Trauma Surgery & Acute Care Open

Resuscitative endovascular balloon occlusion of the aorta (REBOA) may be superior to resuscitative thoracotomy (RT) in patients with traumatic brain injury (TBI)

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To cite: Brenner M, Zakhary B, Coimbra R, *et al*. *Trauma Surg Acute Care Open* 2022;**7**:e000715.

ABSTRACT

Background The effects of aortic occlusion (AO) on brain injury are not well defined. We examined the impact of AO by resuscitative endovascular balloon occlusion of the aorta (REBOA) and resuscitative thoracotomy (RT) on outcomes in the setting of traumatic brain injury (TBI).

Methods Patients sustaining TBI who underwent RT or REBOA in zone 1 (thoracic aorta) from September 2013 to December 2018 were identified. The indication for REBOA or RT was hemodynamic collapse due to hemorrhage below the diaphragm. Primary outcomes included mortality and systemic complications.

Results 282 patients underwent REBOA or RT. Of these, 76 had mild TBI (40 REBOA, 36 RT) and 206 sustained severe TBI (107 REBOA, 99 RT). Overall, the mean (±SD) age was 42±17 years, with an Injury Severity Score (ISS) of 40±17 and mean systolic blood pressure (SBP) at the time of REBOA or RT of 81±34 mm Hg. REBOA patients had a mean SBP at the time of AO of 78.39±29.45 mm Hg, whereas RT patients had a mean SBP of 83.18±37.87 mm Hg at the time of AO (p=0.24). 55% had ongoing cardiopulmonary resuscitation (CPR) at the time of AO, and the in-hospital mortality was 86%. Binomial logistic regression controlling for TBI severity, age, ISS, SBP at the time of AO, crystalloid infusion, and CPR during AO demonstrated that the odds of mortality are 3.1 times higher for RT compared with REBOA. No significant differences were found in systemic complications between RT and REBOA.

Discussion Patients with TBI who receive REBOA may have improved survival, but no difference in systemic complications, compared with patients who receive RT for the same indication. Although some patients are receiving RT prior to arrest for extrathoracic hemorrhagic shock, these results suggest that REBOA should be considered as an alternative to RT when RT is chosen for the sole purpose of resuscitation in the setting of TBI.

Level of evidence 4.

INTRODUCTION

Resuscitative endovascular balloon occlusion of the aorta (REBOA) has been used as an adjunct to resuscitation and hemorrhage control in trauma for several years. Although the optimum patient selection criteria have not been identified by level 1 studies, some propensity score matching studies suggest a survival benefit in similar patients compared with those who do not receive REBOA,[1–3] as well as compared with similar patients who receive resuscitative thoracotomy (RT) for the same indications.[4–6]

A cohort of patients who receive REBOA for exsanguinating hemorrhage also have traumatic brain injury (TBI), and the effects of aortic occlusion (AO) on brain injury are not well defined. Whether AO occurs with RT or REBOA, cerebral blood flow, carotid blood flow, and other measures which can affect outcomes have been demonstrated to increase.[7–9] Because hypotension and hypertension can be problematic for the injured brain,[10–15] AO must be used with caution. AO increases systolic blood pressure (SBP) to prevent cardiovascular collapse, or in the case of arrest to achieve return of spontaneous circulation (ROSC) by perfusing cerebral and coronary circulation. However, the SBP increase after AO has not been investigated in patients with TBI, nor has the potential effect on outcomes. Our aim was to examine the impact of AO by REBOA and RT on outcomes in the setting of TBI.

METHODS

Data collection

No consent for the REBOA procedure was required. Data were collected prospectively and entered by volunteer registrars designated by each center into an online data collection portal managed by the American Association for the Surgery of Trauma (AAST).

Adult trauma and acute care surgery (aged 18 years and older) patients with blunt TBI undergoing AO zone 1 REBOA or RT with AO after injury were enrolled. TBI was identified by head Abbreviated Injury Scale (AIS) score of ≥1. The decision to perform REBOA was physician-dependent, and most patients received REBOA based on at least one previously published algorithm. De-identified data of patients with TBI who received REBOA and RT were obtained from the AAST database from September 2013 to December 2018. Patients were stratified based on procedure and severity of TBI. Mild TBI was defined as head AIS score of ≤2, whereas severe TBI was defined as head AIS

score of ≥3. Patients were excluded if they received REBOA in zone 2 (area of visceral vessel origins) or zone 3 (distal abdominal aorta), or if successful AO was not achieved. Patients with penetrating injury were also excluded. Captured data included patient demographics, admission laboratory vitals, and Injury Severity Score (ISS). In addition, physiology at the time of AO and response to initial AO (highest SBP within 5 minutes after AO) were recorded along with hospital discharge information including Glasgow Coma Scale (GCS) and Glasgow Outcome Scale Extended (GOSE). Outcomes such as mortality and complications were collected.

Missing data

In assessing missing vitals and blood characteristic data, multiple imputation was performed. The Markov Chain Monte Carlo method was used to predict missing data within continuous variables that possessed less than 35% missing data. Variables were scanned and analyzed for patterns to assure randomness in missing data. Random number generation was then employed to coordinate values to the missing data. These values were iterated three times through a linear regression analysis using other demographic and correlated variables as predictors. Iterations produced imputed data pooled within the range of the original available continuous data. The third iteration was then used for statistical analysis.

Statistical analysis

Univariate χ^2 analysis with continuity correction was performed for comparisons between RT and REBOA patients who achieved successful AO. Fisher's exact test was used for categorical variables containing cells with less than 10 events. Continuous variables were reported as mean (SD), whereas categorical variables were reported by count with corresponding percentages. In assessing continuous variables, independent t-test was used in comparing means across the two groups examined. Hospital length of stay, intensive care unit (ICU) stay, and duration of mechanical ventilation were collected. The primary outcomes were mortality and complications. Systemic complications were coded into a binary variable, resulting in at least one complication, due to the infrequent count of each type. Systemic complications were assessed separately for patients who survived beyond the operating room. This was also reflected in the outcome for the binary logistic regression model examining complications. Binomial logistic regression analyses were then performed to determine difference in odds of mortality, discharge GCS, GOSE, and systemic complications between RT and REBOA when controlling for covariates such as TBI severity, age, ISS, AO initiation SBP, admission lactate, cardiopulmonary resuscitation (CPR) during AO, and volume of blood transfusions. Models were pre-examined using univariate correlation matrices in assessing correlated variables with mortality that need to be controlled for. In assessing cohorts for each TBI severity subpopulation, separate models for each subpopulation (mild and severe TBI) were also assessed for outcomes of all population mortality. Models were validated using the Hosmer and Lemeshow significance test in assessing their validity. All statistical analyses were conducted using Statistical Package for the Social Sciences (SPSS) V.25.

RESULTS

Demographics

There were 282 blunt-injured patients with TBI abstracted from the AAST data registry; 147 underwent REBOA and 135 underwent RT. Of these patients, 76 had mild TBI (40 REBOA, 36 RT) and 206 sustained severe TBI (107 REBOA, 99 RT). Overall, the mean (±SD) age was 42±17 years, with an ISS of 40±17 and mean SBP at the time of REBOA or RT of 81±34 mm Hg. REBOA patients had a mean SBP at the time of AO of 78.39±29.45 mm Hg, whereas RT patients had a mean SBP of 83.18±37.87 mm Hg at the time of AO (p=0.24). Of the patients, 55% had ongoing CPR at the time of AO, and the in-hospital mortality was 86%. Of the procedures, 76.2% were performed by trauma/acute care surgery attendings, 12.1% were performed by surgery residents, 8.9% were performed by surgery fellows, and 1.1% were by vascular surgery attendings.

Univariate analysis

Patients with TBI who underwent REBOA were significantly older than RT patients. Admission GCS and hemoglobin were significantly higher among REBOA patients, whereas admission lactate and base deficit value were significantly higher among RT patients (table 1). GCS at AO and post-AO were significantly higher among REBOA than RT. Of the RT patients, 82.2% had ongoing CPR during AO, whereas only 29.9% of REBOA patients needed CPR during AO. SBP post-AO was higher in REBOA than RT, and REBOA patients also had significantly higher volume of blood transfusions of packed red blood cells, fresh frozen plasma, and crystalloid (table 1). Among patients with mild TBI, GCS at AO was significantly higher in REBOA than in RT patients. However, there were no significant differences in ISS or other physiologic variables between treatment groups within patients with mild TBI. CPR during AO was more frequent among RT than REBOA patients in the mild TBI cohort (table 2). Among patients with severe TBI, admission GCS and heart rate at AO and post-AO were significantly higher within REBOA patients than RT patients. CPR at admission and during AO were significantly more common among RT patients than REBOA patients. Blood transfusion volumes such as packed red blood cells and fresh frozen plasma were significantly higher among REBOA patients (table 2).

Outcomes

Overall, mortality was 86.2%, with over a third of those occurring in the ICU, with REBOA patients having lower mortality overall than RT patients, 77.6% vs. 95.6% (table 3). Nearly 70% of all patients died within 6 hours of admission, and RT patients died sooner than REBOA patients (table 3). As a result, hospital length of stay, ICU stay, and mechanical ventilation days were significantly higher among REBOA patients than RT patients (p<0.01). Discharge GCS was also significantly higher among REBOA patients than RT patients (table 4). There were no significant differences in overall complications between RT and REBOA. Only bacteremia showed a significantly higher incidence among REBOA patients than RT patients (table 4). Access complications in the REBOA group are listed in table 3. When isolating patients who had ongoing CPR at the time of AO, there was no difference in outcomes, time of death, or complications (table 5). Only duration of ventilation for the RT group was significantly higher than the REBOA group.

Logistic regression

In assessing the outcome of mortality between RT and REBOA patients, we controlled for several significant covariates. Using a binomial logistic regression model controlling for TBI severity, age, ISS, SBP at AO, admission lactate, crystalloid infusion, duration of initial AO, and CPR during AO, RT patients had a threefold higher mortality rate than REBOA patients, and severe TBI patients were three times more likely to die than those with

Table 1 Demographics of all patients with blunt TBI

	Total (N=282, 100%)	REBOA (n=147, 52.1%)	RT (n=135, 48.9%)	P value
Age, years, mean (SD)	42.3 (17)	44.7 (17)	39.8 (17)	0.02*
Gender, n (%)				0.47
Male	216 (76.6)	110 (74.8)	106 (78.5)	
Female	66 (23.4)	37 (25.2)	29 (21.5)	
ISS, mean (SD)	40.1 (17)	39.4 (16)	41.0 (18)	0.43
Chest AIS score, mean (SD)	3.2 (1)	3.0 (1)	3.3 (2)	0.10
Abdomen AIS score, mean (SD)	2.7 (2)	2.6 (2)	2.9 (2)	0.32
TBI, n (%)				0.92
Mild TBI	76 (27.0)	40 (27.2)	36 (26.7)	
Severe TBI	206 (73.0)	107 (72.8)	99 (73.3)	
Admission vital signs, mean (SD)				
SBP, mm Hg	102.4 (37)	101.1 (35)	103.8 (38)	0.53
HR, bpm	112.2 (31)	113.6 (31)	110.7 (31)	0.43
GCS	4.4 (3)	4.9 (4)	4 (2)	0.01**
Hgb	10.8 (3)	11.2 (2)	10.0 (4)	0.02*
InR	1.9 (2)	2.0 (2)	1.8 (1)	0.19
pH	7.1 (0.2)	7.1 (0.2)	7.0 (0.2)	0.11
Lactate	8.8 (5)	8.2 (5)	9.4 (5)	0.05*
Base deficit (–)	13.6 (7)	12.7 (7)	14.6 (7)	0.02*
AO initiation vitals, mean (SD)				
SBP, mm Hg	80.7 (34)	78.4 (29)	83.2 (38)	0.24
HR, bpm	108.8 (31)	112.2 (30)	105.0 (32)	0.05*
GCS	3.3 (2)	3.5 (2)	3.0 (0)	0.01*
Response to AO vitals, mean (SD)				
SBP, mm Hg	114.7 (32)	115.2 (32)	114.1 (32)	0.79
HR, bpm	106.0 (31)	108.5 (30)	103.2 (32)	0.15
GCS	3.2 (1)	3.4 (2)	3.0 (0.3)	0.04*
Change after AO, mean (SD)				
Change in SBP, mm Hg	35.0 (44)	39.8 (39)	8.0 (59)	0.01*
Change in HR, bpm	–0.2 (25)	–0.9 (24)	2.1 (27)	0.60
Change in GCS	–0.1 (0.8)	–0.1 (1)	0.03 (0.3)	0.08
Lowest base deficit (–), mean (SD)	14.8 (6)	14.1 (7)	15.6 (6)	0.05
Highest InR, mean (SD)	2.1 (2)	2.1 (3)	2.0 (1)	0.41
Highest lactate, mg/dL, mean (SD)	10.2 (5)	9.8 (5)	10.6 (5)	0.20
Lowest Hgb, g/L, mean (SD)	9.1 (3)	9.3 (3)	8.8 (3)	0.15
Lowest pH, mean (SD)	7.0 (0.2)	7.1 (0.2)	7.0 (0.2)	0.05
CPR in progress on arrival, n (%)	88 (31.2)	33 (22.4)	55 (40.7)	<0.01**
CPR duration, minutes, mean (SD)	18 (14)	15 (14)	20 (14)	0.02*
CPR during AO, n (%)	155 (55.0)	44 (29.9)	111 (82.2)	<0.001**
Duration of initial AO, minutes, mean (SD)	40.0 (47)	47.1 (55)	32.1 (33)	0.02*
Resuscitation products, mean (SD)				
Packed red blood cells	15.9 (15)	17.8 (15)	13.9 (14)	0.03*
Fresh frozen plasma	12.5 (14)	14.2 (14)	10.6 (13)	0.03*
Platelets	6.3 (12)	7.3 (13)	5.3 (10)	0.14
Cryoprecipitate	1.7 (5)	2.0 (7)	1.4 (3)	0.30
Crystalloids	4.0 (5)	4.6 (7)	3.3 (3)	0.04*

*P<0.05, **P<0.01.
AIS, Abbreviated Injury Scale; AO, aortic occlusion; bpm, beats per minute; CPR, cardiopulmonary resuscitation; GCS, Glasgow Coma Scale; Hgb, hemoglobin; HR, heart rate; InR, international normalized ratio; ISS, Injury Severity Score; REBOA, resuscitative endovascular balloon occlusion; RT, resuscitative thoracotomy; SBP, systolic blood pressure; TBI, traumatic brain injury.

lesser TBI severity (table 6). There were no significant differences in mortality between RT and REBOA within mild or severe subgroups. After controlling for TBI severity, age, ISS, SBP at AO, admission lactate, crystalloid infusion, duration of AO, and CPR during AO, there was no difference in discharge GCS, GOSE, or systemic complications (table 7).

Table 2 Demographics of patients by TBI severity

	Mild TBI (n=76, 27.0%)		Severe TBI (n=206, 73.0%)	
	REBOA zone 1 (n=40, 52.6%)	RT (n=36, 47.4%)	REBOA zone 1 (n=107, 51.9%)	RT (n=99, 48.1%)
Age, years, mean (SD)	49.9 (17)	45.8 (19)	42.8 (17)	37.6 (16)*
Gender, n (%)				
Male	31 (77.5)	29 (80.6)	79 (73.8)	77 (77.8)
Female	9 (22.5)	7 (19.4)	28 (26.2)	22 (22.2)
ISS, mean (SD)	29.9 (11)	34.0 (19)	42.9 (16)	43.5 (17)
Chest AIS score, mean (SD)	2.8 (1)	3.1 (2)	3.1 (1)	3.4 (2)
Abdomen AIS score, mean (SD)	2.8 (2)	3.1 (2)	2.6 (2)	2.8 (2)
Admission vitals, mean (SD)				
SBP, mm Hg	105.3 (30)	99.3 (39)	99.5 (37)	105.4 (38)
HR, bpm	112.3 (26)	108.5 (29)	114.1 (32)	111.4 (32)
GCS	6.8 (5)	4.8 (4)	4.3 (3)	3.5 (2)*
Hgb, g/L	11.2 (3)	9.8 (34)	11.2 (2)	10.6 (3)
InR	2.2 (3)	1.6 (1)	1.9 (2)	1.8 (1)
pH	7.1 (0.2)	7.1 (0.2)	7.1 (0.2)	7.1 (0.2)
Lactate	9.1 (5)	11.1 (5)	7.9 (5)	8.8 (5)
Base deficit (–)	13.6 (7)	16.6 (7)	12.3 (7)	13.9 (7)
AO initiation vitals, mean (SD)				
SBP, mm Hg	75.3 (29)	74.0 (33)	79.6 (30)	86.5 (39)
HR, bpm	100.6 (32)	95.7 (33)	116.5 (28)	108.5 (30)*
GCS	4.3 (3)	3.0 (0)*	3.2 (2)	3.0 (0)
Post-AO vitals, mean (SD)				
SBP, mm Hg	115.8 (40)	107 (33)	114.9 (28)	116.8 (32)
HR, bpm	98.3 (30)	104.1 (34)	112.3 (29)	102.9 (31)*
GCS	4.1 (3)	3.0 (0.2)	3.2 (1)	3.0 (0.3)
Change after AO, mean (SD)				
Change in SBP, mm Hg	49.0 (45)	25.0 (49)	36.5 (36)	0.9 (63)**
Change in HR, bpm	5.2 (29)	–11.2 (16)	–3.2 (22)	5.5 (29)
Change in GCS	–0.2 (0.9)	0.03 (0.2)	–0.1 (1)	0.03 (0.3)
Lowest base deficit (–), mean (SD)	15.3 (6.9)	17.1 (6)	13.6 (7)	15.0 (6)
Highest InR, mean (SD)	1.8 (0.9)	1.8 (1)	2.3 (3)	2.0 (1)
Highest lactate, mg/dL, mean (SD)	10.5 (6)	11.6 (5)	9.6 (5)	10.2 (5)
Lowest Hgb, mean (SD)	9.6 (2.9)	8.0 (4)	9.2 (3)	9.1 (3)
Lowest pH, mean (SD)	7.0 (0.2)	7.0 (0.2)	7.1 (0.2)	7.0 (0.2)
CPR in progress on arrival, n (%)	9 (22.5)	13 (36.1)	24 (22.4)	42 (42.4)**
CPR duration, minutes, mean (SD)	16 (19)	16 (12)	14 (12)	22 (15)**
CPR during AO, n (%)	14 (35.0)	30 (83.3)**	30 (28.0)	81 (81.8)**
Duration of initial AO, minutes, mean (SD)	34.8 (32)	31.4 (22)	52.5 (62)	32.4 (36)*
Resuscitation products, mean (SD)				
Packed red blood cells	17.8 (16)	16.4 (14)	17.8 (15)	13.9 (14)*
Fresh frozen plasma	13.9 (15)	13.3 (14)	14.3 (13)	9.6 (13)**
Platelets	10.1 (19)	4.9 (9)	6.3 (10)	5.4 (10)
Cryoprecipitate	3.3 (9)	1.3 (3)	1.5 (6)	1.4 (3)
Crystalloids	3.7 (2)	2.9 (3)	5.0 (7)	3.5 (4)

*P<0.05, **P<0.01.
AIS, Abbreviated Injury Scale; AO, aortic occlusion; bpm, beats per minute; CPR, cardiopulmonary resuscitation; GCS, Glasgow Coma Scale; Hgb, hemoglobin; HR, heart rate; InR, international normalized ratio; ISS, Injury Severity Score; REBOA, resuscitative endovascular balloon occlusion; RT, resuscitative thoracotomy; SBP, systolic blood pressure; TBI, traumatic brain injury.

DISCUSSION

The Aortic Occlusion and Resuscitation for Trauma and Acute Care Surgery (AORTA) trial has been capturing RT and REBOA patients from voluntarily enrolled centers since 2013, which has given us a great deal of information regarding the implementation, adoption, and evolving use of these procedures. This cohort has similar SBP at the time of AO as the REBOA patients. This argues against the theory that RT patients are more compromised than patients who receive REBOA, as seen in this study and in others from the same database.[4 16] The

Table 3 Outcomes and complications of REBOA and RT overall

Outcomes	Total (N=282, 100%)	REBOA zone 1 (n=147, 52.1%)	RT (n=135, 48.9%)	P value
In-hospital mortality, n (%)	243 (86.2)	114 (77.6)	129 (95.6)	<0.01**
ICU, n (%)	90 (31.9)	51 (34.7)	39 (28.9)	<0.01**
Operating room, n (%)	80 (28.4)	29 (19.7)	51 (37.8)	
Emergency room, n (%)	70 (24.8)	32 (21.8)	38 (28.1)	
Interventional radiology, n (%)	1 (0.2)	1 (0.7)	0 (0)	
Other, n (%)	2 (0.7)	1 (0.7)	1 (0.7)	
Death hours after admission, mean (SD)	3.2 (4)	4.1 (4)	2.6 (3)	0.01**
<6, n (%)	196 (69.5)	86 (58.5)	110 (81.5)	0.07
6–12, n (%)	33 (11.7)	18 (12.2)	15 (11.1)	
12–18, n (%)	13 (4.6)	10 (6.8)	3 (2.2)	
18–24, n (%)	1 (0.4)	0 (0.0)	1 (0.7)	
Hospital LOS, days, mean (SD)	6.4 (14)	9.7 (17)	2.9 (9)	<0.01**
ICU stay, n (%)	148 (52.5)	92 (62.6)	56 (41.5)	<0.01**
ICU days, mean (SD)	6.4 (9)	8.0 (10)	3.82 (7)	0.01**
Ventilator days, n (%)	214 (75.9)	116 (78.9)	98 (72.6)	0.17
Ventilator days, mean (SD)	4.4 (8)	6.3 (10)	2.1 (4)	<0.01**
Discharge GCS, mean (SD)	5.1 (4)	6.1 (5)	3.7 (2)	<0.01**
Discharge GOSE, mean (SD)	1.6 (1)	1.8 (1)	1.5 (1)	0.10
Discharge disposition, n (%)				<0.01**
Rehabilitation/nursing facility	30 (10.6)	26 (17.7)	4 (3.0)	
Home	6 (2.1)	5 (3.4)	1 (0.7)	
Missing	4 (0.9)	2 (1.4)	2 (1.5)	
Lower extremity amputation, n (%)	2 (0.7)	2 (1.4)	0 (0.0)	0.50
Systemic complications, n (%)	62 (22.0)	45 (30.6)	17 (12.6)	<0.01**
Acute kidney injury	36 (12.8)	27 (18.4)	9 (6.7)	0.01**
Pneumonia	25 (8.9)	19 (12.9)	6 (4.4)	0.02*
ALI or ARDS	22 (7.8)	15 (10.2)	7 (5.2)	0.18
Multi-organ dysfunction syndrome(MODS)	22 (7.8)	15 (10.2)	7 (5.2)	0.18
Sepsis or septic shock	13 (4.6)	9 (6.1)	4 (3.0)	0.26
AKI - dialysis required	13 (4.6)	10 (6.8)	3 (2.2)	0.09
Bacteremia	11 (3.9)	11 (7.5)	0 (0.0)	0.01**
Stroke	5 (1.8)	3 (2.0)	2 (1.5)	0.99
Paraplegia	4 (1.4)	4 (2.7)	0 (0.0)	0.12
Myocardial infarction	1 (0.4)	1 (0.7)	0 (0.0)	0.99

Systemic complications include having at least one of the following: AKI, pneumonia, ALI or ARDS, MODS, sepsis, AKI - dialysis required, bacteremia, paraplegia, stroke, and myocardial infarction.
*P<0.05, **P<0.01.
AKI, acute kidney injury; ALI, acute lung injury; ARDS, acute respiratory distress syndrome; GCS, Glasgow Coma Scale; GOSE, Glasgow Outcome Scale Extended; ICU, intensive care unit; LOS, length of stay; REBOA, resuscitative endovascular balloon occlusion; RT, resuscitative thoracotomy.

value of SBP at the time of AO is the most important measurement of physiologic demise from hemorrhage and solidifies the similarity between these two groups of patients. ISS, admission SBP, heart rate, and pH were also not different between the groups. Admission lactate and GCS were significantly different; however, these were not obtained at the time of AO and thus may not be the most accurate depiction of physiology. Another important variable which can confound baseline comparisons between the groups is ongoing CPR at the time of AO. Because fewer REBOA patients had ongoing CPR at the time of AO than RT patients, this variable was included in the logistic regression models. The finding that not all patients were in arrest at the time of RT (almost 20%) has been consistently demonstrated by this database. It appears that although outcomes from RT have not improved during the past decades,[17] it is still the choice for AO in some patients in the absence of thoracic hemorrhage.

Similar mean increases in post-AO SBP and mean post-AO SBP have been demonstrated in other AORTA studies, confirming the effectiveness of RT and REBOA in improving proximal arterial pressure.[4 16] Studies have documented worse outcomes in patients with TBI with hypotension,[10–14] which AO can mitigate. In the setting of TBI, the peak post-AO SBP could be particularly concerning, as hypertension has been shown to worsen TBI.[11–15] Guidelines from the Brain Trauma Foundation (BTF) recommend keeping SBP >100 mm Hg for patients 50 to 69 years old and >110 mm Hg or above for patients 15 to 49 years old or >70 years old.[18] The mean post-AO SBP values (which are peak values) for both RT and REBOA patients in this study are in keeping with the guidelines and may not worsen TBI. One study using continuous vital sign monitoring investigated hemodynamics before, during, and after AO with REBOA and found that, although

Table 4 Complications of REBOA and RT in patients who survived beyond the operating room

Outcomes	Total (n=132, 100%)	REBOA zone 1 (n=86, 65.2%)	RT (n=46, 34.8%)	P value
Access complications, n (%)	7 (5.3)	7 (8.1)	–	NA
Pseudoaneurysm	1 (0.8)	1 (1.2)	–	NA
Distal embolism	4 (3.2)	4 (4.7)	–	NA
Extremity ischemia	5 (4.0)	5 (5.8)	–	NA
Lower extremity amputation	1 (0.8)	1 (1.2)	0 (0.0)	0.65
Systemic complications, n (%)	58 (43.9)	42 (48.8)	16 (34.8)	0.17
Acute kidney injury	33 (25.0)	24 (27.9)	9 (19.6)	0.40
Pneumonia	25 (18.9)	19 (22.1)	6 (13.0)	0.24
ALI or ARDS	22 (16.7)	15 (17.4)	7 (15.2)	0.81
Multi-organ dysfunction syndrome (MODS)	20 (15.2)	14 (16.3)	6 (13.0)	0.41
Sepsis or septic shock	12 (9.1)	9 (10.5)	3 (6.5)	0.34
AKI - dialysis required	13 (9.8)	10 (11.6)	3 (6.5)	0.54
Bacteremia	11 (8.3)	11 (12.8)	0 (0.0)	0.01**
Stroke	5 (3.8)	3 (3.5)	2 (4.3)	0.57
Paraplegia	4 (3.0)	4 (4.7)	0 (0.0)	0.18
Myocardial infarction	1 (0.8)	1 (1.2)	0 (0.0)	0.65

Access complications include having at least one of the following: pseudoaneurysm, distal embolism, and extremity ischemia.
Systemic complications include having at least one of the following: AKI, pneumonia, ALI or ARDS, MODS, sepsis, AKI - dialysis required, bacteremia, paraplegia, stroke, and myocardial infarction.
**P<0.01.
AKI, acute kidney injury; ALI, acute lung injury; ARDS, acute respiratory distress syndrome; NA, not applicable due to open surgical technique vs. endovascular technique; REBOA, resuscitative endovascular balloon occlusion; RT, resuscitative thoracotomy.

SBP can vary after AO, during the majority of the duration of AO the mean SBP stays within the BTF guidelines.[19] The complex shifts in blood flow after sudden AO are related to a complex interplay between arterial and venous capacitance, vasoconstriction, and cardiac function.[20] These resultant compensations are more pronounced with higher levels of AO. The fluctuations in SBP that may occur with AO and then release of AO/balloon deflation may be just as deleterious to TBI as singular episodes of hypotension or hypertension. Unfortunately, the values for post-AO SBP correspond to one maximum value within 5 minutes after occlusion, and thus the SBP values throughout the duration of AO are not captured.

The logistic regression analysis, which controlled for factors potentially affecting outcomes, found RT to worsen the odds of survival threefold. The survival benefit of REBOA has been demonstrated in patients without TBI compared with RT patients from the AAST AORTA database in previous publications[4 19]; however, this is the first to demonstrate the same benefit in patients with brain injury. No correlation to specific aspects of REBOA can be identified as factors resulting in improved survival, and further study is needed to identify cause and effect. Discharge GCS was also found to be higher in REBOA patients than RT patients, which is a positive outcome in all patients, and patients with TBI in particular. Differences in systemic complications were not significant between groups, and the rates of extremity ischemia and amputation from REBOA are similar to prior studies from the same database.

This study does not answer the question of whether AO harms patients with TBI. A propensity-scored matching study from Japan showed that patients with TBI who receive REBOA fare worse than those who do not receive REBOA,[21] but translational data show that increases in intra-cranial pressure (ICP) and carotid flow do not correlate with progression of TBI on imaging.[7 22] Furthermore, blood resuscitation was found to worsen TBI more than REBOA.

In terms of clinical recommendations, the difficulty is being able to identify patients with TBI prior to AO. Patients in shock from hemorrhage often have decreased GCS, as do most patients with more than mild TBI. So in most cases it is difficult to diagnose TBI without imaging. REBOA and RT patients usually do not travel to the CT scanner until after AO and hemorrhage control. This makes guidelines for use of AO in patients with TBI a challenge. It is most often a secondary finding after hemorrhagic shock that we find TBI well after the decision to perform AO has occurred. Even in the setting of non-survivable TBI and exsanguinating hemorrhage, REBOA has allowed a patient to survive to organ donation in at least one published institutional series.[23] The key for patients with TBI and exsanguinating hemorrhage is treatment of the most life-threatening injury first and foremost. This may require AO by RT or REBOA to control hemorrhage, which may delay or halt coagulopathy and reduce the burden of primary and secondary brain injury. These results suggest REBOA may be a superior alternative to RT in this setting.

There are several limitations to this study, including its voluntary and observational nature. Not all variables for all patients were available, and multiple imputation was used to correct for this. Neither cause of death nor organ donation was captured. The patients in this database only represent some of the institutions performing REBOA and RT, including high-volume REBOA centers. The results may not translate to low-volume REBOA centers. The indications for using RT or REBOA were based on physician discretion, although life-threatening hemorrhage below the diaphragm was the indication for use in all patients. The study period spans different time periods of REBOA evolution, including the early days and exponential learning curves with larger devices at some centers, and later more refined use of REBOA with a smaller

Table 5 Outcomes of REBOA and RT for patients who required CPR at AO

Outcomes	Total (n=155, 100%)	Zone 1 (n=44, 28.4%)	RT (n=111, 71.6%)	P value
In-hospital mortality, n (%)	150 (96.8)	42 (95.5)	108 (97.3)	0.56
Duration of initial AO, mean (SD)	27 (23)	25 (26)	28 (22)	0.64
Hours dead after admission, mean (SD)	2.5 (3)	2.1 (3)	2.6 (3)	0.49
<6 hours dead after admission, n (%)	129 (83.2)	38 (86.4)	91 (82.0)	0.38
6–12 hours dead after admission, n (%)	17 (11.0)	3 (6.8)	14 (12.6)	
12–18 hours dead after admission, n (%)	3 (1.9)	1 (2.3)	2 (1.8)	
18–24 hours dead after admission, n (%)	1 (0.6)	0 (0.0)	1 (0.9)	
Hospital LOS, days, mean (SD)	2.3 (7)	3.2 (12)	2.0 (4)	0.34
ICU stay, n (%)	57 (36.8)	14 (31.8)	43 (38.7)	0.50
ICU days, mean (SD)	3.3 (4)	3.1 (5)	3.4 (6)	0.85
Ventilator days, n (%)	110 (71.0)	25 (56.8)	85 (76.6)	0.02*
Ventilator days, mean (SD)	2.4 (6)	3.4 (9)	2.1 (4)	0.32
Discharge GCS, mean (SD)	3.5 (2)	3.8 (3)	3.4 (2)	0.47
Discharge GOSE, mean (SD)	1.5 (1)	1.5 (1)	1.5 (1)	0.90
Discharge disposition, n (%)				0.34
Rehabilitation/nursing facility	3 (1.9)	2 (4.5)	1 (0.9)	
Home	1 (0.6)	0 (0.0)	1 (0.9)	
Missing	2 (1.3)	0 (0.0)	2 (1.8)	
Need for amputation, n (%)	1 (0.6)	1 (2.3)	0 (0.0)	0.28
Systemic complications, n (%)	18 (11.6)	5 (11.4)	13 (11.7)	0.60
Acute kidney injury	10 (6.5)	3 (6.8)	7 (6.3)	0.58
Pneumonia	5 (3.2)	1 (2.3)	4 (3.6)	0.56
ALI or ARDS	5 (3.2)	0 (0.0)	5 (4.5)	0.18
Multi-organ dysfunction syndrome (MODS)	8 (5.2)	1 (2.3)	7 (6.3)	0.28
Sepsis or septic shock	3 (1.9)	0 (0.0)	3 (2.7)	0.36
AKI – dialysis required	4 (2.6)	1 (2.3)	3 (2.7)	0.68
Bacteremia	1 (0.6)	1 (2.3)	0 (0.0)	0.28
Stroke	3 (1.9)	1 (2.3)	2 (1.8)	0.64
Paraplegia	0 (0.0)	0 (0.0)	0 (0.0)	–
Myocardial infarction	0 (0.0)	0 (0.0)	0 (0.0)	–

Systemic complications include having at least one of the following: AKI, pneumonia, ALI or ARDS, MODS, sepsis, AKI - dialysis required, bacteremia, paraplegia, stroke, and myocardial infarction.
*P<0.05.
AKI, acute kidney injury; ALI, acute lung injury; AO, aortic occlusion; ARDS, acute respiratory distress syndrome; CPR, cardiopulmonary resuscitation; GCS, Glasgow Coma Scale; GOSE, Glasgow Outcome Scale Extended; ICU, intensive care unit; LOS, length of stay; REBOA, resuscitative endovascular balloon occlusion; RT, resuscitative thoracotomy.

Table 6 Mortality overall and by severity controlling for age, gender, ISS, AO initiation SBP, admission lactate, duration of initial AO, crystalloid infusion, and CPR during AO

Independent covariates	All patients with TBI mortality OR (95% CI)	Mild TBI mortality OR (95% CI)	Severe TBI mortality OR (95% CI)
RT vs. zone 1	3.14 (1.03 to 9.64)*	2.49 (0.30 to 20.9)	4.21 (0.91 to 19.5)
Severe vs. mild TBI	3.03 (1.06 to 8.63)*	NA	NA
Age	1.05 (1.02 to 1.08)†	1.05 (1.01 to 1.11)*	1.05 (1.01 to 1.09)*
ISS	1.03 (0.99 to 1.06)	1.01 (0.94 to 1.09)	1.03 (0.99 to 1.08)
AO initiation SBP	1.00 (0.98 to 1.01)	0.98 (0.95 to 1.00)	1.01 (0.98 to 1.03)
Admission lactate	1.21 (1.07 to 1.37)†	1.43 (1.11 to 1.85)†	1.16 (0.99 to 1.35)
Crystalloids	0.96 (0.91 to 1.01)	0.78 (0.55 to 1.11)	0.97 (0.91 to 1.02)
CPR during AO	7.39 (2.26 to 24.2)†	1.28 (0.16 to 10.4)	23.7 (2.7 to 212)†
Duration of initial AO	1.00 (0.99 to 1.02)	0.98 (0.95 to 1.01)	1.01 (0.99 to 1.03)

*P<0.05
†**P<0.01.
AO, aorta occlusion; CPR, cardiopulmonary resuscitation; ISS, Injury Severity Score; NA, not applicable due to stratification by TBI severity; RT, resuscitative thoracotomy; SBP, systolic blood pressure; TBI, traumatic brain injury.

Table 7 Neurologic outcomes and systemic complications when controlling for age, gender, ISS, AO initiation SBP, admission lactate, duration of initial AO, crystalloid infusion, and CPR during AO in patients who survived beyond the operating room

Independent covariates	Patients with TBI Discharge GCS t-value (95% CI)	Patients with TBI Discharge GOSE t-value (95% CI)	Patients with TBI with systemic complications OR (95% CI)
RT vs. zone 1	−0.62 (−4.68 to 3.44)	−0.14 (−1.24 to 0.94)	0.86 (0.24 to 3.13)
Severe vs. mild TBI	−1.73 (−5.0 to 1.55)	−0.20 (−1.16 to 0.76)	1.06 (0.35 to 3.23)
Age	−0.05 (−0.13 to 0.04)	−0.01 (−0.03 to 0.02)	0.99 (0.96 to 1.02)
ISS	−0.04 (−0.14 to 0.07)	0.01 (−0.02 to 0.04)	1.00 (0.97 to 1.04)
AO initiation SBP	−0.002 (−0.05 to 0.05)	0.001 (−0.01 to 0.01)	0.98 (0.96 to 0.99)**
Admission lactate	−0.29 (−0.69 to 0.12)	−0.09 (−0.19 to 0.01)	1.00 (0.89 to 1.12)
Crystalloids	0.24 (−0.17 to 0.64)	−0.08 (−0.03 to 0.18)	1.24 (1.06 to 1.44)**
CPR during AO	−3.60 (−7.79 to 0.59)	−0.52 (−1.65 to 0.60)	0.33 (0.08 to 1.35)
Duration of initial AO	−0.02 (−0.06 to 0.01)	−0.004 (−0.01 to 0.004)	0.98 (0.96 to 0.99)*

*P<0.05, **P<0.01.
AO, aorta occlusion; CPR, cardiopulmonary resuscitation; GCS, Glasgow Coma Scale; GOSE, Glasgow Outcome Scale Extended; ISS, Injury Severity Score; RT, resuscitative thoracotomy; SBP, systolic blood pressure; TBI, traumatic brain injury.

device at other centers. Whether these factors impact the results is unknown, but the data do represent both low-volume and high-volume centers, large and small devices, and both early and evolving AO practice patterns.

CONCLUSION

Patients with TBI who receive REBOA in zone 1 may have improved survival, but no difference in systemic complications, compared with patients who receive RT for the same indication. Although some patients are receiving RT prior to arrest for extrathoracic hemorrhagic shock, these results suggest that REBOA should be considered as an alternative to RT when RT is chosen for the sole purpose of resuscitation in the setting of TBI.

Contributors MB: study design, data interpretation, writing, final review. BZ: statistical analyses, data interpretation, final review. RC, JM, TS, LJM, JP, JBH, KI, JWC, MS, CS, CF, EEM, and JAI: final review. AAST Multi-Institutional Trials Committee: patient enrollment and data collection.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests MB, JM, CF: Prytime Medical, Clinical Advisory Board Members. LJM: Frontline Medical, Clinical Advisory Board Member, Consultant.

Patient consent for publication Not required.

Ethics approval The subjects in this study are from an established de-identified database and no IRB is required to publish results. The prospective AORTA study was approved by the AAST Multi-Institutional Trials Committee. All collaborating centers obtained local IRB approval before participation.

Provenance and peer review Commissioned; externally peer reviewed.

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REFERENCES

1 García AF, Manzano-Nunez R, Orlas CP, Ruiz-Yucuma J, Londoño A, Salazar C, Melendez J, Sánchez Álvaro I, Puyana JC, Ordoñez CA. Association of resuscitative endovascular balloon occlusion of the aorta (REBOA) and mortality in penetrating trauma patients. Eur J Trauma Emerg Surg 2020. [Epub ahead of print: 16 Apr 2020].
2 Yamamoto R, Cestero RF, Suzuki M, Funabiki T, Sasaki J. Resuscitative endovascular balloon occlusion of the aorta (REBOA) is associated with improved survival in severely injured patients: a propensity score matching analysis. Am J Surg 2019;218:1162–8.
3 Aoki M, Abe T, Hagiwara S, Saitoh D, Oshima K. Resuscitative endovascular balloon occlusion of the aorta may contribute to improved survival. Scand J Trauma Resusc Emerg Med 2020;28:62.
4 Brenner M, Inaba K, Aiolfi A, DuBose J, Fabian T, Bee T, Holcomb JB, Moore L, Skarupa D, Scalea TM. Resuscitative endovascular balloon occlusion of the aorta (reboa) may be superior to resuscitative (RT) in select patients with hemorrhagic shock: early results the AAST AORTA rRegistry. J *Am Coll Surg* 2018;226:730–40.
5 Moore LJ, Brenner M, Kozar RA, Pasley J, Wade CE, Baraniuk MS, Scalea T, Holcomb JB. Implementation of resuscitative endovascular balloon occlusion of the aorta as an alternative to resuscitative thoracotomy for noncompressible truncal hemorrhage. J Trauma Acute Care Surg 2015;79:523–32.
6 Teeter W, Bradley M, Romagnoli A, Hu P, Li Y, Stein D, Scalea T, Brenner M. Treatment effect or effective treatment? total cardiac compression fraction and end tidal CO2 is higher in patients receiving REBOA compared to RT. Am *Surg* 2018;84:1691–5.
7 Johnson MA, Williams TK, Ferencz S-AE, Davidson AJ, Russo RM, O'Brien WT, Galante JM, Grayson JK, Neff LP. The effect of resuscitative endovascular balloon occlusion of the aorta, partial aortic occlusion and aggressive blood transfusion on traumatic brain injury in a swine multiple injuries model. J Trauma Acute Care Surg 2017;83:61–70.
8 Bailey ZS, Cardiff K, Yang X, Gilsdorf J, Shear D, Rasmussen TE, Leung LY. The effects of balloon occlusion of the aorta on cerebral blood flow, intracranial pressure, and brain tissue oxygen tension in a rodent model of penetrating Ballistic-Like brain injury. Front Neurol 2019;10:1309.
9 Hoehn MR, Teeter WA, Morrison JJ, Gamble WB, Hu P, Stein DM, Brenner ML, Scalea TM. Aortic branch vessel flow during resuscitative endovascular balloon occlusion of the aorta. J Trauma Acute Care Surg 2019;86:79–85.
10 Brenner M, Stein DM, Hu PF, Aarabi B, Sheth K, Scalea TM. Traditional systolic blood pressure targets underestimate hypotension-induced secondary brain injury. J Trauma Acute Care Surg 2012;72:1135–9.
11 Chesnut RM, Marshall LF, Klauber MR, Blunt BA, Baldwin N, Eisenberg HM, Jane JA, Marmarou A, Foulkes MA. The role of secondary brain injury in determining outcome from severe head injury. J Trauma 1993;34:216–22.
12 Zafar SN, Millham FH, Chang Y, Fikry K, Alam HB, King DR, Velmahos GC, de Moya MA. Presenting blood pressure in traumatic brain injury: a bimodal distribution of death. J Trauma 2011;71:1179–84.
13 Fuller G, Hasler RM, Mealing N, Lawrence T, Woodford M, Juni P, Lecky F. The association between admission systolic blood pressure and mortality in significant traumatic brain injury: a multi-centre cohort study. Injury 2014;45:612–7.
14 Butcher I, Maas AIR, Lu J, Marmarou A, Murray GD, Mushkudiani NA, McHugh GS, Steyerberg EW. Prognostic value of admission blood pressure in traumatic brain injury: results from the impact study. J Neurotrauma 2007;24:294–302.
15 Barmparas G, Liou DZ, Lamb AW, Gangi A, Chin M, Ley EJ, Salim A, Bukur M. Prehospital hypertension is predictive of traumatic brain injury and is associated with higher mortality. J Trauma Acute Care Surg 2014;77:592–8.
16 DuBose JJ, Scalea TM, Brenner M, Skiada D, Inaba K, Cannon J, Moore L, Holcomb J, Turay D, Arbabi CN, *et al*. The AAST prospective aortic occlusion for resuscitation in trauma and acute care surgery (aorta) registry: data on contemporary utilization and outcomes of aortic occlusion and resuscitative balloon occlusion of the aorta (REBOA). J Trauma Acute Care Surg 2016;81:409–19.

17 DuBose J, Fabian T, Bee T, Moore LJ, Holcomb JB, Brenner M, Skarupa D, Inaba K, Rasmussen TE, Turay D, *et al*. Contemporary utilization of resuscitative thoracotomy: results from the AAST aortic occlusion for resuscitation in trauma and acute care surgery (aorta) multicenter registry. Shock 2018;50:414–20.
18 Brain Trauma Foundation. https://braintrauma.org/uploads/07/04/Guidelines_for_the_Management_of_Severe_Traumatic.97250__2_.pdf.
19 Wasicek PJ, Li Y, Yang S, Teeter WA, Scalea TM, Hu P, Brenner ML. Examination of hemodynamics in patients in hemorrhagic shock undergoing resuscitative endovascular balloon occlusion of the aorta (REBOA). Injury 2019;50:1042–8.
20 Zammert M, Gelman S. The pathophysiology of aortic cross-clamping. Best Pract Res Clin Anaesthesiol 2016;30:257–69.
21 Norii T, Crandall C, Terasaka Y. Survival of severe blunt trauma patients treated with resuscitative endovascular balloon occlusion of the aorta compared with propensity score-adjusted untreated patients. J Trauma Acute Care Surg 2015;78:721–8.
22 Park TS, Batchinsky AI, Belenkiy SM, Jordan BS, Baker WL, Necsoiu CN, Aden JK, Dubick MA, Cancio LC. Resuscitative endovascular balloon occlusion of the aorta (REBOA): comparison with immediate transfusion following massive hemorrhage in swine. J Trauma Acute Care Surg 2015;79:930–6.
23 Brenner M, Teeter W, Romagnoli A, Hoehn M, Stein D, Scalea T. Resuscitative endovascular balloon occlusion of the aorta (REBOA) is a feasible option for proximal aortic control in severe hemorrhage and arrest. JAMA Surg 2018;153:130–5.