academic Level I trauma center with an emphasis on trauma resuscitation training.

Part of the perceived difficulty for nonsurgical specialists performing the LAT is that the standard thoracotomy tray found in many EDs has a bewildering array of equipment. When developing the MCT, clinicians at London's Air Ambulance incorporated human factors and specifically reduced the number of instruments in the MCT tray to those familiar to emergency physicians. Their justification for the reduction was that unfamiliar equipment can lead to confusion. They used familiar instruments that are in daily use by emergency physicians and envisioned the MCT as an extension of the familiar tube thoracostomy.[4,12,17] The thoracotomy tray setup is a significant component of each thoracotomy technique. We constructed the trays as they are in their current respective environment (US ED versus London's Air Ambulance Thoracotomy kit).[1,17]

We did not find a significant difference in time to successful procedure completion between the 2 techniques. Time to exposure of the heart and time to cross clamping of the aorta also did not differ. Flaris et al[3] similarly found no significant difference in procedural time with clamshell thoracotomy and LAT performed by surgery residents. Time from skin incision to placement of rib spreaders was 2.39 minutes with the LAT versus 2.33 minutes with the clamshell (P=.34), and total procedure time was 6.62 and 4.63 minutes, respectively (P=.46). However, time to repair of a standardized simulated right ventricle injury was significantly faster with the clamshell technique (4.16 and 1.85 minutes; P=.018).[3] Puchwein et al[13] measured time from skin incision to both hands on the heart with the

MCT performed by nonsurgeons, with mean times ranging from 2.15 to 3.38 minutes. Dumas et al[11] measured time from incision to pericardiotomy and aortic cross clamping in a large urban hospital ED resuscitation bay and reported median times of 2.35 and 3.71 minutes. Our times are slightly longer but include the time before opening of the surgical instrument tray and time required to fully inspect and visualize for any injuries. Because the focus of our study was the resuscitative thoracotomy technique, our cadaver model also had an investigator-completed finger thoracostomy before data collection to ensure standardization and simulate the procedural starting point outlined in London's Air Ambulance's protocol. A direct comparison cannot be performed because of the difference in subject population and study methodology.

The combined overall success of both resuscitative thoracotomy procedures was 53.3% (16/30). The overall poor success may be attributable to requiring 100% aortic occlusion for successful clamp placement. It is unclear whether a partially occluded aorta may provide clinical benefit. Procedure failure in our population was most likely due to failure to properly occlude the aorta (6/9 LAT failures versus 3/5 MCT failures) (Table 3). Simms et al[15] demonstrated that the MCT provides better exposure and access to the aorta than an LAT approach and supports our findings of more failed aortic occlusions with the LAT. All subjects reported that the MCT provided an adequate or very adequate view, whereas only 40% reported the view was adequate or very adequate with the LAT.

We found a significant difference in the occurrence of iatrogenic injuries between the LAT and MCT. Iatrogenic injuries occurred in all LAT trials, whereas 5 MCT trials were without iatrogenic injury (Table 2). The most common injury among both trials was fractured ribs. There were 5 heart lacerations in the LAT trial and 2 in the MCT trial. The heart lacerations were attributed to previous pericardial adhesions and in one case an operator's not recognizing previous pericardiectomy. The MCT trial had the only stomach injury as a result of a paraesophageal hernia that was unrecognized by the operator. The MCT trial had 2 diaphragm lacerations, likely from aggressive opening of the chest cavity. Puchwein et al[13] reported similar results, with 28% of trials having iatrogenic injuries: 3 cases with ventricular lacerations that occurred with incision of the pericardium and 1 case of a phrenic nerve injury.

Most of our subjects preferred the MCT to the LAT technique. Reported ease of performance, anatomic exposure, and comfort with tray setup were all superior with the MCT. Simms et al[15] also reported improved anatomic exposure with the clamshell approach compared with the LAT. The MCT equipment tray simplification addresses human factors in procedure performance, using familiar equipment and limiting confusion.[4]

Our study was limited to a laboratory setting. Ideally, future work would compare the LAT and MCT techniques in a clinical setting. However, a prospective randomized controlled trial would be financially and logistically prohibitive.[2,5,7,11] Therefore, further prospective studies should compare the LAT and MCT in a live-tissue large-animal model to simulate live physiology and evaluate hemorrhage control. The procedural success was also lower than anticipated, given the capable subject population, and suggests that further evaluation is needed to identify the shortcomings in procedural training, maintenance of competency, and performance. The ideal equipment to be used in an ED and out-of-hospital setting is unclear and should be evaluated in future work.

Overall, resuscitative thoracotomy success was lower than expected in our population. The MCT technique did not differ from the LAT technique regarding procedural success and procedural time when performed by nonsurgical specialists in this cadaver model. For emergency medicine staff–performed trials, the MCT technique was more successful than the LAT technique; however, a sufficiently powered study is required to determine whether statistical significance remains and whether this difference is clinically relevant. The MCT also resulted in fewer periprocedural iatrogenic injuries, was preferred by our study population, had improved anatomic exposure, increased ease of performance, and had superior equipment comfort. This pilot study of the MCT technique warrants further consideration but these findings cannot be directly extrapolated to the clinical setting. For nonsurgical specialists, the MCT is a feasible alternative resuscitative thoracotomy technique that requires further investigation. Future development should focus on identifying gaps in procedural training, maintenance of competency, procedural performance, and standardization of a simplified instrument tray.

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