Resuscitative endovascular balloon occlusion of the aorta: an option for noncompressible torso hemorrhage?

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Purpose of review
Hemorrhage is the major cause of early death in severely injured patients. In civilian emergency medical services, the majority of life-threatening bleedings are found in noncompressible body regions (e.g. abdomen and pelvis). Resuscitative endovascular balloon occlusion of the aorta (REBOA) has therefore been discussed in recent years as a possible lifesaving procedure and numerous studies, meta-analyses and guidelines have been published. In this review, the data situation of REBOA in the management of bleeding trauma patients is discussed and practical implementation is depicted.

Recent findings
The typical indication for REBOA is a traumatic life-threatening hemorrhage below the diaphragm in patients unresponsive or only transiently responsive to the usual conservative therapeutic measures. REBOA appears to be a safe and effective procedure to reduce blood loss and stabilize the patient's hemodynamic status. However, surgical hemostasis has to be achieved within 30–60 min after occlusion of the aorta. Data on clear advantages of REBOA over resuscitative thoracostomy are inconclusive.

Summary
REBOA could play an important role in the management of the severely bleeding patient in the future. Together with transfusion and therapy of coagulation disorders, REBOA may be an additional tool in the anesthetist's hands for trauma management in interprofessional care concepts.

Keywords
aortic occlusion, emergency trauma room, management of bleeding, resuscitative endovascular balloon occlusion of the aorta, trauma

INTRODUCTION

Hemorrhage is responsible for 30–40% of fatalities among severely injured patients. In particular, hypotensive trauma patients with serious noncompressible bleeding have a high mortality rate of up to 85%. Although bleeding in the extremities can generally be managed by manual compression, the vast majority of cases of life-threatening bleeding encountered by civilian rescue services in Europe are found in noncompressible body regions such as the pelvis and the abdomen. For these regions, there are unfortunately no effective measures for early hemorrhage control, with the exception of the pelvic sling/binder. As a result, the mortality of patients with such injuries is high [1,2].

Aortic occlusion is a potentially valuable tool for early resuscitation of patients nearing extremis or in arrest from severe hemorrhage. Resuscitative endovascular balloon occlusion of the aorta (REBOA) can quickly and significantly reduce blood loss in case of major bleeding from abdominal and pelvic injuries, and increase afterload for the perfusion of the heart and brain. It has therefore been discussed in recent years as a possible lifesaving procedure and has been mentioned in numerous published studies, meta-analyses and guidelines [3▪▪,4▪,5–14,15▪,16–18,19▪].

This procedure has been applied for many years in vascular surgical clinics to temporarily control

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Curr Opin Anesthesiol 2019, 31:000–000
DOI:10.1097/ACO.0000000000000699

KEY POINTS

- Noncompressible torso hemorrhage continues to be a problem in the management of severely injured patients, and often results in death.
- For life-threatening hemorrhage in the subphrenic region, REBOA appears to be a safe and effective procedure for rapidly reducing blood loss and for stabilizing the hemodynamic status.
- REBOA can provide approximately 30–60 min of time until definitive surgical hemostasis in the abdomen or pelvis.
- To date, it is unclear whether resuscitative thoracotomy with open compression of the aorta or REBOA should be the preferred method.
- Before REBOA and be implemented, clear interdisciplinary instructions must be developed, and training courses for the entire team must take place.

bleeding in patients with ruptured aortic aneurysms. REBOA has also been successfully used to reduce blood loss during elective pelvis and liver surgery, following rupture of a splenic artery aneurysm, for postpartum hemorrhage in clinical as well as out-of-hospital settings, and even in a combat environment [20–28].

The objective of this overview is to show the potential of REBOA in the acute medical care of bleeding trauma patients, to explain its technical application – particularly under emergency medical conditions – to discuss the advantages and disadvantages of REBOA and to compare them to other invasive procedures (e.g. resuscitative thoracotomy) and to draw practical conclusions for the establishment of REBOA in the field of emergency medicine.

MATERIALS AND METHODS

This narrative review summarizes current literature about REBOA in patients with life-threatening (traumatic) torso hemorrhage. As far as possible, it was written in accordance with the PRISMA guidelines [29]. In August 2018, we conducted a literature review in the PubMed database for the period 2016–2018 using the keywords 'REBOA', 'balloon occlusion' and 'trauma'. The authors supplemented their findings with a manual search of publications as well as their own clinical experience and opinions [14].

ENDOVASCULAR BALLOON OCCLUSION OF THE AORTA

Preparation

All required material (introducer sheath, guide wires, occlusion catheters, surgical set for vessel exposure and fixation of the catheter) must be checked for compatibility and packed in a set in advance. Figure 1 [14] and Table 1 [14] provide an overview of currently available products and their characteristics. As REBOA is not performed frequently, an interdisciplinary and interprofessional checklist should be prepared.

Because of low incidence rates even in major trauma centers (i.e. 1–2 cases per year per level I trauma center in the United Kingdom [30] or Germany [31]), suitable training programmes for all members of the trauma team must be organized, with special emphasis on local equipment and standards [32–34] (c.f. Figure 2a–h) [34].

Arterial cannulation

The major rate-limiting step when using REBOA is the safe cannulation of the common femoral artery (CFA) in a patient in shock [19▪], especially in cardiac arrest [35]. The site of access for REBOA is the CFA [3▪▪]. Neither the superficial femoral artery nor the iliac artery should be used. Whether to remove a previously applied pelvis binder/sling is a decision of the trauma leader. We feel that removal should be avoided, and recommend pelvis slings that allow medical personnel to cut a triangular opening in the groin region with clothing scissors so that the artery is accessible [5].

Cannulation is generally carried out via an ultrasound-guided percutaneous puncture, or alternatively via an open surgical cut-down technique [4▪,5,13,19▪]. The use of ultrasound is essential for safe puncture of the CFA.

If the primary survey reveals injuries to the abdomen or pelvis that might be indications for REBOA, clinicians should consider using the CFA as the primary site for invasive blood pressure measurement as opposed to the radial artery. In this way, REBOA can be established easily if indicated in the further course without an additional puncture. Operators must ensure the compatibility of the sheath system guide wires with the catheters for invasive blood pressure measurement in advance.

Position of the balloon

For positioning of the balloon, three different sections of the aorta are distinguished (Fig. 3) [36,14]:

(1) Zone I: branch of the left subclavian artery to branch of the celiac trunk,
(2) Zone II: between celiac trunk and renal arteries (nonocclusion zone),
(3) Zone III: infrarenal abdominal aorta.

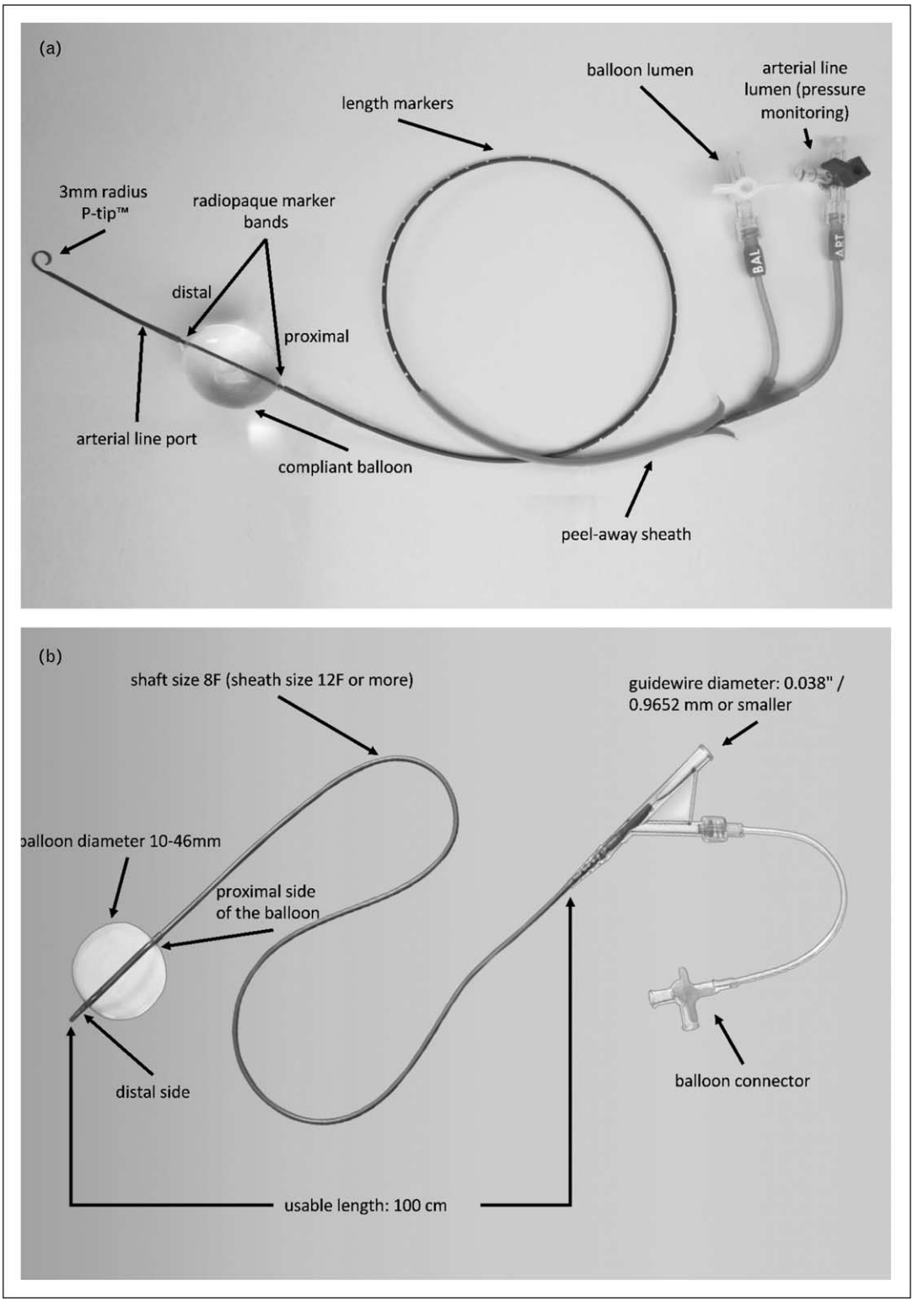

FIGURE 1. (a) ER-REBOA catheter. Modified figure courtesy of Prytime Medical, Boerne, Texas, USA. Adapted from Knapp *et al.* [14]. (b) RELIANT Stent Graft Balloon Catheter. Modified figure courtesy of Medtronic, Santa Rosa, California, USA. Adapted from Knapp *et al.* [14].

The balloon catheter is inflated in zone I for control of severe intra-abdominal or retroperitoneal hemorrhage, or for patients with traumatic arrest. For patients with severe pelvic, junctional or proximal lower extremity hemorrhage, zone III occlusion is called for [19▪]. Positioning the balloon in zone II should be avoided because of the possible occlusion

Table 1. Description of various endovascular catheters for resuscitative endovascular balloon occlusion of the aorta

Product	Manufacturer	Minimal sheath size	Balloon diameter	Length	Characteristics
ER-REBOA	Prytime Medical Devices (Boerne, Texas, USA)	7 Fr	32 mm	72 cm	Connector for invasive blood pressure monitoring Soft, specially shaped tip (c.f. Figure 1A) No guide wire needed Visible length and radiographic marker Arterial monitoring port distal balloon
Rescue Balloon Occlusion Catheter	Tokai Medical Products (Kasugai, Aichi, Japan)	7 Fr	40 mm	100 cm	Visible length and radiographic marker Soft tip Set with a special guide wire in order to keep the balloon in position (e.g. during partial REBOA) Market leader in Japan
Coda	COOK Medical (Bloomington, Indiana, USA)	14 Fr	46 mm	120 cm	Standard tip
Coda-LP	COOK Medical (Bloomington, Indiana, USA)	12 Fr	32 mm	100 cm	Standard tip
RELIANT Stent Graft Balloon Catheter	Medtronic (Santa Rosa, California, USA)	12 Fr	10–46 mm	100 cm	Standard tip (c.f. Figure 1B) Guide wire needed (0.038'' or smaller) REBOA and further indications
Fogarty Occlusion Catheter	Edwards Lifesciences (Irvine, California, USA)	8 Fr	45 mm	80 cm	Different configurations available
Q50 PLUS Stent Graft Balloon Catheter	Qx Médical (Montreal, Quebec, Canada)	12 Fr	10–50 mm	65 cm and 100 cm models	Initially designed for EVAR / TEVAR and so on. Guide wire needed (0.038'' or 0.035'')
ResQ Occlusion Balloon Catheter	Qx Médical (Montreal, Quebec, Canada)	11 Fr	10–38 mm	67 cm	Available only in the United States

EU, European Union; EVAR, endovascular aortic repair; Fr, French; TEVAR, thoracic endovascular aortic repair.
The specifications came from the manufacturers (modified from Knapp *et al.* [14]).

of the celiac trunk or the superior mesenteric artery, leading to mesenteric ischemia [36].

The approximate insertion depth for positioning the balloon in the desired zone should be estimated beforehand on the basis of anatomical landmarks [37–40]:

(1) Zone I occlusion: the direct distance between the puncture site and the middle of the patient's sternum (proximal end of the balloon, c. f. Figure 1a–b)
(2) Zone III occlusion: the direct distance between the puncture site and the navel. Alternatively, the balloon can be allowed to migrate in a distal direction until occlusion is achieved above the aortic bifurcation. The latter is the preferred method in the prehospital setting.

During resuscitation, the correct position of the balloon must be reassessed regularly. For zone I placements, a transesophageal echocardiogram can be used as with the placement of intra-aortic balloon pumps. Alternatively, a radiograph of the chest or abdomen will normally allow clinicians to check the approximate position of the balloon. For a zone I REBOA, the balloon should be positioned in the thoracic spine from Th 4 to Th 11, and for a zone III occlusion below L 2. Under good ultrasound conditions, abdominal sonography may suffice for assessing positions in zone III. Of course, the position can also be checked with whole-body computed tomography.

Occlusion phase and immediate surgical hemostasis

The volume required to inflate the balloon depends on the manufacturer and the balloon's position (Table 1). In zone I, the aorta usually has a diameter of 1.8–2.5 cm. Consequently, 8 ml of insufflation volume is required for an ER-REBOA catheter and 9–10 ml for a RELIANT catheter. The volumes needed for zone III occlusion (physiological aortic diameter: 1.3–1.8 cm) are 5 and 4–6 ml, respectively. The goal is a loss of pulsatile blood flow

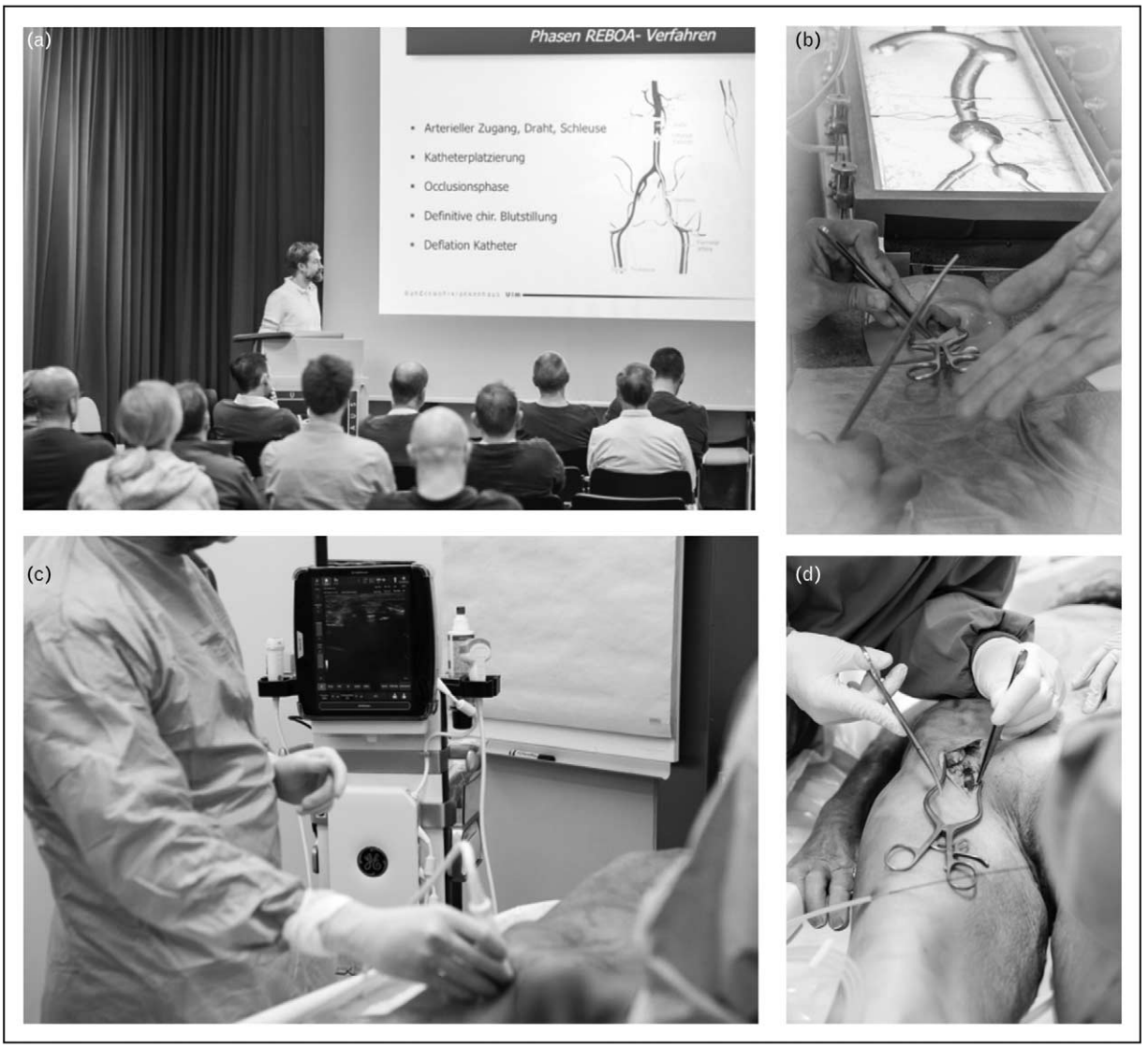

FIGURE 2. (a–h): REBOA education (a), training (b–g) and clinical impression (h). (a) Education of REBOA with special emphasis of local equipment. (b) Training with a model. (c) Human cadaver training at the University of Heidelberg, Germany, during the INTECH Advanced Course: Ultrasound of femoral vessels [34]. (d) Human cadaver training at the University of Heidelberg, Germany, during the INTECH Advanced Course: open preparation of femoral artery [34]. (e) Human cadaver training at the University of Heidelberg, Germany, during the INTECH Advanced Course: insertion of sheet [34]. (f) Human cadaver training at the University of Heidelberg, Germany during the INTECH Advanced Course: Placement of REBOA catheter [34]. (g) Perfused human cadaver training during a training course at Armed Forces Hospital, Berlin, Germany (courtesy of Lt Col. Dr. Hauer). (h) Clinical impression of a patient with REBOA in situ after futile resuscitation attempts in the ER.

(measured invasively at the sheath or in the contralateral femoral artery) distal to the balloon. Overinflating the balloon must be avoided.

The balloon position must be well stabilized in order to avoid distal dislocation as a result of blood flow. This is particularly the case if a guide wire-free occlusion catheter such as the ER-REBOA is used. Reasons for dislocation are catheter kinking and the lack of fixation options with various products. Thus, a long sheath is recommended for a zone I occlusion to improve catheter stabilization and assisting staff should hold the catheter in place as long as it is not securely fixed [36].

If a REBOA catheter is used which does not allow blood pressure to be measured distal of the occlusion, pressure must be measured invasively at an upper extremity. This should ideally be done on the left arm in order to rule out overly proximal positioning of the balloon and the risk of cerebral ischemia. If invasive blood pressure is measured on the

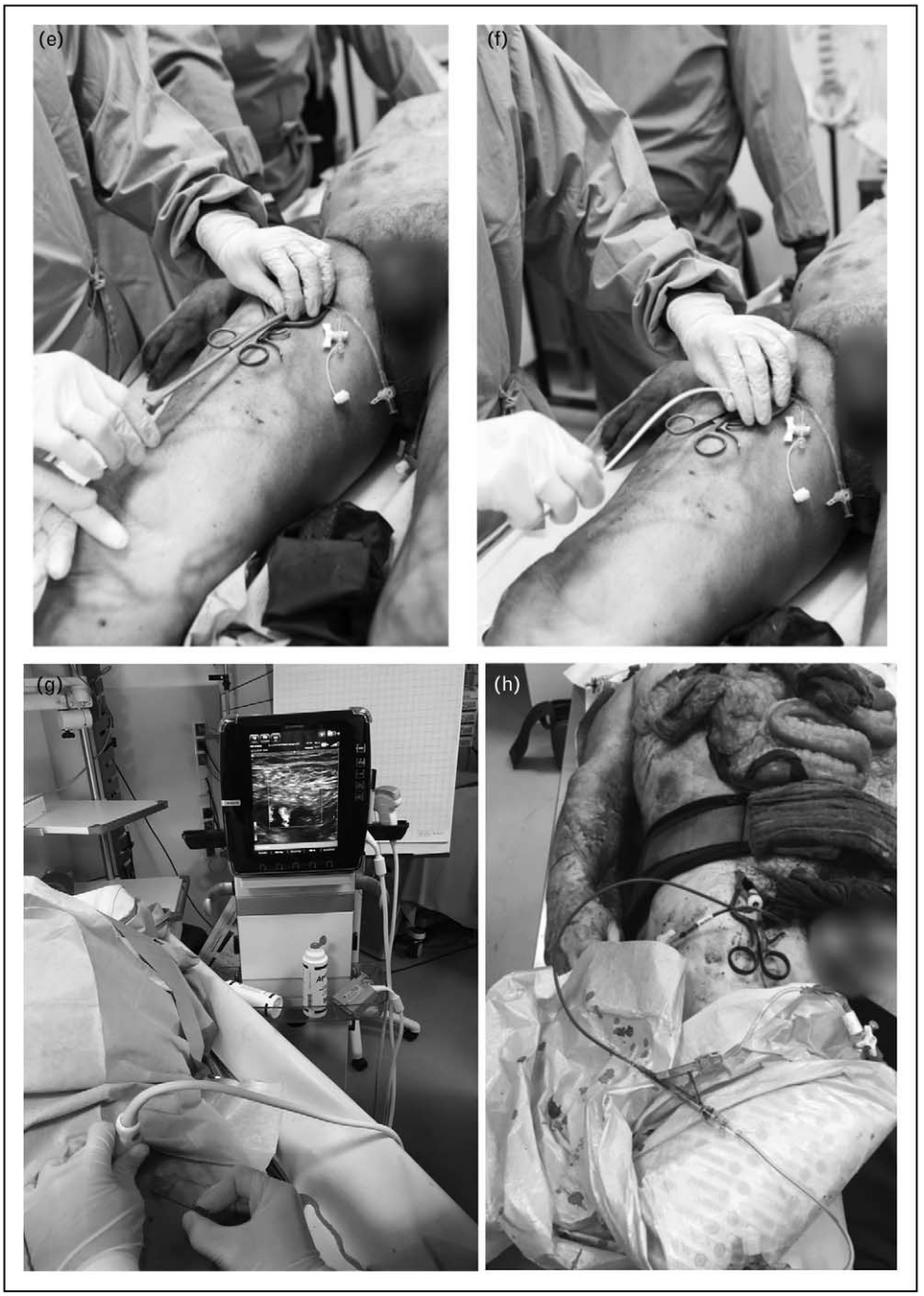

FIGURE 2. (Continued).

right arm, at least a palpable pulse on the left arm should be ensured until deflation of the balloon. Apparent cardiocirculatory stability during the occlusion phase should only be considered as a short gain in time for surgical bleeding control and should in no way lead to a delay in the further surgical or interventional management of the bleeding.

Also, the reported mean occlusion times in zone I and III are 58.5 and 68.0 min, respectively [3▪▪]. Thus, surgical hemostasis should be achieved as quickly as possible, ideally within 45 min in the case of zone I occlusion. Otherwise, a lethal outcome can be expected in most cases [11]. Longer successful occlusion times (up to 120 min) can be tolerated for zone III REBOA, for partial occlusion and for intermittent deflation of the balloon [41]. Damage control surgery should therefore be performed as early as possible. The American College of Surgeons Committee on Trauma (ACS COT) and the American College of Emergency Physicians (ACEP) even recommend that 'REBOA should not be placed in emergency departments in institutions

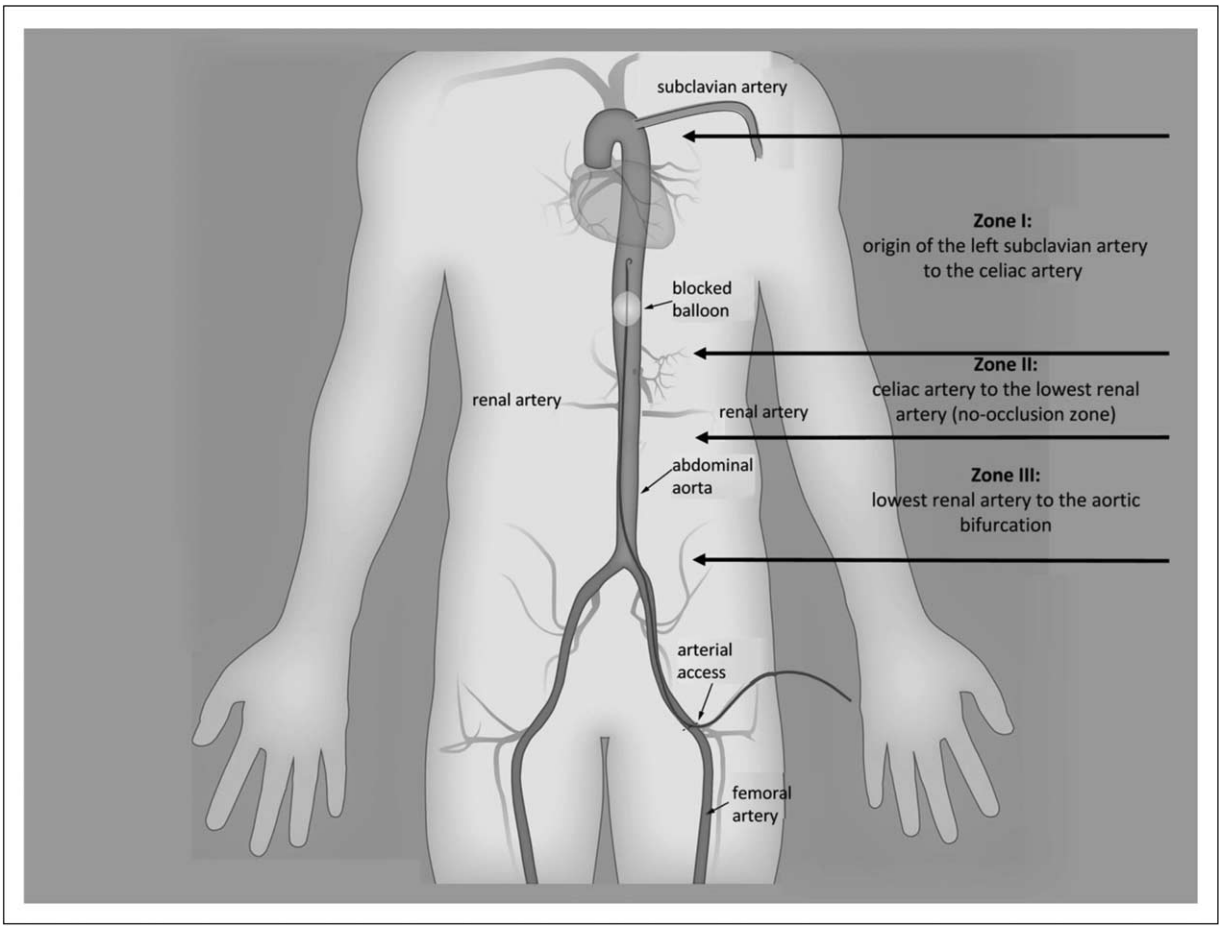

FIGURE 3. REBOA zones. REBOA zone I–III according to Stannard *et al.* 2011 [36] (modified figure courtesy of Prytime Medical Boerne, Texas, USA; adapted from Knapp *et al.* [14]).

where the patient cannot receive definitive surgical care and hemostasis at that same institution' [19▪].

In addition, the concept of permissive hypotension should also be applied to trauma patients without traumatic brain injury (TBI) during the occlusion phase. In patients with TBI, an excessive increase in cerebral perfusion pressure (> 70 mmHg) must be avoided, as this may lead to massive intracranial hemorrhage and worsen neurological outcome [10,42].

Deflation phase

The balloon should be deflated slowly and gradually in order to avoid reperfusion injuries. The literature suggests that the mean arterial pressure distal to the occlusion balloon should be increased by a maximum of 50% above the initial value every 5 min [43]. A more pragmatic approach would be to slowly deflate the balloon milliliter by milliliter and to monitor the hemodynamic response of the patient. In the event of increasing hemodynamic instability, the balloon must be reinflated. Therapeutic measures such as volume replacement, the administration of vasopressors, sodium hydrogencarbonate or glucose/insulin infusion to treat hyperkalemia should be initiated early and proactively. Especially during this period, a blood gas analysis should be conducted every 10 min to monitor the acid-base balance and the electrolyte balance [44]. As clotting is expected to deteriorate, the clotting status of the patient must also be checked regularly, if possible by thromboelastometry.

The patient must be critically re-evaluated before the balloon and sheath are removed, as further bleeding must be expected after deflation of the balloon. Large sheaths (12–14 Fr) should be removed by a vascular surgeon in open surgery. By contrast, most smaller sheaths do not require suturing, and 20–30 min of manual compression is considered to be sufficient [45]. Perfusion distal to the puncture site should be closely monitored both clinically and via Doppler sonography. The role of prophylactic administration of anticoagulants in this situation is unclear and depends on the trauma-induced coagulopathy.

SIDE-EFFECTS AND COMPLICATIONS

In contrast to resuscitative thoracotomy, several narrative reviews and systematic meta-analyses like the ones of Ribeiro *et al.* [46■] and Borger van der Burg *et al.* [3▪▪] focus on side-effects and systemic complications of REBOA. Reviewers state that it is difficult to distinguish whether a complication is associated with the procedure or is a result of the underlying trauma. Furthermore, many patients can be expected to die before a complication becomes obvious.

Procedural complications

Complications connected to vascular access and the insertion of the occlusion balloon appear to be rare (1.5–10%) [3▪▪,4▪,47▪▪]. Reported femoral access complications include arterial disruption, dissection, pseudoaneurysms, hematoma, thromboembolism and extremity ischemia [19▪]. Teeter *et al.* [45] reported no access-related complications at all after using REBOA 33 times. By contrast, Saito *et al.* [48] reported that three patients with vascular injuries or limb ischemia after REBOA required amputation of a lower limb. In a meta-analysis of 13 studies ($n = 424$ trauma patients) with groin access (73.4% percutaneous), Manzano-Nunez *et al.* [47▪▪] found an overall complication rate of 5.6%. Lower limb amputation was required in 2.1%, with at least three cases directly related to the insertion of REBOA. Borger van der Burg *et al.* [3▪▪] analyzed 89 studies with 1482 REBOA patients and found a similar complication rate of 3.6%. Table 2 [5,4▪,9,13,38,45,48,49,50▪,51] provides an overview of complications associated with REBOA. It seems that vascular complications are reduced if smaller sheets and smaller balloons are used [52], but the preferable technique for closing the wound is still under debate [53].

Systemic complications

With regard to systemic complications, typical problems associated with aorta surgery are to be expected, particularly if aortic occlusion takes place in zone I: acute renal failure, hepatic failure, meserentic ischemia and paraplegia as a result of spinal ischemia [19▪,46▪]. A direct connection may be assumed between occlusion time and the position of the aortic occlusion on the one hand, and the severity of ischemia on the other hand. Up until now, no pulmonary complications (acute respiratory distress syndrome and pulmonary edema) after REBOA have been reported in the Aortic Occlusion for Resuscitation in Trauma and Acute Care Surgery (AORTA) register, but after open aortic occlusion (0.0 vs. 4.4%, $P = 0.149$) [13].

The sudden increase in cardiac afterload can lead to myocardial decompensation and consecutive ischemia in initially hypotensive patients, to

Table 2. Procedural complications and systemic side-effects of resuscitative endovascular balloon occlusion of the aorta

Study	Patients	Procedural complications	Systemic side-effects
Brenner *et al.* [5]	$n = 6$ (REBOA)	None	None
Brenner *et al.* [4▪]	$n = 83$ (REBOA) $n = 202$ (RT)	Extremity ischemia ($n = 1$) Distal embolism ($n = 4$) Infection requiring antibiotics only ($n = 1$) Need for patch angioplasty ($n = 2$) Need for amputation ($n = 1$) Retained hemothorax requiring operative evacuation via VATS or thoracotomy ($n = 3$; 1.5%)	None None
DuBose *et al.* [13]	$n = 46$ (REBOA)	Distal embolism ($n = 2$) Pseudo aneurysm ($n = 1$)	ARF ($n = 2$) MOV ($n = 2$) Pneumonia ($n = 2$) Sepsis ($n = 2$)
Martinelli *et al.* [38]	$n = 13$ (REBOA)	Thrombosis femoral artery ($n = 1$)	None
Moore *et al.* [9]	$n = 24$ (REBOA)	None	None
Ogura *et al.* [49]	$n = 7$ (REBOA)	None	None
Sadeghi *et al.* [50▪]	$n = 96$ (REBOA)	13 (miscellaneous)	
Saito *et al.* [48]	$n = 24$ (REBOA)	Vessel injury ($n = 1$) Extremity ischemia ($n = 2$)	ARF ($n = 6$) MOV ($n = 9$)
Teeter *et al.* [45]	$n = 33$ (REBOA)	None	ARF ($n = 1$)
Tsurukiri *et al.* [51]	$n = 16$ (REBOA)	Failed vascular access ($n = 3$)	ARDS ($n = 1$)

ARDS, acute respiratory distress syndrome; ARF, acute renal failure; MOF, multiorgan failure; RT, resuscitative thoracotomy; VATS, video-assisted thoracoscopy.

myocardial ischemia and, due to the rise in pulmonary artery pressure, even to pulmonary edema. This can be somewhat attenuated by slow and initially incomplete occlusion [15▪].

We can only roughly estimate what occlusion times are currently considered to be safe. Animal experiments have shown that 60 min of occlusion in zone I is tolerated, whereas 90 min of occlusion led to organ damage (but the animals survived) [46▪,54,55]. In addition, a narrative review of patients with hemorrhagic shock showed a clear link between occlusion time and patient survival, as only two patients with a REBOA time of greater than 90 min survived [40]. The severity of the trauma could have been the reason for the long occlusion time, however. In the clinical setting, occlusion times between 25 min and a maximum of 40 min in zone I are currently considered safe [16,41]. Longer occlusion times in zone III are presumably tolerable [56].

Partial resuscitative endovascular balloon occlusion of the aorta

Advantages of partial endovascular occlusion of the aorta (P-REBOA) are that proximal hyperperfusion is avoided, occlusion time is prolonged and the hemodynamic and metabolic effects of reperfusion are reduced [12,43,48,57,58▪▪,59]. A current evaluation of Japanese register data showed that a median occlusion time of 58 min for P-REBOA (compared to 33 min for complete REBOA, $P = 0.041$) was safe and tolerated without an increase in the complication rate [52]. Despite the longer occlusion time, patients in the P-REBOA group even demonstrated better hemodynamic stability after deflation than those who had complete REBOA. The death rates for both groups after 24 h and 30 days were comparable [52]. P-REBOA is only possible, however, if patients can hemodynamically tolerate a partial opening of the aorta and greater blood loss than with complete occlusion. Recent findings from Matsumura *et al.* [60▪] revealed that resuscitative thoracotomy and P-REBOA are not mutually exclusive.

PATIENT SELECTION

Table 3 [5,4▪,9,12,13,38,45,48,49,50▪,51,60▪,61▪,62] presents indications for the use of REBOA, trauma mechanisms and treatment outcomes of REBOA patients. On the basis of figures, the patients most likely to benefit from REBOA are those with traumatic life-threatening hemorrhage below the diaphragm who are in hemorrhagic shock and unresponsive or transiently responsive to the usual conservative therapeutic measures (e.g. pelvis sling, infusion, transfusion and vasopressors) [19▪]. REBOA may also be an option for patients arriving

Table 3. Selected studies on resuscitative endovascular balloon occlusion of the aorta

Study	Patients	Procedure investigated/ methods	Results
Aso *et al.* [61▪]	$n = 259$ severe trauma patients Thoracic injuries are excluded	$n = 191$ REBOA (22.0% in cardiopulmonary arrest) $n = 68$ RT (61.8% in cardiopulmonary arrest)	Survival rates: REBOA 52.9 vs. 29.4% for RT, but after risk adjustment via propensity score analysis no difference is detectable
Brenner *et al.* [5]	$n = 6$ patients with abdominal, pelvic trauma in severe hemorrhagic shock Cause of injury: MVA ($n = 4$), shootings ($n = 6$) $n = 1$ patient in TCA	REBOA treatment	$n = 4$ patients survived (67%) Patient with TCA: survived $n = 2$ patients died due to TBI
Brenner *et al.* [4▪]	$n = 285$ patients (American Association for the Surgery of Trauma's Aortic Occlusion in Resuscitation for Trauma and Acute Care Surgery registry) 41.4% penetrating injures ISS (median) 34	RT was used in 71%, and zone I REBOA in 29%	Overall survival beyond the ED was 50% (RT 44%, REBOA 63%; $P = 0.004$) and survival to discharge was 5% (RT 2.5%, REBOA 9.6%; $P = 0.023$) Overall, REBOA can confer a survival benefit over RT, particularly in patients not requiring CPR

Table 3 (*Continued*)

Study	Patients	Procedure investigated/ methods	Results
DuBose *et al.* [13]	$n=114$ patients from eight US trauma centers Cause of injury: MVA ($n=25$), high fall ($n=2$), shooting/stabbing ($n=10$), unclear. ($n=9$) $n=16$ TCA at admission	$n=46$ REBOA (zone I $n=33$, zone II $n=1$, zone III $n=8$) $n=68$ RT	13 of 46 REBOA patients survived (28%)
Irahara *et al.* [62]	$n=14$ patients with abdominal or pelvic trauma with noncompressible hemorrhage Blunt trauma ($n=13$), Penetrating trauma ($n=1$)	REBOA	$n=5$ patients survived (36%)
Martinelli *et al.* [38]	$n=13$ patients with pelvic trauma in shock Cause of injury: MVA ($n=5$), high fall ($n=8$), TCA at any time ($n=2$)	REBOA	$n=6$ patients survived (46%) Patients with TCA survived $n=6$ patients died due to exsanguination, in one case not known
Matsumura *et al.* [60▪]	$n=106$ trauma patients in shock from 18 hospitals requiring REBOA (and RT)	$n=30$ REBOA + RT $n=76$ REBOA only $n=74$ (70%) partial REBOA	Survival rate 64% Describes a combined use of REBOA, partial REBOA and RT
Moore *et al.* [9]	$n=24$ patients with abdominal or pelvic trauma with noncompressible hemorrhage (blunt and penetrating) TCA at admission in seven cases	REBOA	$n=9$ patients survived (38%) Survival rate of TCA patients: 0% Survival rate of non-TCA patients: 53% $n=7$ patients died due to TBI, $n=1$ patient died in MOV Cause of death not reported in eight cases
Norii *et al.* [12]	$n=351$ patients from the Japan Trauma Data Bank (2004–2011) Abdominal or pelvic trauma with noncompressible hemorrhage ISS 35	REBOA treatment Propensity score analysis	Survival rate 24% REBOA treatment is associated with lower survival compared with similarly ill trauma patients who did not receive REBOA (OR: 0.30, 95%-CI: 0.23–0.40)
Ogura *et al.* [49]	$n=7$ patients with abdominal or pelvic trauma in severe hemorrhagic shock despite transfusion	REBOA treatment	6 of 7 patients survived $n=1$ patient died due to TBI
Sadeghi *et al.* [50▪]	Trauma patients in severe hemorrhagic shock ($n=96$ REBOA)	REBOA treatment	Survival rate 44% ($n=42$)
Saito *et al.* [48]	$n=24$ patients with abdominal and/or pelvic trauma in shock and pending Cause of injury: MVA ($n=15$), high fall ($n=4$), not reported ($n=5$)	REBOA treatment	Survival rate 58% ($n=15$) Death due to hemorrhagic shock $n=1$, TBI $n=1$, MOV $n=5$, unclear $n=3$
Teeter *et al.* [45]	$n=33$ patients from five Japanese trauma centers in severe hemorrhagic shock Cause of injury: blunt trauma ($n=31$), unclear ($n=2$) TCA at admission $n=14$	REBOA treatment	Survival rate 48% ($n=16$) Patients with TCA 29% ($n=4$) survival rate Patients without TCA 63% ($n=12$) survival rate
Tsurukiri *et al.* [51]	$n=16$ patients in hemorrhagic shock (SBP <90 mmHg or shock index ≥ 1.0) Cause of injury: MVA ($n=10$), high fall ($n=5$), stabbing ($n=1$)	REBOA treatment	Survival rate 44% ($n=7$) $n=6$ patients died due to exsanguination, $n=1$ due to ARDS, TBI $n=3$

ARDS, acute respiratory distress syndrome; CI, confidence interval; MVA, motor vehicle accident; OR, odds ratio; RT, resuscitative thoracotomy; TBI, traumatic brain injury; TCA, traumatic cardiac arrest.

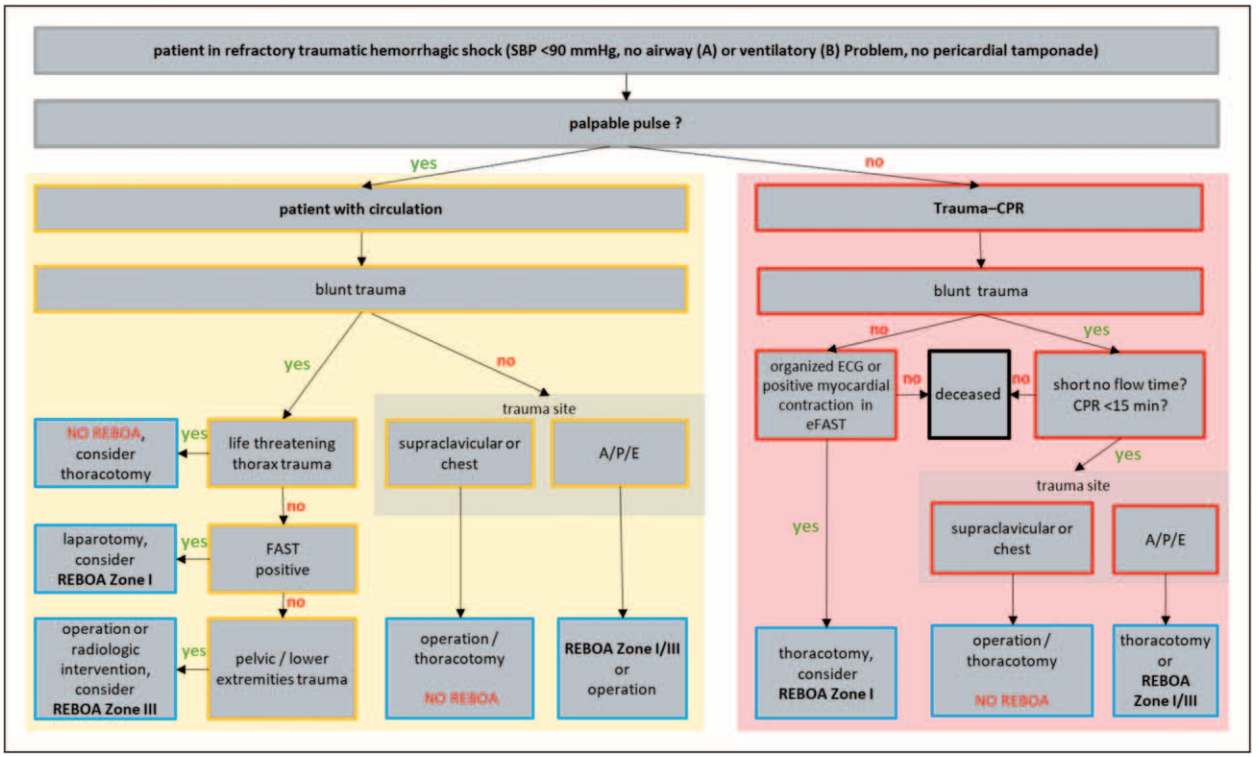

FIGURE 4. Clinical decision tree for the in-hospital use of REBOA in adult patients in traumatic hemorrhagic shock. A/P/E, abdomen/pelvis/extremities; ECG, electrocardiogram; Efast, extended focused assessment with sonography in trauma; Trauma-CPR, cardiopulmonary resuscitation after traumatic event. [18,63] (modified from Knapp *et al.* [14]).

in arrest from injury due to presumed life-threatening hemorrhage below the diaphragm if resuscitative thoracotomy is not immediately available. A possible clinical decision tree is depicted in Fig. 4 [14,18,63].

REBOA should not be used in patients with a major source of bleeding in the chest, mediastinum or supraclavicular injuries, as this would intensify the bleeding [64,65]. In patients with concomitant traumatic brain injuries, clinicians must bear in mind the problem of proximal hyperperfusion with consecutive increases in intracranial pressure. Although this problem may be avoided with P-REBOA, some experts nevertheless consider severe TBI as a contraindication for REBOA [59]. Another contraindication is severe aortic ectasia because of the lower maximum diameter of newer occlusion catheters (Table 1). Other contraindications are vascular implants or endoluminal stents at the puncture site or in the occlusion zone.

The advantage of REBOA over a resuscitative thoracotomy with supradiaphragmatic compression of the aorta is that the procedure is less invasive. Although resuscitative thoracotomy involves general anesthesia if the patient does not require CPR, and, as a result, the hemodynamic situation often deteriorates even further, it is possible to easily conduct REBOA under local anesthesia or analgosedation. In addition, REBOA allows a more selective approach to aorta occlusion than thoracic clamping in a resuscitative thoracotomy so that, in theory, fewer systemic side-effects are to be expected. The prospective AORTA register of the American Association for the Surgery of Trauma demonstrated that less time is required for successful aortic occlusion with REBOA (3.5 min) than with resuscitative thoracotomy (5.0 min; $P = 0.624$).

Borger van der Burg *et al.* [3▪▪] summarized the data of more than 2960 exsanguating patients. In patients with trauma, systolic blood pressure increased by an average of 78.9 mmHg. Despite their statistical finding that REBOA has a clear survival benefit in contrast to other treatment options for patients in severe shock [odds ratio 0.25; 95% confidence interval (CI) (0.11–0.56)], the authors state in the discussion of their meta-analysis that 'the majority of studies lack a sound control group'.

Few data are currently available on the use of REBOA for patients with traumatic cardiac arrest. A clinical study comparing REBOA with resuscitative thoracotomy in such patients was presented at the American College of Surgeons 2016 Annual Clinical Congress. This study identified a trend toward a higher mean systolic blood pressure in the REBOA group compared to the resuscitative thoracotomy group. There was, however, no significant difference in

survival between the two groups. Only one of the 36 patients in this study survived until discharge [63]. In view of current findings, resuscitative thoracotomy should be carried out on trauma patients requiring CPR provided that a correct indication has been established in accordance with current guidelines [17,66]. In summary, it is currently not possible to favor one method over the other on the basis of scientific findings, because of different injury patterns, indications and medical treatment situations [13,67–69].

The results of studies on REBOA treatment outcomes are shown in Table 3. Moore *et al.* [9] compared the treatment outcome of patients who, over a period of 18 months, underwent REBOA ($n = 24$) or a resuscitative thoracotomy with direct aortic cross-clamping ($n = 72$) in the trauma rooms of two large US trauma centers. They found a significantly higher survival rate for REBOA patients than for patients with open aortic clamping (38 vs. 10%, $P = 0.003$). However, 71% of the REBOA patients still had vital signs upon admission. This was the case in only 38% of the resuscitative thoracotomy patients. On the basis of case series and observational studies in the literature, it is not possible to say whether the treatment outcome of the patients is improved by REBOA and whether resuscitative thoracotomy or REBOA is the preferred procedure.

In this context, the results of several Japanese studies have to be discussed. One study used the propensity score method to compare the treatment outcome of 625 patients who underwent REBOA with the treatment outcome of 625 similarly injured patients who did not undergo REBOA [11]. The REBOA patient group had a significantly higher hospital mortality rate [62 vs. 45% (95% CI: 11–22%)]. The authors attributed this finding to the fact that it took a median time of 97 min (95% CI: 90–104 min) to perform surgery after the patient was admitted to the trauma room, and that enormous ischemia/reperfusion damage could be the reason for the negative treatment outcomes. Nevertheless, these results clearly show that, after REBOA, an intervention for definitive bleeding control (e.g. surgery and embolization) must be conducted without delay. In addition, in particular in zone I, REBOA cannot currently be recommended for patients who must be transported to a suitably equipped trauma center for further treatment. In 2017, Aso *et al.* [61▪] published another retrospective Japanese register study which found no survival benefit between REBOA and resuscitative thoracotomy in the case of trauma.

CONCLUSION

In the future, REBOA could assume an important role as an endovascular and catheter-based procedure for controlling bleeding in the clinical primary care of patients with hemorrhagic shock. Together with other endovascular procedures such as embolization and interprofessional care concepts (e.g. trauma hybrid operating room and resuscitation with angiography, percutaneous techniques and operative repair) [32,70–73], REBOA could become an additional important pillar for treatment of hemorrhage in severely injured patients, especially if resuscitative thoracotomy is not immediately available.

Acknowledgements

We thank Ms. Jeannie Wurz, Medical Editor, Department of Anaesthesiology and Pain Medicine, Bern University Hospital, for her editorial support.

Financial support and sponsorship

PD J.K. reports nothing to disclose.
Prof. E. P. reports nothing to disclose.
Outside this article, M.K. reports: 'grants' from German Federal Ministry of Defence (SoFo 34K3-17 1515 DigiPen), 'other' from German Interdisciplinary Association of Critical Care and Emergency Medicine (DIVI), 'other' from German Federal Ministry of Education (Research Grant: Verbundprojekt: Verbesserung der Versorgungsforschung in der Akutmedizin durch den Aufbau eines nationalen Notaufnahmeregisters'),'other' from Gemeinsamer Bundesausschuss ? ENQuIRE - Evaluierung der Qualitätsindikatoren von Notaufnahmen auf Outcome-Relevanz für den Patienten'' (VSF1_2017-020).

Conflicts of interest

J.K., E.P. and M.K. report no conflict of interest regarding the review's topic.

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