European Journal of Trauma and Emergency Surgery (2019) 45:231–243
https://doi.org/10.1007/s00068-018-0982-z

REVIEW ARTICLE

A systematic review of 3251 emergency department thoracotomies: is it time for a national database?

Edward John Nevins[1] · Nicholas Thomas Edward Bird[1] · Hassan Zakria Malik[2,3] · Simon Jude Mercer[2,4] · Khalid Shahzad[1,2] · Raimundas Lunevicius[1,2] · John Vincent Taylor[1,2] · Nikhil Misra[1,2]

Received: 15 April 2018 / Accepted: 10 July 2018 / Published online: 14 July 2018

Abstract

Purpose Emergency department thoracotomy (EDT) is a potentially life-saving procedure, performed on patients suffering traumatic cardiac arrest. Multiple indications have been reported, but overall survival remains unclear for each indication. The objective of this systematic review is to determine overall survival, survival stratified by indication, and survival stratified by geographical location for patients undergoing EDT across the world.

Methods Articles published between 2000 and 2016 were identified which detailed outcomes from EDT. All articles referring to pre-hospital, delayed, or operating room thoracotomy were excluded. Pooled odds ratios (OR) were calculated comparing differing indications.

Results Thirty-seven articles, containing 3251 patients who underwent EDT, were identified. There were 277 (8.5%) survivors. OR demonstrate improved survival for; penetrating vs blunt trauma (OR 2.10; p 0.0028); stab vs gun-shot (OR 5.45; $p < 0.0001$); signs of life (SOL) on admission vs no SOL (OR 5.36; $p < 0.0001$); and SOL in the field vs no SOL (OR 19.39; $p < 0.0001$). Equivalence of survival was demonstrated between cardiothoracic vs non-cardiothoracic injury (OR 1.038; p 1.000). Survival was worse for USA vs non-USA cohorts (OR 1.59; p 0.0012).

Conclusions Penetrating injury remains a robust indication for EDT. Non-cardiothoracic cause of cardiac arrest should not preclude EDT. In the absence of on scene SOL, survival following EDT is extremely unlikely. Survival is significantly higher in the non-USA publications; reasons for this are highly complex. A UK multicentre prospective study which collects standardised data on all EDTs could provide robust evidence for better patient stratification.

Keywords Emergency department thoracotomy · Traumatic cardiac arrest · Indications · Outcome · Survival

Introduction

Emergency department thoracotomy (EDT) is a controversial, potentially life-saving procedure. The development of closed chest cardio-pulmonary resuscitation (CPR) protocols, inotropic pharmaco-therapeutics, and the advent of cardiac defibrillators has produced a reduction in the indications for open chest CPR. Currently the only accepted indication for EDT in any clinical setting, is for patients suffering cardio-pulmonary arrest secondary to trauma, or severe refractory hypotension secondary to trauma [1–3].

The cardiac rhythm for most patients sustaining traumatic cardiac arrest is pulseless electrical activity (PEA). It is therefore often a low cardiac output state, resulting in no palpable pulse, rather than true cardiac standstill [4]. For this reason, it is accepted that the single intervention which will result in good neurological outcome following traumatic cardiac arrest secondary to penetrating trauma is EDT [5]. EDT has now also been adopted in the setting of blunt trauma, but outcomes are less successful [1–4, 6].

The primary objective of EDT is to control and maintain perfusion to the cardio-respiratory and central nervous system. This can be achieved by the relief of tension

✉ Edward John Nevins
dr.e.nevins@gmail.com

1 Emergency General Surgery and Trauma Unit, University Hospital Aintree, Longmoor Lane, Liverpool L9 7AL, UK

2 Liverpool Medical School, University of Liverpool, Liverpool, UK

3 North West Hepatobiliary Unit, University Hospital Aintree, Longmoor Lane, Liverpool L9 7AL, UK

4 Department of Anaesthesia, University Hospital Aintree, Longmoor Lane, Liverpool L9 7AL, UK

pneumothorax, pericardiotomy for the relief of tamponade and cessation of cardiac haemorrhage, control of thoracic exsanguination, open cardiac massage, expulsion of massive air embolism, and temporary occlusion of the descending thoracic aorta for control of sub-diaphragmatic haemorrhage and redistribution of blood to supra-diaphragmatic organs [2, 3, 7].

There is extensive debate regarding the exact contraindications for EDT. Authors have disputed the accepted length of time without signs of life (SOL), anatomical location of major injury and mechanism of injury which should preclude EDT [1–3]. Rationalisation of indication for this procedure is required to reduce inappropriate performance of EDT on patients unlikely to survive to discharge. The objective of this article is to systematically review the recently published EDT data by:

1. Defining the overall survival of EDT for all indications.
2. Defining overall survival of EDT stratified by indication (specifically penetrating vs blunt trauma, anatomical location of major injury, and SOL vs no SOL).
3. Defining overall survival of EDT stratified by geographical location.
4. Defining neurological outcome following EDT.

Methods

Search strategy

Meta-analysis of Observational Studies (MOOSE) guidelines were used to identify eligible studies. Exploded and linked search terms were used on MEDLINE, PUBMED and EMBASE search engines to ensure adequate acquisition of articles. The search terms employed were "emergency", "thoracotomy", "cardiac", "arrest", "resuscitation", "trauma", "penetrating", and "blunt". Only articles published in English between January 2000 and July 2016 were included, all pre-2000 cohorts were considered historical series. The reference lists of all relevant articles were then analysed to identify any publications which were not previously found during the electronic database search.

Inclusion and exclusion criteria

All articles that were not published in the English language were excluded. All review articles and all abstracts were excluded. Publications were excluded if they did not report data specific to EDT. EDT was defined as thoracotomy which was performed in the emergency department or in a specific trauma resuscitation room, immediately after the patients' arrival to hospital. Publications reporting both EDT and urgent thoracotomy or non-urgent thoracotomy as a homogenous group were excluded. Pre-hospital thoracotomy cohorts were also excluded. Thoracotomy undertaken in the operating room were also excluded as the literature supports favourable outcomes if thoracotomy is performed in the operating room compared to the emergency department; we believe that this is because these patients are likely to have less severe injury, have likely had time for optimum monitoring to be in place, and operating room conditions are usually better than that of the emergency department, for this reason they should not be compared directly. Publications were excluded if insufficient overall survival data were available. Articles using previously published data from identical cohorts were excluded to avoid replication of data and multiplicity error.

Data extraction and analysis

End-points assessed were: total number of EDT survivors; mechanism of injury; location of major injury; SOL in the emergency room; SOL in the field; survival data and neurological sequelae. SOL was defined as any recordable vital signs (pulse, blood pressure, and respiratory rate), electrical cardiac activity on ECG, pupillary response, spontaneous ventilation, or movement of extremity. Survival was defined as either survival at discharge from hospital, or 30- or 28-day survival, highlighting the variation in reported outcomes.

Univariate pooled odds ratios (OR) for outcomes were produced using Chi-squared contingency tables. Only p values below 0.05 were considered significant. Statistical analysis was undertaken using GraphPad Prism 7.0.

Results

Thirty-seven publications met our inclusion criteria. Reason for excluded publications can be seen in Fig. 1. The cumulative number of EDTs performed was 3251 with 277 survivors, producing a total survival rate of 8.5% (range 0–50%). The median number of EDTs performed was 53 (range 4–959). All publications had significantly more males who underwent EDTs (1214/1369, $p < 0.0001$), and average age was less than 44 years where reported (see Table 1).

Twenty-eight papers differentiated between penetrating and blunt trauma. There were 1721 EDTs performed for penetrating trauma with 178 survivors (survival rate; 10.3%). There were 365 EDTs for blunt trauma with 19 survivors (survival rate; 5.2%). Univariate analysis demonstrates an OR of survival for penetrating vs blunt injury of 2.10 ($p = 0.0028$). Patients are therefore more likely to survive EDT following penetrating injury.

Fifteen publications were used to compare between stab wound and gun-shot wound. 250 EDTs were performed for stabbings resulting in 59 survivors (survival rate; 23.6%). In

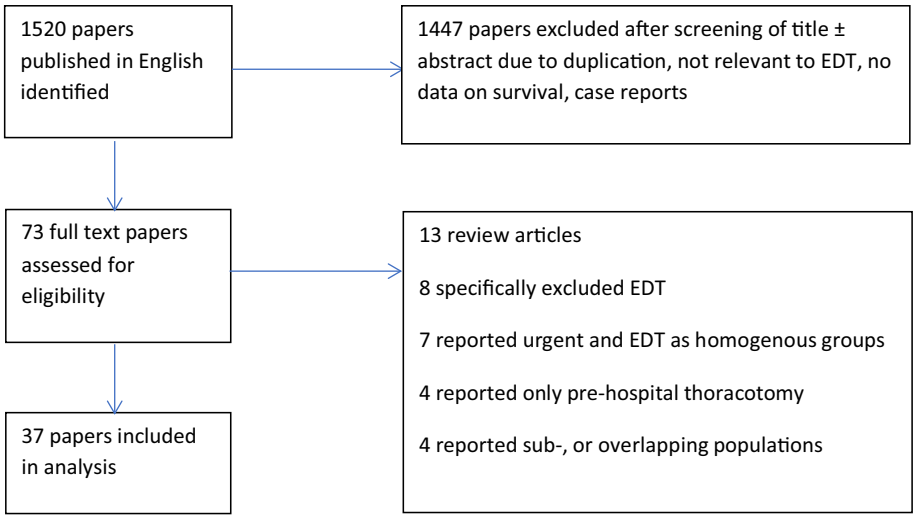

Fig. 1 PRISMA diagram demonstrating included papers

total, there were 839 performed for gun-shot victims with 45 survivors (survival rate; 5.4%) producing an OR of survival for stabbings vs gun-shot wounds of 5.45 ($p < 0.0001$) (see Table 2).

Fourteen papers reviewed anatomical location of major injury. One thousand and sixty-five EDTs were performed with 112 survivors (survival rate; 10.5%). Nine hundred and sixty-seven patients had EDT performed for primary cardiothoracic injury, resulting in 102 survivors (survival rate; 10.5%). Ninety-eight EDTs were performed for non-cardiothoracic injuries with 10 survivors (survival rate; 10.2%) producing an OR of 1.038 ($p = 1.0000$) (see Table 3).

Sixteen papers reported on SOL on arrival to the emergency department. Five hundred and sixty-one patients had EDTs with recorded SOL on arrival to hospital, in this group, 82 patients survived (survival rate; 14.6%). Five hundred and seventeen patients had no SOL on arrival to hospital and 16 patients survived (survival rate; 3.1%). Therefore, the odds of surviving EDT if the patient has SOL on arrival is 5.36 ($p < 0.0001$) when compared to no SOL on arrival to EDT. Nine papers reported on SOL in the field. Fifty-two of 288 patients with SOL in the field survived (survival rate; 18.1%), compared to 1 patient of 89 without SOL in the field (survival rate; 1.1%) producing an OR of 19.39 ($p < 0.0001$) (see Table 4).

There was an all-cause survival rate of 7.7% (199/2585) in 20 studies from USA, compared to 11.7% (78/666) all-cause survival rate in 17 publications from outside of the USA. The all-cause OR of surviving non-USA EDT compared to USA EDT was 1.59 ($p = 0.0012$). Sub-group analysis demonstrated that publications from the USA had a significantly higher proportion of penetrating injury (1393/1507, 92.4%) compared to the non-USA (270/483, 55.9%). The survival of patients with penetrating injury was worse in the USA (130/1393, 9.3%) compared to non-USA (45/270, 16.7%), ($p = 0.0007$, OR 1.94). In patients undergoing EDT for blunt injury there was a trend for worse survival of patients in USA compared to the non-USA cohort, although the difference was not statistically significant, 3.5% (4/114) vs 7.0% (15/213), respectively ($p = 0.2244$, OR 2.08).

18 publications reported outcomes of 144 patients who had survived EDT, 112 (77.8%) were neurologically intact. Neurological disability varied amongst survivors with some reporting mild cognitive deficit, and others reporting profound physical and mental disability (see Table 5).

Discussion

This review and quantitative analysis had demonstrated that different indications produce significantly different outcomes for patients undergoing EDT. Pooled odds ratios demonstrate improved survival for; penetrating vs blunt indication (OR 2.10; p 0.0028); stab wound vs gun-shot wound indication (OR 5.45; $p < 0.0001$); SOL on admission vs no SOL indication (OR 5.36; $p < 0.0001$); SOL in the field vs no SOL in the field indication (OR 19.39; $p < 0.0001$). Equivalence was demonstrated between cardiothoracic vs non-cardiothoracic indication (OR 1.038; p 1.000). Survival was significantly worse for USA vs non-USA patients (OR 1.59; p 0.0012), the reasons for this are highly complex and multifactorial.

Trauma remains the most common cause of death in the population aged less than 35 [45, 46]. Globally the number of moribund patients arriving at the emergency department is increasing, possibly due to improved trauma protocols and advances in rapid transport networks which enable prompt transfer of critically injured patients to dedicated Major Trauma Centres [2, 3, 5, 47]. EDT may become an increasingly important component in the treatment of the traumatically injured patient who previously would have died en route to hospital.

Table 1 Survival rates for EDT

Author	Year	Location	EDT performed (*n*)	Males (*n*)	Age (mean)	Survivors (*n*)	Survival rate (%)
Powell et al. [8]	2004	Denver, USA	959	–	–	62	6.5
Seamon et al. [9]	2009	Philadelphia, USA	283	272	27.1	15	5.3
Tyburski et al. [10]	2000	Detroit, USA	152	–	–	12	7.9
Karmy-Jones et al. [11]	2004	Washington, USA	125	–	–	25	20.0
Passos et al. [12]	2012	Toronto, Canada	123	105	30	3	2.4
Mollberg et al. [13]	2011	California, USA	120	112	28.2	7	5.8
Pahle et al. [14]	2010	Oslo, Norway	109	75	30	20	18.4
Schnüriger et al. [15]	2012	California, USA	108	–	–	3	2.8
Kennedy et al. [16]	2000	California, USA	102	–	–	7	6.9
Gomez et al. [17]	2010	Indiana USA	102	97	32	8	7.8
Edens et al. [18]	2009	Iraq	101	96	25.6	12	11.9
Okoye et al. [19]	2013	California, USA	97	–	–	8	8.3
Molina et al. [20]	2008	Philadelphia, USA	94	89	28.4	8	8.5
Capote et al. [21]	2013	California, USA	87	75	30.9	13	14.9
Ladd et al. [22]	2002	Indiana, USA	79	69	–	2	2.5
Huber-Wagner et al. [23]	2007	Germany	77	–	–	10	13.0
Rabinovici et al. [24]	2014	Boston, USA	67	56	38	9	13.4
Paydar et al. [25]	2014	Iran	58	50	43.3	1	1.7
Berg et al. [26]	2012	California, USA	53	–	–	2	3.8
Asensio et al. [27]	2002	California, USA	51	–	–	3	5.9
Lustenberger et al. [28]	2012	Zurich, Switzerland	49	38	39	10	20.4
Aihara et al. [29]	2001	Boston, USA	49	–	–	10	20.4
Matsumoto et al. [30]	2009	Chiba, Japan	47	36	–	0	0.0
Sheppard et al. [31]	2006	Denver, USA	27	–	–	3	11.1
Kaljusto et al. [32]	2015	Oslo, Norway	21	–	–	4	19.1
Kandler et al. [33]	2012	Denmark	21	17	40	7	33.3
Burack et al. [34]	2007	New York, USA	13	–	–	2	15.4
Cawich et al. [35]	2007	Jamaica	13	13	32.6	1	7.7
Van Waes et al. [36]	2012	Netherlands	12	10	32	3	25.0
Huerta et al. [37]	2006	Dallas, USA	11	–	–	0	0.0
Alanezi et al. [38]	2002	Ontario, Canada	10	–	–	1	10.0
Martin et al. [39]	2002	California, USA	6	–	–	0	0.0
Balkan et al. [40]	2002	Ankara, Turkey	6	–	–	1	16.7
Ferris et al. [41]	2008	Edinburgh, UK	6	–	–	1	16.7
Soreide et al. [42]	2007	Stavanger, Norway	5	–	–	0	0.0
Johannesdottir et al. [43]	2013	Reykjavik, Iceland	4	4	39.8	2	50.0
Morrison et al. [44]	2011	Afghanistan	4	–	–	2	50.0
Total			3251	–	–	277	8.5

There are, however a number of health and socio-economic implications associated with this procedure. EDT is high-risk for the patient and any healthcare practitioners involved. Risk of transmission of blood borne disease is significant, possibly due to the lack of personal protection used in the emergency department scenario, and the large volumes of blood involved [7, 46, 48–50]. EDT also harbours a high financial cost. Costs of up to $7200 for each EDT have been reported [51–54], and historic estimations predicted that the cost of EDT per neurologically intact survivor to range between $93,175–$109,025 [51, 53, 55]. In addition to the fiscal barriers, EDT results in high emotional cost to both patients, relatives, and healthcare providers [3, 8, 12, 48, 53, 56, 57]. Conversely, not performing EDT harbours emotional cost with healthcare providers questioning if they had performed EDT could the patient have survived? Poorly selected EDT may also prolong life without meaningful neurological recovery [58,

Table 2 Survival rates for EDT performed for penetrating and blunt trauma, stab wounds and gun-shot wounds

Author	Penetrating			Blunt			Stab wound			Gun-shot wound		
	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)
Seamon et al. [9]	283	15	5.3	–	–	–	33	8	24.2	250	7	2.8
Tyburski et al. [10]	152	12	7.9	–	–	–	59	12	20.3	93	0	0.0
Karmy-Jones et al. [11]	125	25	20.0	–	–	–	39	16	41.0	86	9	10.5
Passos et al. [12]	96	3	3.1	27	0	0.0	27	2	7.4	33	1	3.0
Mollberg et al. [13]	120	7	5.8	–	–	–	–	–	–	–	–	–
Pahle et al. [14]	27	10	37.0	82	10	12.2	–	–	–	–	–	–
Schnüriger et al. [15]	58	3	19.3	38	0	0.0	16	3	18.8	42	0	0.0
Kennedy et al. [16]	94	7	7.5	8	0	0.0	–	–	–	–	–	–
Gomez et al. [17]	102	8	7.8	–	–	–	–	–	–	–	–	–
Edens et al. [18]	94	12	12.8	7	0	0.0	–	–	–	42	5	11.9
Okoye et al. [19]	97	8	8.3	–	–	–	–	–	–	97	8	8.3
Molina et al. [20]	94	8	8.5	–	–	–	12	4	33.3	82	4	4.9
Capote et al. [21]	59	11	18.6	28	2	7.1	–	–	–	–	–	–
Ladd et al. [22]	79	2	2.5	–	–	–	14	0	0.0	65	2	3.1
Rabinovici et al. [24]	50	9	18.0	17	0	0.0	36	8	22.2	14	1	7.1
Berg et al. [26]	–	–	–	53	2	3.8	–	–	–	–	–	–
Asensio et al. [27]	51	3	5.9	–	–	–	–	–	–	–	–	–
Lustenberger et al. [28]	10	7	70.0	39	3	7.7	5	3	60.0	4	4	100.0
Aihara et al. [29]	47	10	21.3	2	0	0.0	–	–	–	–	–	–
Matsumoto et al. [30]	–	–	–	47	0	0.0	–	–	–	–	–	–
Sheppard et al. [31]	27	3	11.1	–	–	–	3	1	33.3	17	1	5.9
Kandler et al. [33]	11	5	45.5	10	2	20.0	–	–	–	–	–	–
Burack et al. [34]	13	2	15.4	–	–	–	–	–	–	–	–	–
Cawich et al. [35]	13	1	7.7	–	–	–	5	1	20.0	8	0	0.0
Van Waes et al. [36]	12	3	25.0	–	–	–	–	–	–	–	–	–
Martin et al. [39]	–	–	–	6	0	0.0	–	–	–	–	–	–
Johannesdottir et al. [43]	3	2	66.7	1	0	0.0	1	1	100.0	2	1	50.0
Morrison et al. [44]	4	2	50.0	–	–	–	–	–	–	4	2	50.0
Total	1721	178	10.3	365	19	5.2	250	59	23.6	839	45	5.4

Table 3 Survival rates of EDT comparing cardiothoracic and non-cardiothoracic injury

Author	Cardiothoracic injury			Non-cardiothoracic injury		
	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)
Seamon et al. [9]	207	12	5.8	–	–	–
Tyburski et al. [10]	152	12	7.9	–	–	–
Karmy-Jones et al. [11]	125	25	20.0	–	–	–
Mollberg et al. [13]	120	7	5.8	–	–	–
Edens et al. [18]	40	6	15.0	54	6	11.1
Okoye et al. [19]	97	8	8.3	–	–	–
Molina et al. [20]	94	8	8.5	–	–	–
Rabinovici et al. [24]	50	8	16.0	17	1	5.9
Aihara et al. [29]	49	10	20.4	–	–	–
Sheppard et al. [31]	–	–	–	27	3	11.1
Cawich et al. [35]	9	1	11.1	–	–	–
Van Waes et al. [36]	12	3	25.0	–	–	–
Alanezi et al. [38]	10	1	10.0	–	–	–
Johannesdottir et al. [43]	2	1	50.0	–	–	–
Total	967	102	10.5	98	10	10.2

59]. Therefore, trauma teams have a duty to ensure that EDT is not performed in futile situations.

In the present data, there is an overall survival rate for EDT of 8.5%, between 2000 and 2016 with survival ranging between 0 and 50%. This variation is likely to reflect selection biases when performing this procedure, variation in surgical technique and decision-making, or variation in case-mix, with certain centres receiving a higher proportion of patients with more complex injuries. The American College of Surgeons (ACS) paper reporting cases between 1974 and 1998, concluded that overall survival of EDT was 7.8% [58], and a comprehensive review by Rhee and co-workers, reporting cases between the same dates, demonstrated an overall survival rate of 7.4% [2]. These are comparable to the current findings; unfortunately, despite modernisation of services and improvements in intensive care support, overall survival rates for these patients have not significantly changed.

Mechanism of injury

The 2001 review by The ACS and the 2000 meta-analysis by Rhee et al. stated that survival rates for blunt trauma were only 1.6 and 1.4%, respectively [2, 58]. In light of this, in 2007, Brown and colleagues demonstrated that EDTs were only cost effective if performed following penetrating trauma [59]. Moreover, guidelines published in 2003 by The ACS 'Committee On Trauma' state that EDT does not appear to have a role in traumatic cardio-pulmonary arrest due to blunt trauma [60, 61]. However, in the present review, survival of EDT following blunt injury has modestly improved (5.2%) compared to these sources. Re-consideration of these guidelines may now be appropriate in light of these findings.

The Eastern Association for the Surgery of Trauma are in agreement with this, they conditionally recommend EDT for patients who present with SOL to the emergency department following blunt injury, but not in those without SOL [1]. Slessor and Hunter's review of EDT following blunt trauma demonstrated survivors of EDT with 15 min of cardiac arrest, but again conclude that EDT should not be performed if there are no SOL at scene, or prolonged CPR or obvious head injury that is incompatible with good outcome [6]. It is likely that during blunt trauma, resulting in cardio-pulmonary arrest, the initial cardiac rhythm is ventricular fibrillation, this results in distention of the myocardium. Surgical experience with cardio-pulmonary bypass suggests that when the myocardium is fibrillating and distended, restarting the heart is unlikely. With a penetrating cardiac injury, the myocardium will not distent; this may be at least one of the reasons why blunt trauma survival rates are worse [62].

The meta-analysis by Rhee and co-workers, reported 16.8% survival in patients undergoing EDT due to stabbing, but only 4.3% in patients with EDTs following gun-shot wounds [2]. In the present analysis it is demonstrated that survival following EDT for both mechanisms of penetrating injury have modestly improved, 23.6 and 5.4%, respectively. This improved survival trend was highlighted by Seamon and colleagues who reviewed 283 patients with EDT for penetrating cardiac or great vessel injury. The authors demonstrated that the chance of survival was 11 times greater in patients with stab wounds compared to gun-shot wounds [9].

Table 4 Survival rates of EDT performed for patients with and without SOL on arrival to hospital, and in the field

Author	SOL on arrival to hospital			No SOL on arrival to hospital			SOL in field			No SOL in filed		
	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)	EDT performed (*n*)	Survivors (*n*)	Survival rate (%)
Seamon et al. [9]	176	10	5.6	107	5	4.7	–	–	–	–	–	–
Tyburski et al. [10]	42	9	21.4	110	3	2.7	–	–	–	–	–	–
Karmy-Jones et al. [11]	24	8	33.3	62	1	1.6	–	–	–	–	–	–
Pahle et al. [14]	–	–	–	–	–	–	86	19	22.1	21	1	4.8
Schnüriger et al. [15]	41	3	7.3	50	0	0.0	–	–	–	28	0	0.0
Edens et al. [18]	82	11	13.4	18	1	5.6	–	–	–	–	–	–
Molina et al. [20]	15	5	33.3	79	3	3.8	56	8	14.3	–	–	–
Ladd et al. [22]	47	2	4.3	28	0	0.0	70	2	2.9	3	0	0.0
Rabinovici et al. [24]	57	9	15.8	10	0	0.0	–	–	–	–	–	–
Lustenberger et al. [28]	33	9	27.3	16	1	6.3	46	10	21.7	–	–	–
Aihara et al. [29]	–	–	–	–	–	–	21	10	47.6	28	0	0.0
Kaljusto et al. [32]	3	3	100.0	18	1	5.6	–	–	–	8	0	0.0
Kandler et al. [33]	19	6	31.6	2	1	50.0	–	–	–	–	–	–
Cawich et al. [35]	9	1	11.1	2	0	0.0	–	–	–	–	–	–
Van Waes et al. [36]	7	3	42.9	5	0	0.0	–	–	–	–	–	–
Martin et al. [39]	3	0	0.0	3	0	0.0	–	–	–	–	–	–
Ferris et al. [41]	1	1	100.0	5	0	0.0	6	1	16.7	–	–	–
Johannesdottir et al. [43]	2	2	100.0	2	0	0.0	3	2	66.7	1	0	0.0
Total	561	82	14.6	517	16	3.1	288	52	18.1	89	1	1.1

SOL signs of life

Table 5 Neurological sequelae following EDT

Author	Neurological outcome in survivors		
	Normal neurology (*n*)	Abnormal neurology (*n*)	Neurologically intact (%)
Powell et al. [8]	15	11	57.7
Seamon et al. [9]	13	2	86.7
Passos et al. [12]	2	1	66.7
Mollberg et al. [13]	6	1	85.7
Pahle et al. [14]	18	2	90.0
Schnüriger et al. [15]	2	1	66.7
Kennedy et al. [16]	5	2	71.4
Gomez et al. [17]	5	2	71.4
Edens et al. [18]	6	0	100.0
Molina et al. [20]	8	0	100.0
Capote et al. [21]	11	2	84.6
Ladd et al. [22]	1	1	50.0
Rabinovici et al. [24]	7	2	77.8
Aihara et al. [29]	7	3	70.0
Sheppard et al. [31]	2	1	66.7
Cawich et al. [35]	0	1	0.0
Van Waes et al. [36]	3	0	100.0
Ferris et al. [41]	1	0	100.0
Total	112	32	77.8

The modality of penetrating injury should therefore be a primary consideration for the physician in stratifying a patient for EDT. Given the albeit improving but continuously dismal survival rates for gun-shot wounds, patients sustaining penetrating injury should not be viewed as a homogenous group. In particular, it is clear that stab wounds to the heart are likely to result in anterior right ventricular wounds which are relatively easy to control compared to through and through cardiac injuries resulting from gun-shot wounds, where the posterior wound is often difficult to control [63].

Location of major injury

It has been previously demonstrated that survival of EDT was best if the injury was predominantly cardiac, when compared to thoracic, abdominal or multiple injury locations (19.4, 10.7, 4.5, 0.7%, respectively) [2]. Typically the highest survival rates for EDT were for patients with penetrating cardiac injury, in the particular setting of cardiac tamponade [2, 3]. The ACS review reported excellent survival rates of 31.1% in 1165 patients who underwent EDT for penetrating cardiac injury [58]. The authors of the present study believe that at the time of patient presentation it is difficult to diagnose isolated cardiac injuries to aid in decision-making as to whether to perform EDT. In the arrested patient, the surgeon is likely to perform the EDT on the basis that there is suspicion of cardiac injury.

The use of ultrasound has been advocated to aid decision-making when performing EDT. It can be used quickly in patients in PEA to identify those with cardiac motion, these patients are much more likely to survive traumatic cardiac arrest with rapid transfusion and EDT to stem haemorrhage [4, 64]. ECG has also been suggested as a useful tool to predict survivors, patients with ECG evidence of asystole in traumatic cardiac arrest inevitably expire [64]. Both of these measures, however, may be time consuming.

The present analysis has not demonstrated a significant difference in survival rates between the cardiothoracic or non-cardiothoracic indication for EDT. Accordingly, non-cardiothoracic cause for traumatic arrest should not preclude EDT. Interestingly, there were a few survivors following EDT with head and neck injuries [18, 31], although we would not advocate EDT if significant head injury is present.

Signs of life

In the present analysis, it has been demonstrated that patients with SOL on arrival to hospital are 5.36 times more likely to survive EDT than patients without SOL in the emergency department. Authors have argued that EDT should not be performed in patients who do not have SOL when paramedics arrive at the scene [15, 16, 22, 29, 32, 60]. However, Rhee and colleagues demonstrated rate of survival of 1.2% if there were no SOL in the field [2]. Multiple additional publications have demonstrated survival without SOL on scene [8, 65]. Powell and colleagues had four patients who sustained blunt trauma, loss of SOL in the field, and whom subsequently survived to discharge; however, all had severe neurological disability [8]. As there are a small number of documented survivors in this scenario, it is possible that patients who loose SOL have a "golden period" where EDT is beneficial. Unfortunately, the time-dependent nature in this specific scenario is yet to be defined.

In the present analysis only one patient survived without SOL recorded in the field [14]. Patients in this scenario are therefore 19.39 times less likely to survive EDT than patients with recorded SOL in the field. Given these dismal odds of survival, we believe that loss of SOL in the field should be utilised to stratify patients to non-operative treatment and be declared dead at scene. That is, unless expertise for immediate pre-hospital thoracotomy is available [66].

Geographical location of EDT

The majority of the evidence regarding EDT comes from the USA. The present analysis has demonstrated that survival of EDT is greater outside of the USA when compared to USA EDTs. The difference for this is multifactorial. This

may reflect the differing trauma epidemiology between USA and the non-USA populations. In the USA, there are some regions where 5% of African-American males are fatally stabbed or shot before the age of 30, whereas there are fewer than 200 fatal gun-shot or stab wound injuries per year in England and Wales [7]. Although penetrating violent crime is on the rise in Europe [33], penetrating injuries cause only 5–10% of the traumatic cardiac arrests compared to 30–50% in the USA [36].

In this analysis, there was a significantly greater proportion of EDT performed for penetrating trauma in the USA cohort (92.4 vs 55.9%), which theoretically should favour improved USA outcomes. However, this does not take into account the severity of injury, differing trauma mechanisms, access to health care, transport times, and training and techniques employed by pre-hospital technicians. In addition, a proportion of penetrating injury in the USA is likely to result from military assault rifles and high-calibre hand guns which are available for sale to the public; this type of weapon is unlikely to be used outside the military setting in the rest of the world.

This variation in survival rates may mean that the abundance of data from the USA, which historically has been used to make decision algorithms for EDT, may lack applicability to the rest of the world. In light of this, we would remind trauma teams that treatment algorithms produced elsewhere should be used with caution.

Future direction of EDT

Historic reviews, and large cohorts of USA populations were used to produce decision-making algorithms for EDT [2, 8, 52, 56, 58]. Despite the introduction of algorithms and protocols, there still remains great variation in surgical decision-making in EDT globally [67, 68]. This is possibly due to the trauma team performing EDT in a futile attempt at sustaining life. Mollberg and co-workers demonstrated that when the EDT is performed with adherence to specified guidelines survival improves from 5.8 to 8.6% [13].

Although guidelines improve survival rates, they must be locally or regionally produced with reference to specific geographical, logistical and socio-economic considerations, they should not be indiscriminately applied to all populations. It has been demonstrated that blunt trauma is more survivable, especially in Europe, than previously believed. The authors suggest that a nationalised audit tool applicable to UK populations should be introduced by the UK Trauma Network. This audit should take as a template the epidemiological and logistical considerations utilised in the NELA audit to produce a prospectively collected dataset of all EDTs undertaken in the UK [69]. This would provide robust co-ordinated population data which could enable production of contemporaneous guidelines and protocols specifically for the UK population.

Neurological outcomes

Arguably survival should not be considered the only important outcome measure; neurologically intact survival is more important. In the meta-analysis by Rhee et al. 92.4% of survivors of EDT had normal neurological outcome [2]. However, the ACS review demonstrated that 15% of patients had neurological sequale [58]. Here, the pooled results have demonstrated that 22.2% of patients who survive have some neurological deficit. This increasing trend in neurologically damaged survivors is concerning, although it may reflect that the modern day literature reports subtle neurological deficits. For example, Seamon et al. reported that 74% of survivors reported long-term social, cognitive, functional or psychological impairment after EDT [70]. Unemployment, alcoholism and drug abuse is also common post-EDT [71]. This being said, it is impossible to define what level of neurological deficit should define an EDT as a failure.

Interestingly, Powell et al. reported good neurological outcomes in 81% of patients who required pre-hospital CPR prior to EDT [8]. Therefore, good neurological outcome should not only be expected in patients who have EDT immediately after cardiac arrest. Furthermore, patients with poor neurological outcome should not necessarily define EDT as a failure. Schnüriger et al. demonstrated that in 263 EDT, there were 11 patients who could have become potential organ donors, but only 3 did. Further data are required to analyse the benefit of patients undergoing EDT for organ donation purpose [15].

Military evidence

There have been four articles regarding traumatic cardiac arrest and thoracotomy from military populations from recent conflicts in the Middle East [18, 44, 64, 72]. Data from two of these articles have been excluded in the present review as they report both survival data for EDT and operating room thoracotomy as homogenous groups (see exclusion criteria) [64, 72].

Military trauma differs from civilian trauma, there is a predominance of blast and high-energy ballistic injury, multiple extra-thoracic injuries, often with more extensive wound contamination and tissue destruction [73]. Despite this, the largest military experience of EDT by Edens et al. demonstrate comparable survival rates (12 survivors of 101 EDTs) [18]. Importantly they found that combat casualties who survived EDT had penetrating injuries and arrived in the ED with SOL. Furthermore, as per our review they concluded that anatomical location of injury was less important when predicting survival

[18]. Morrison et al. also reports four cases of military EDT with two survivors [44].

Both of these papers have demonstrated that despite extensive injury, EDT can be successful, although it should be remembered that the general fitness of the military population will exceed that of the civilian population. Moreover, in the patient with extensive multisystem injury, EDT should be considered only assuming that concurrent damage control resuscitation is delivered [72].

The role of human factors and good preparation in decision-making in EDT

The reorganisation of trauma centres in the UK has led to the development of the trauma team. There are now standard operating procedures for the activation of the team and their constituents. It is usually consultant led with other senior team members. A period of preparation prior to arrival of the patient will allow the preparation of equipment and the briefing of the trauma team to ensure that they all have a developed mental module of the likely scenario; this promotes good team work and followership [74, 75]. A brief pause and assessment, on arrival of the patient, should be performed to ensure the correct decision is made prior to beginning EDT [75]. Once the decision is made, immediate damage control resuscitation should begin in conjunction to EDT [74].

Karmy-Jones et al. demonstrated that dedicated trauma rooms within the emergency department, which function like an operating room improve outcomes when compared to performing EDT in a standard emergency department bay [11]. Cawich et al. highlighted that one of their EDTs was delayed due to equipment not being ready, this patient went on to die [35]. We advocate dedicated trauma resuscitation bays which allow immediate access to equipment required should EDT be necessary.

Capote et al. demonstrated that when EDT was performed by a surgeon, compared to an emergency physician, patients were 3.5 times more likely to survive, although the authors did acknowledge that surgeons were more likely to adhere to protocols than ED physicians [21]. To the contrary, Coats et al. did not demonstrate a difference in outcome when comparing both pre-hospital thoracotomy and EDT performed by surgeon or anaesthetist [76]. Regardless of who performs the procedure, it is important that EDT should be performed by trauma teams with adequate training and experience in damage control resuscitation strategies.

Limitations

Analysis of the EDT literature is difficult, variation in the definition EDT complicates this. There have been multiple publications reviewing the EDT literature; however, they have included historic literature [1, 2, 58], or they have included pre-hospital or operating room thoracotomies [77], or been specific to local populations [78]. To our knowledge, this is the first paper to review worldwide modern EDT literature excluding all non-emergency department patients.

In addition, many publications have not utilised a protocol-driven approach to EDT, relying on the judgement of the trauma team to decide when and if to perform EDT; if they are too liberal in performing EDT in patients who would inevitably survive without the procedure they will demonstrate excellent survival rates. This should not be forgotten when interpreting the present results. Readers are also reminded that this report only details outcome of EDT published in the English language. It is possible that the results pertaining to geographical analysis of outcomes following EDT may be biased because of this.

Conclusions

Penetrating trauma, in particular, stab wounds are likely predictors of good outcome following EDT. Although it is possible that EDT for blunt trauma is now becoming more survivable. Non-cardiothoracic cause of traumatic cardiac arrest should not preclude patients from undergoing EDT. It is unlikely that patients without recorded signs of life in the field will survive EDT.

The present series has also demonstrated that survival following EDT is higher in the non-USA publications, the reasons for this are highly complex.

A UK multicentre prospective cohort study which collects detailed, standardised data on all EDTs performed could provide robust evidence for patient stratification. This is particularly achievable in the UK, given the Trauma Audit and Research, and Major Trauma Centre Networks.

Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest to declare and received no funding for the production of this manuscript.

Informed consent This research involved no human or animal participants, therefore informed consent was not required for the production of this manuscript.

References

1. Seamon MJ, Haut ER, Van Arendonk K, Barbosa RR, Chiu WC, Dente CJ, Fox N, Jawa RS, Khwaja K, Lee JK, Magnotti LJ, Mayglothling JA, McDonald AA, Rowell S, To KB, Falck-Ytter Y, Rhee P. An evidence-based approach to patient selection for emergency department thoracotomy: a practice management guideline from the Eastern Association for the Surgery of Trauma. J Trauma Acute Care Surg. 2015;79(1):159–73.

2. Rhee PM, Acosta J, Bridgeman A, Wang D, Jordan M, Rich N. Survival after emergency department thoracotomy: review of published data from the past 25 years. J Am Coll Surg. 2000;190(3):288–98.
3. Cothren CC, Moore EE. Emergency department thoracotomy for the critically injured patient: objectives, indications, and outcomes. World J Emerg Surg. 2006;1:4.
4. Smith JE, Rickard A, Wise D. Traumatic cardiac arrest. J R Soc Med. 2015;108(1):11–6.
5. Lockey DJ, Lyon RM, Davies GE. Development of a simple algorithm to guide the effective management of traumatic cardiac arrest. Resuscitation. 2013;84(6):738–42.
6. Slessor D, Hunter S. To be blunt: are we wasting our time? Emergency department thoracotomy following blunt trauma: a systematic review and meta-analysis. Ann Emerg Med. 2015;65(3):297–307.e16
7. Hunt PA, Greaves I, Owens WA. Emergency thoracotomy in thoracic trauma—a review. Injury. 2006;37(1):1–19.
8. Powell DW, Moore EE, Cothren CC, Ciesla DJ, Burch JM, Moore JB, Johnson JL. Is emergency department resuscitative thoracotomy futile care for the critically injured patient requiring prehospital cardiopulmonary resuscitation? J Am Coll Surg. 2004;199(2):211–5.
9. Seamon MJ, Shiroff AM, Franco M, Stawicki SP, Molina EJ, Gaughan JP, Reilly PM, Schwab CW, Pryor JP, Goldberg AJ. Emergency department thoracotomy for penetrating injuries of the heart and great vessels: an appraisal of 283 consecutive cases from two urban trauma centers. J Trauma. 2009;67(6):1250–7.
10. Tyburski JG, Astra L, Wilson RF, Dente C, Steffes C. Factors affecting prognosis with penetrating wounds of the heart. J Trauma. 2000;48(4):587–90.
11. Karmy-Jones R, Nathens A, Jurkovich GJ, Shatz DV, Brundage S, Wall MJ, Engelhardt S, Hoyt DB, Holcroft J, Knudson MM, Michaels A, Long W. Urgent and emergent thoracotomy for penetrating chest trauma. J Trauma. 2004;56(3):664–8.
12. Passos EM, Engels PT, Doyle JD, Beckett A, Nascimento B, Rizoli SB, Tien HC. Societal costs of inappropriate emergency department thoracotomy. J Am Coll Surg. 2012;214(1):18–25.
13. Mollberg NM, Glenn C, John J, Wise SR, Sullivan R, Vafa A, Snow NJ, Massad MG. Appropriate use of emergency department thoracotomy: implications for the thoracic surgeon. Ann Thorac Surg. 2011;92(2):455–61.
14. Pahle AS, Pedersen BL, Skaga NO, Pillgram-Larsen J. Emergency thoracotomy saves lives in a Scandinavian hospital setting. J Trauma. 2010;68(3):599–603.
15. Schnüriger B, Talving P, Inaba K, Barmparas G, Branco BC, Lam L, Demetriades D. Biochemical profile and outcomes in trauma patients subjected to open cardiopulmonary resuscitation: a prospective observational pilot study. World J Surg. 2012;36(8):1772–8.
16. Kennedy F, Sharif S. Emergency room thoracotomy: a single surgeon's thirteen-year experience. Am Surg. 2000;66(1):56–60.
17. Gomez G, Fecher A, Joy T, Pardo I, Jacobson L, Kemp H. Optimizing outcomes in emergency room thoracotomy: a 20-year experience in an urban level I trauma center. Am Surg. 2010;76(4):406–10.
18. Edens JW, Beekley AC, Chung KK, Cox ED, Eastridge BJ, Holcomb JB, Blackbourne LH. Longterm outcomes after combat casualty emergency department thoracotomy. J Am Coll Surg. 2009;209(2):188–97.
19. Okoye OT, Talving P, Teixeira PG, Chervonski M, Smith JA, Inaba K, Noguchi TT, Demetriades D. Transmediastinal gunshot wounds in a mature trauma centre: changing perspectives. Injury. 2013;44(9):1198–203.
20. Molina EJ, Gaughan JP, Kulp H, McClurken JB, Goldberg AJ, Seamon MJ. Outcomes after emergency department thoracotomy for penetrating cardiac injuries: a new perspective. Interact Cardiovasc Thorac Surg. 2008;7(5):845–8.
21. Capote A, Michael A, Almodovar J, Chan P, Skinner R, Martin M. Emergency department thoracotomy: too little, too much, or too late. Am Surg. 2013;79(10):982–6.
22. Ladd AP, Gomez GA, Jacobson LE, Broadie TA, Scherer LR III, Solotkin KC. Emergency room thoracotomy: updated guidelines for a level I trauma center. Am Surg. 2002;68(5):421–4.
23. Huber-Wagner S, Lefering R, Qvick M, Kay MV, Paffrath T, Mutschler W, Kanz KG. Outcome in 757 severely injured patients with traumatic cardiorespiratory arrest. Resuscitation. 2007;75(2):276–85.
24. Rabinovici R. Sixty-seven consecutive resuscitative thoracotomies by a single surgeon. Scand J Surg. 2014;103(2):156–60.
25. Paydar S, Moghaninasab A, Asiaei E, Sabetian Fard Jahromi G, Bolandparvaz S, Abbasi H. Outcome of patients underwent emergency department thoracotomy and its predictive factors. Emergency (Tehran, Iran). 2014;2(3):125–9.
26. Berg R, Okoye O, Teixeira P, Inaba K, Demetriades D. The double jeopardy of blunt thoracoabdominal trauma. Arch Surg. 2012;147(6):498–504.
27. Asensio JA, Arroyo H, Veloz W, Forno W, Gambaro E, Roldan GA, Murray J, Velmahos G, Demetriades D. Penetrating thoracoabdominal injuries: ongoing dilemma—which cavity and when? World J Surg. 2002;26(5):539–43.
28. Lustenberger T, Labler L, Stover JF, Keel MJB. Resuscitative emergency thoracotomy in a Swiss trauma centre. Br J Surg. 2012;99(4):541–8.
29. Aihara R, Millham FH, Blansfield J, Hirsch EF. Emergency room thoracotomy for penetrating chest injury: effect of an institutional protocol. J Trauma. 2001;50(6):1027–30.
30. Matsumoto H, Mashiko K, Hara Y, Kutsukata N, Sakamoto Y, Takei K, Kanemaru K, Tomita Y, Saito N, Yagi T, Tetsu S, Iida H, Masuda Y, Koami H, Yokota H. Role of resuscitative emergency field thoracotomy in the Japanese helicopter emergency medical service system. Resuscitation. 2009;80(11):1270–4.
31. Sheppard FR, Cothren CC, Moore EE, Orfanakis A, Ciesla DJ, Johnson JL, Burch JM. Emergency department resuscitative thoracotomy for nontorso injuries. Surgery. 2006;139(4):574–6.
32. Kaljusto M, Skaga N, Pillgram-Larson J, Tonnessen T. Survival predictor for penetrating cardiac injury; a 10-year consecutive cohort from a scandinavian trauma centre. Scand J Trauma Resusc Emerg Med. 2015;23(41):1–7.
33. Kandler K, Konge L, Rafiq S, Larsen CF, Ravn J. Emergency thoracotomies in the largest trauma center in Denmark: 10 years' experience. Eur J Trauma Emerg Surg. 2012;38(2):151–6.
34. Burack JH, Kandil E, Sawas A, O'Neill PA, Sclafani SJA, Lowery RC, Zenilman ME. Triage and outcome of patients with mediastinal penetrating trauma. Ann Thorac Surg. 2007;83(2):377–82.
35. Cawich SO, Mitchell DIG, Williams EW, Mcfarlane ME, Martin A, Plummer JM, Blake G, Newnham MS, Brown H. Emergency department thoracotomy in Jamaica: a case controlled study. Int J Surg. 2007;5(5):311–5.
36. Van Waes OJF, Van Riet PA, Van Lieshout EMM, Hartog DD. Immediate thoracotomy for penetrating injuries: ten years' experience at a Dutch level I trauma center. Eur J Trauma Emerg Surg. 2012;38(5):543–51.
37. Huerta S, Bui TD, Nguyen TH, Banimahd FN, Porral D, Dolich MO. Predictors of mortality and management of patients with traumatic inferior vena cava injuries. Am Surg. 2006;72(4):290–6.
38. Alanezi K, Milencoff GS, Baillie FGH, Lamy A, Urschel JD. Outcome of major cardiac injuries at a Canadian trauma center. BMC Surg. 2002;2:4.
39. Martin SK, Shatney CH, Sherck JP, Ho C-C, Homan SJ, Neff J, Moore EE. Blunt trauma patients with prehospital

pulseless electrical activity (PEA): poor ending assured. J Trauma. 2002;53(5):876–81.
40. Balkan ME, Oktar GL, Kayi-Cangir A, Ergül EG. Emergency thoracotomy for blunt thoracic trauma. Ann Thorac Cardiovasc Surg. 2002;8(2):78–82.
41. Ferris JD, Smith I, Robertson CE. Emergency department at the cutting edge. Eur J Emerg Med. 2008;15(2):67–70.
42. Soreide K, Soiland H, Lossius HM, Vetrhus M, Soreide JA, Soreide E. Resuscitative emergency thoracotomy in a Scandinavian trauma hospital—is it justified? Injury. 2007;38(1):34–42.
43. Johannesdottir BK, Mogensen B, Gudbjartsson T. Emergency thoracotomy as a rescue treatment for trauma patients in Iceland. Injury. 2013;44(9):1186–90.
44. Morrison JJ, Midwinter MJ, Jansen JO. Ballistic thoracoabdominal injury: analysis of recent military experience in Afghanistan. World J Surg. 2011;35(6):1396–401.
45. Lyn-Sue J, Siram S, Williams D, Mezghebe H. Epidemiology of trauma deaths in an urban level-1 trauma center predominantly among African Americans—implications for prevention. J Natl Med Assoc. 2006;98(12):1940–4.
46. Morgan BS, Garner JP. Emergency thoracotomy—the indications, contraindications and evidence. J R Army Med Corps. 2009;155(2):87–93.
47. Smith RM, Conn AK. Prehospital care—scoop and run or stay and play? Injury 2009;40(suppl. 4):S23–6.
48. Esposito TJ, Jurkovich GJ, Rice CL, Maier RV, Copass MK, Ashbaugh DG. Reappraisal of emergency room thoracotomy in a changing environment. J Trauma. 1991;31(7):881–5.
49. Sloan EP, McGill BA, Zalenski R, Tsui P, Chen EH, Duda J, Morris M, Sherer R, Barrett J. Human immunodeficiency virus and hepatitis B virus seroprevalence in an urban trauma population. J Trauma. 1995;38(5):736–41.
50. Sikka R, Millham FH, Feldman JA. Analysis of occupational exposures associated with emergency department thoracotomy. J Trauma Injury Infect Crit Care. 2004;56(4):867–72.
51. Boyd M, Vanek VW, Bourguet CC. Emergency room resuscitative thoracotomy: when is it indicated? J Trauma. 1992;33(5):714–21.
52. Branney SW, Moore EE, Feldhaus KM, Wolfe RE. Critical analysis of two decades of experience with postinjury emergency department thoracotomy in a regional trauma center. J Trauma. 1998;45(1):85–7.
53. Mazzorana V, Smith RS, Morabito DJ, Brar HS, McCarthy MC, Lechner GW, Ledgerwood AM, Reed DN, Bachulis B. Limited utility of emergency department thoracotomy. Am Surg. 1994;60(7):516–21.
54. Danne PD, Finelli F, Champion HR. Emergency bay thoracotomy. J Trauma. 1984;24(9):796–802.
55. Hoyt DB, Shackford SR, Davis JW, Mackersie RC, Hollingsworth-Fridlund P. Thoracotomy during trauma resuscitations—an appraisal by board-certified general surgeons. J Trauma. 1989;29(10):1318–21.
56. Cogbill TH, Moore EE, Millikan JS, Cleveland HC. Rationale for selective application of emergency department thoracotomy in trauma. J Trauma Injury Infect Crit Care. 1983;23(6):453–60.
57. Velmahos GC, Degiannis E, Souter I, Allwood AC, Saadia R. Outcome of a strict policy on emergency department thoracotomies. Arch Surg. 1995;130(7):774–7.
58. Working Group, Ad Hoc subcommittee on outcomes, American college of surgeons-committee on trauma. Practice management guidelines for emergency department thoracotomy. J Am Coll Surg. 2001;193(3):303–9.
59. Brown TB, Romanello M, Kilgore M. Cost-utility analysis of emergency department thoracotomy for trauma victims. J Trauma. 2007;62(5):1180–5.
60. Hopson LR, Hirsh E, Delgado J, Domeier RM, McSwain NE, Krohmer J, Weldon C, Friel M, Hoyt DB. Guidelines for withholding or termination of resuscitation in prehospital traumatic cardiopulmonary arrest. J Am Coll Surg. 2003;196(3):475–81.
61. Kortbeek JB, Al Turki SA, Ali J, Antoine JA, Bouillon B, Brasel K, Brenneman F, Brink PR, Brohi K, Burris D, Burton RA, Chapleau W, Cioffi W, Collet e Silva FDS, Cooper J, Cortes A, Eskesen V, Fildes J, Gautam S, Gruen RL, Gross R, Hansen KS, Henny W, Hollands MJ, Hunt RC, Jover Navalon JM, Kaufmann CR, Knudson P, Koestner A, Kosir R, Larsen CF, Livaudais W, Luchette F, Mao P, McVicker JH, Meredith HW, Mock C, Mori ND, Morrow C, Parks SN, Pereira PM, Pogetti RS, Ravn J, Rhee P, Salomone JP, Schipper IB, Schoettker P, Schreiber MA, Smith RS, Svendsen LB, Taha W, van Wijngaarden-Stephens M, Varga E, Voiglio EJ, Williams D, Winchell RJ, Winter R. Advanced trauma life support, 8th edition, the evidence for change. J Trauma. 2008;64(6):1638–50.
62. Yousef R, Carr JA. Blunt cardiac trauma: a review of the current knowledge and management. Ann Thorac Surg. 2014;98(3):1134–40.
63. Carr JA, Buterakos R, Bowling WM, Janson L, Kralovich KA, Copeland C, Link R, Roiter C, Casey G, Wagner JW. Long-term functional and echocardiographic assessment after penetrating cardiac injury: 5-year follow-up results. J Trauma Injury Infect Crit Care. 2011;70(3):701–4.
64. Tarmey NT, Park CL, Bartels OJ, Konig TC, Mahoney PF, Mellor AJ. Outcomes following military traumatic cardiorespiratory arrest: a prospective observational study. Resuscitation. 2011;82(9):1194–7.
65. Moore EE, Knudson MM, Burlew CC, Inaba K, Dicker RA, Biffl WL, Malhotra AK, Schreiber MA, Browder TD, Coimbra R, Gonzalez EA, Meredith JW, Livingston DH, Kaups KL. Defining the limits of resuscitative emergency department thoracotomy: a contemporary Western Trauma Association perspective. J Trauma. 2011;70(2):334–9.
66. Nevins EJ, Moori PL, Smith-Williams J, Bird NTE, Taylor JV, Misra N. Should pre-hospital resuscitative thoracotomy be reserved only for penetrating chest trauma? Eur J Trauma Emerg Surg. 2018. https://doi.org/10.1007/s00068-018-0937-4
67. Miglietta M, Robb T, Eachempati S, Porter B, Cherry R, Brause J, PS B. Current opinion regarding indications for emergency department thoracotomy. J Trauma Injury Infect Crit Care. 2001;51(4):670–6.
68. Dennis B, Medvecz A, Gunter O, Guillamondegui O. Survey of trauma surgeon practice of emergency department thoracotomy. Am J Surg. 2016;212:440–5.
69. Anderson I, Cripps M, Cromwell D, Emma M, Ms D, Drake S, Grocott M, Kuryba A, Lourtie J, Moonesinghe R, Murray D, Oliver M, Papadimitriou D, Peden C, Walker K. The first patient report of the national emergency laparotomy audit (NELA) executive summary. R Coll Anaesth. 2015:1–149.
70. Seamon MJ, Chovanes J, Fox N, Green R, Manis G, Tsiotsias G, Warta M, Ross SE. The use of emergency department thoracotomy for traumatic cardiopulmonary arrest. Injury. 2012;43(9):1355–61.
71. Keller D, Kulp H, Maher Z, Santora TA, Goldberg AJ, Seamon MJ. Life after near death: long-term outcomes of emergency department thoracotomy survivors. J Trauma Acute Care Surg. 2013;74(5):1315–20.
72. Morrison JJ, Poon H, Rasmussen TE, a Khan M, Midwinter MJ, Blackbourne LH, Garner JP. Resuscitative thoracotomy following wartime injury. J Trauma Acute Care Surg. 2013;74(3):825–9.
73. Eastridge BJ, Hardin M, Cantrell J, Oetjen-Gerdes L, Zubko T, Mallak C, Wade CE, Simmons J, Mace J, Mabry R, Bolenbaucher R, Blackbourne LH. Died of wounds on the battlefield: causation and implications for improving combat casualty care. J Trauma. 2011;71(1 Suppl):S4–8.

74. Mercer S, Park C, Tarmey N. Human factors in complex trauma. Contin Educ Abaesthesia Crit Care Pain. 2014;15(5):231–6.
75. Arul G, Pugh H, Mercer S, Midwinter M. Human factors in decision making in major trauma in Camp Bastion, Afghanistan. Ann R Coll Surg Engl. 2015;97:262–268.
76. Coats TJ, Keogh S, Clark H, Neal M. Prehospital resuscitative thoracotomy for cardiac arrest after penetrating trauma: rationale and case series. J Trauma. 2001;50(4):670–3.
77. Dayama A, Sugano D, Spielman D, Stone ME, Kaban J, Mahmoud A, Mcnelis J. Basic data underlying clinical decision-making and outcomes in emergency department thoracotomy: tabular review. ANZ J Surg. 2016;86(1–2):21–26.
78. Narvestad JK, Meskinfamfard M, Soreide K. Emergency resuscitative thoracotomy performed in European civilian trauma patients with blunt or penetrating injuries: a systematic review. Eur J Trauma Emerg Surg. 2016;42(6):677–85.