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Resuscitative Thoracotomy and Aortic Cross-Clamp and Resuscitative Endovascular Balloon Occlusion of the Aorta

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In traumatic hemorrhagic shock, there are situations where rapid aortic occlusion is required. In such cases, the best aortic occlusion should be determined based on the situation. Therefore, it is essential to understand the various types of aortic occlusion, their characteristics, and their indications. However, aortic occlusion is not hemostasis but temporary proximal control of arterial bleeding; definitive hemostasis should not be delayed even if blood pressure is elevated after aortic occlusion. We describe the indications, characteristics and implementation of each aortic occlusion and the comparison between resuscitative thoracotomy with aortic cross-clamp (RTACC) and resuscitative endovascular balloon occlusion of the aorta (REBOA). It is not necessary to discuss the superiority or inferiority of RTACC and REBOA. The appropriate determination of a combination of these tactics will increase the range of strategies and tactics.

Keywords: *Resuscitative Thoracotomy and Aortic Cross-Clamp (RTACC); Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA); Abdominal Aortic Compression/Occlusion*

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INTRODUCTION

There are three main methods of aortic occlusion. 1) cross-clamping the descending aorta after left anterolateral thoracotomy [1]; 2) compressing the aorta above the celiac artery after laparotomy; and 3) resuscitative endovascular balloon occlusion of the aorta (REBOA) [2,3]. Cross-clamping of the descending aorta is performed during resuscitative thoracotomy and called resuscitative thoracotomy with aortic cross-clamp (RTACC). It is essential to understand the characteristics of each of these methods, including REBOA, and use them appropriately according to the situation or in combination, depending on the situation.

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Ethical Approval and Informed Consent

Ethical approval was not required. Informed consent was not required.

INDICATIONS FOR AORTIC OCCLUSION

The algorithm for aortic occlusion is shown in Figure 1.

First, if the patient is hemodynamically unstable, early access to the femoral artery should be started in parallel with resuscitation [4]. If femoral artery access is rapidly achieved, REBOA is more advantageous than RTACC due to minimally invasive aortic occlusion [5]. Moreover, early arterial access makes REBOA more advantageous in terms of quickness than RTACC [6]. However, in an aging society such as Japan, even when early arterial access is achieved, it is often difficult to safely insert a guidewire or catheter through the artery

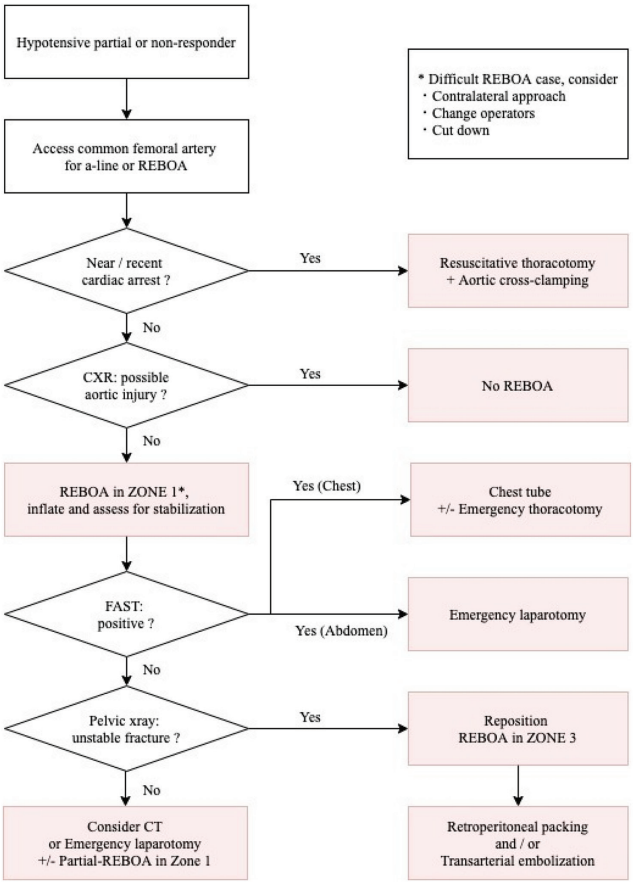

Figure 1 The algorithm for aortic occlusion.

due to vascular meandering, so it is desirable always to be ready to switch to RTACC.

In cardiac arrest or impending cardiac arrest, RTACC is more advantageous than REBOA in terms of quickness and accuracy [7]. On the other hand, in situations of non-impending cardiac arrest, the method of aortic occlusion should be selected according to the expected significant site of injury, whether arterial access is achieved or not, and the skill and proficiency of staff or the facility.

In the case of a thoracic aortic injury suspected by chest X-ray or ultrasonography, REBOA is not indicated because guidewire and catheter manipulation [5], as well as the elevation of blood pressure after occlusion, may exacerbate the injury and make it fatal [8]. If there is no suspect of thoracic aortic injury, REBOA should be placed in Zone 1, proceeding to resuscitation and hemostasis.

If a massive hemothorax is shown in the chest X-ray or Focused Assessment with Sonography for Trauma (FAST) is positive in the intrathoracic cavity, a chest tube should be placed, and emergency thoracotomy should be considered based on the amount of drainage and vital signs. If FAST is positive in the intraperitoneal cavity, emergency laparotomy should be performed.

When an unstable pelvic fracture is revealed in the pelvis X-ray with negative FAST, REBOA should be moved from Zone 1 to Zone 3, followed by angioembolization, retroperitoneal packing, and external fixation.

In the absence of an unstable pelvic fracture, the most common source of bleeding that causes shock despite "triple-negative" (chest and pelvis X-ray and FAST are all negative) may be non-cavitary hemorrhage, including high retroperitoneal hemorrhage. Traditionally, fundamental principles of Advanced Trauma Life Support (ATLS)® [9,10] and Japan Advanced Trauma Evaluation and Care (JATECTM) [11], Japanese trauma guidelines, include the policy that treatment should be prioritized to computed tomography (CT) diagnosis; thus, emergency laparotomy should be performed to investigate the cause of injury, even in the triple-negative situation. A CT scan in such a situation is beyond the current guideline. However, in such cases, a contrast-enhanced CT scan with partial REBOA in Zone 1 may be an option if the facility can perform a CT scan of shocked patients quickly or provide care in a hybrid emergency room (ER) [12,13].

If the primary source of bleeding is in the abdomen and open abdominal hemostasis is performed, abdominal aortic occlusion may be an option. In particular, it may be chosen in situations where laparotomy can be started quickly but femoral artery access is not yet achieved. When interventional radiology (IR) is chosen as hemostasis, abdominal aortic occlusion is not an option, and REBOA can be performed. However, if the cause of hemorrhagic shock requiring aortic occlusion is diagnosed as abdominal trauma, the principle of the treatment should remain that open abdominal hemostasis should be performed. IR after resuscitation with REBOA may be an option only when the cause of shock is a parenchymal organ injury (liver or spleen injury), and IR can be performed immediately to stop the bleeding in a hybrid ER or when a CT scan can be performed quickly [14].

Abdominal aortic compression is not an option in an isolated pelvic fracture. The Zone 3 REBOA is a good option anatomically when diagnosed as an isolated pelvic fracture. RTACC must be chosen in patients with cardiac arrest or impending cardiac arrest or in patients without arterial access.

Do not stick to a single aortic occlusion method even when chosen or attempted. Depending on the situation, alternative methods should be considered, and "plan B" should be chosen at any moment. For example, when REBOA is being attempted but arterial access is difficult to achieve, simultaneous attempts from another side, change of surgeon, or conversion to a cut-down technique should be considered. Furthermore, in case of impending cardiac arrest during the procedure, RTACC should be performed without hesitation.

Aortic occlusion is a "bridge" to definitive hemostasis, and too much time should not be taken to establish it. The priority is not to delay definitive hemostasis by surgery, IR, or the combination of both, and REBOA is a means to connect to that. Since aortic occlusion is not

hemostasis but temporary proximal control of arterial bleeding, definitive hemostasis should not be delayed even if blood pressure is elevated after aortic occlusion.

CHARACTERISTICS OF AORTIC OCCLUSION OTHER THAN REBOA

Resuscitative Thoracotomy with Aortic Cross-Clamp

Advantages and disadvantages of RTACC

RTACC is an aortic occlusion method that can quickly and securely clamp the aorta by identifying the descending thoracic aorta through direct visual inspection or manual palpation. It is characterized by its high degree of certainty and safety and is effective in treating impending cardiac arrest. It is often performed in resuscitative thoracotomy and can be performed simultaneously to relieve cardiac tamponade, hemostasis for cardiac, great vessel, pulmonary, chest wall injuries, prevention of air embolism, and direct cardiac massage [1,15,16]. Non-surgeons with good training and experience can perform it [17]; however, thoracotomy is a highly invasive procedure because it creates a new injury of Abbreviated Injury Scale (AIS) score of 3 points or more. There is a risk of postoperative bleeding, hypothermia, vascular injuries, intercostal arteriovenous injury, and spinal artery injury. In addition, if the patient has a history of thoracotomy or chronic lung disease with adhesions between the lung and pleura, it will take more time to perform the procedure. If the chest is left open for a long time, the patient is exposed to hypothermia as well as bleeding from the chest wall. It takes time and effort to close the chest. Also, it cannot be performed prophylactically like REBOA. RTACC requires a certain amount of clinical experience and simulation training because such rapidity and certainty depend on the performer's experience.

Tips and pitfalls of RTACC

It is necessary to develop a field of view that allows direct vision for definite aortic clamping. Since this may be difficult in the prehospital environment, aortic clamping may be performed by confirming the location of the aorta based on manual palpation. Since there is a possibility of incomplete clamping or insufficient clamping during transport, occlusion status must be checked frequently. When performing aortic clamping, the descending aorta can be easily visualized by dissecting the inferior pulmonary ligament and mobilizing the lung ventrally and cephalad. When clamping the aorta with Satensky clamp, it is possible to clamp the aorta with the parietal pleura if the descending aorta is protruding on the left side. However, in cases of shock, the aorta may collapse and be withdrawn to the mediastinum. In such cases, clamping the aorta with the parietal pleura may result in incomplete occlusion. In this case, the parietal pleura is incised and dissected to expose the aorta, and the descending aorta could be clamped securely. If the aortic clamping takes a long time or incomplete occlusion is anticipated, manual compression of the aorta toward the vertebral body should be performed. Since aortic occlusion is a vital resuscitation technique for temporary hemorrhage control, incomplete occlusion must be avoided to avoid cardiac arrest and save the patient's life. Although manual compression requires a staff member's hand, there are some situations in which manual compression is more reliable than continued uncertain use of Satensky clamp.

Abdominal Aortic Compression/Occlusion

The abdominal aortic compression/occlusion is a method of supraceliac aortic occlusion performed on the premise of laparotomy [18]. This aortic occlusion is when the assistant manually compresses the proximal aorta of the bifurcation of the celiac artery in the lesser omentum as soon as the upper abdomen is opened at the time of crash laparotomy. Continuously, the laparotomy wound is extended to the lower abdomen, and hemostasis is performed. Abdominal aortic compression is immediately followed after crash laparotomy and can be performed without invasion because it does not create new damage due to aortic occlusion, unlike RTACC [19]. It is beneficial because hemostasis and repair of damaged organs can be performed in the same surgical field after rapid manual compression [20]; however, to shift from manual compression to the aortic clamping, it is necessary to expose the aorta by making a sharp incision in the right diaphragmatic leg after incising the lesser omentum, bluntly widening it with the fingers. Because this technique is a little complicated and requires familiarity and experience, it is often performed by manual compression or compression with a special compressor [21]. At the same time, securing arterial access and implementing REBOA is also a good option. It is important to note that there are situations where the manual compressions may interfere with hemostasis or repair of the injured organ. RTACC is appropriate in cases of concomitant thoracic trauma, and this procedure is not an option when laparotomy is not required. RTACC is appropriate in cases of concomitant thoracic trauma, and this procedure is not an option when laparotomy is not required. This method has the following disadvantages: it cannot be performed prophylactically as in RTACC, it takes a long time in cases of the previous laparotomy due to adhesions, and it is performed only by physicians who can perform laparotomy [18,20].

ADVANTAGES AND DISADVANTAGES OF REBOA COMPARED TO RTACC

See Table 1.

Table 1 Advantages and disadvantages of REBOA compared to RTACC.

Advantages	*Disadvantages*
Less invasive	Maximally invasive
Can be performed with only local anesthesia before administration of analgesics and sedatives or tracheal intubation	Cannot be performed unless arterial access is achieved
Prophylactic use or early utilization	Lack of rapidity (not always the case if arterial access is already achieved)
Adjusting the balloon inflation volume is possible according to blood pressure (partial REBOA)	Risk of complications such as ischemia and necrosis of lower limb, vessel injury or dissection
Can be performed by both emergency physicians and surgeons with endovascular training	Difficulty of applying or high risk of complications in elderly patients with arteriosclerosis or aortic tortuosity
Accurate and rapid placement can be achieved with ultrasound	Fluoroscopy is preferrable for rapid and precise procedure

Advantages of Minimal Invasiveness

The most significant advantage of REBOA is that it is minimally invasive [3,22]. If arterial access is achieved, aortic occlusion can be performed quickly (reportedly more quickly than RTACC) and without invasion, such as creating a new open chest wound. In addition, RTACC and abdominal aortic occlusion require invasive surgical procedures such as thoracotomy or laparotomy, which require administration of analgesics and sedatives except in cardiac arrest, and are often preceded by secure airway management (usually tracheal intubation). The administration of these drugs in hemorrhagic shock increases the risk of hemodynamic instability and cardiac arrest. Therefore, the presence of anesthesiologists and/or trauma surgeons is essential for rapid and precise management, and these specialties should be involved from the beginning of trauma treatment.

On the other hand, REBOA can be performed with only local anesthesia in the inguinal region. Therefore, REBOA can be used not only for resuscitation but also for early utilization in a physiologically stable state, such as proximal control during investigating bleeding sites in exploratory laparotomy for intra-abdominal hemorrhage ("intraoperative REBOA") [23,24], temporary hemodynamic stabilization during preparation or transfer for definitive hemostasis, and prophylactic use preparing for hemodynamic collapse before definitive hemostasis such as surgery or IR after detection of active bleeding. When the common femoral artery (CFA) access was difficult to achieve, the sheath can be placed into the aorta under direct vision. Thereafter, it can be removed under vision and the defect can be repaired. This is an option of arterial access of intraoperative REBOA.

In cases of multiple blunt trauma, even if hemodynamics are temporarily stable in the early phase of injury, sudden hemodynamic collapse often occurs during treatment. Different modalities (surgery, IR, external fixation, etc.) are often required to stop bleeding from multiple sources. Therefore, while performing priority hemostasis, REBOA can also provide temporary control for bleeding from other sites to help reduce blood loss and maintain hemodynamic stability. For example, laparotomy is performed with Zone 1 REBOA first in patients with both abdominal and pelvic trauma. Once the abdominal bleeding is controlled, REBOA is moved to Zone 3. Intraoperatively, with additional pelvic retroperitoneal packing, a Zone 3 REBOA may be effective as a "bridge" between the procedure and transfer to the angiography room for pelvic fracture.

In other words, because of its less invasiveness and rapidity, REBOA can be used as a means of resuscitation and a means of preventing hemodynamic collapse until definitive hemostasis is achieved and as a temporary proximal control during surgery.

Advantages of Safety

There seems to be no disagreement about the usefulness of achieving arterial access before the hemodynamic collapse and the safety of ultrasound-guided puncture. On the other hand, it is unclear at what severity the benefits exceed the risk of prophylactic insertion of the REBOA catheter by upsizing the sheath. In addition to the risks associated with the insertion technique and physiological changes associated with aortic occlusion, there is also a delay until definitive hemostasis can be achieved. Since the benefits of REBOA vary depending on the trauma care system in each institution, neither a clear recommendation nor a criticism can be made so far, but it may be an option for the utilization of REBOA.

In addition, by adjusting the balloon inflation volume to partial REBOA, precise control of aortic occlusion strength can be easily performed, and the risk of complications can be reduced, which is an attractive feature of REBOA not found in RTACC. The procedure itself can be performed by both emergency physicians and surgeons with training.

Disadvantages of Rapidity and Certainty

The disadvantage of REBOA compared to RTACC is that occlusion cannot be performed unless arterial access is achieved. In addition, since it is necessary to insert the sheath, apply the REBOA catheter in the

appropriate position from the sheath, and inflate the catheter, it may take some time to perform aortic occlusion, making rapidity an issue when arterial access has not been achieved. As mentioned before, REBOA can be performed faster than RTACC once arterial access is achieved [6]; however, in elderly patients with arteriosclerosis and aortic meandering, the risk of complications such as aortic dissection, aortic injury, and thromboembolism is high. There is uncertainty that aortic occlusion with REBOA cannot be done due to the difficulty of sheath insertion or applying the catheter. On the other hand, the rapidity and accuracy would be improved when REBOA can be performed in an angiographic or fluoroscopic environment.

TO "REBOA AND RTACC" INSTEAD OF "REBOA VERSUS RTACC"

The number of studies comparing REBOA and RTACC is small and limited. These studies do not include the practitioner's expertise and experience, the target patients, and the conditions of the procedure (sheath diameter, device, etc.), so there is no evidence to conclude which is more useful currently. Therefore, we should consider the patient background (elderly, obese), site of injury (presence or absence of chest trauma, perforating or blunt), circulatory dynamics (resuscitative, proximal control, prophylactic), facility environment (resuscitation room, operating room, angiography room, hybrid ER), and the skill of the practitioner (surgeon, emergency physician, IR physician), taking into account the available resources according to the situation and conditions. It is crucial to consider the available resources and determine the appropriate treatment. It is not necessary to discuss the superiority or inferiority of RTACC and REBOA. The appropriate determination of a combination of these tactics will increase the range of strategies and tactics.

Converting from RTACC to REBOA

In particular, RTACC should be performed promptly for impending cardiac arrest or cardiac arrest. Consecutively, early conversion to REBOA can be helpful [25]. While RTACC can be performed by opening the chest with only a scalpel and a Cooper, there is a risk of hemorrhagic shock caused by the procedure itself due to postoperative bleeding from the chest wall, unexpected complications in the thoracic cavity, bleeding due to traumatic coagulopathy, and hypothermia because the thoracotomy is performed without any hemostatic manipulation at once. Therefore, if it is no longer necessary to keep the chest open after aortic clamping, we should strive to prevent hypothermia by early chest wall hemostasis and chest closure. If rapid conversion to REBOA can be achieved after ensuring the speed and certainty of RTACC, it will be easier to secure the field of view during chest wall hemostasis, and early chest closure will lead to the prevention of hypothermia and reduction of chest wall bleeding (Figure 2).

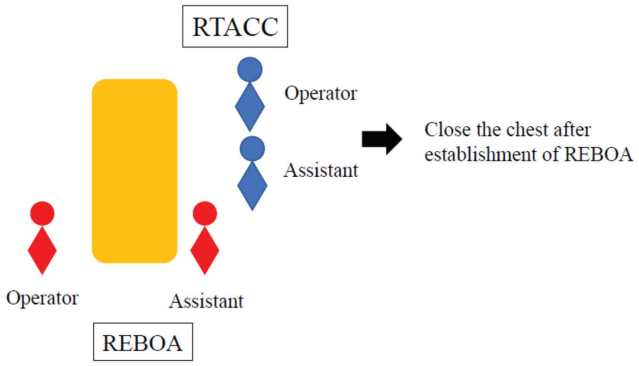

Figure 2 Conversion to REBOA from RTACC.

Conversion of Open Aortic Clamping to REBOA

The strategy of converting to REBOA after abdominal aortic compression/occlusion is also helpful. As soon as REBOA is established, the assistant's hand compressing the aorta in the abdominal cavity can be removed, and the view of the surgical field can be improved (Figure 3). There are some opinions and arguments that abdominal aortic compression is sufficient for temporary bleeding control and does not need to be converted to REBOA. Indeed, if a massive blood transfusion is performed quickly, the injury site is a single injury, and temporary hemostasis can be achieved quickly by manual maneuver, the operation can be completed without conversion to REBOA. However, in the case of complex injuries such as complicated intra-abdominal organ injuries, vascular injuries, retroperitoneal organ injuries, and severe pelvic fractures, and when there are multiple targets to be controlled during laparotomy, REBOA can be helpful as an aortic occlusion method because of its advantage in securing the operative field view.

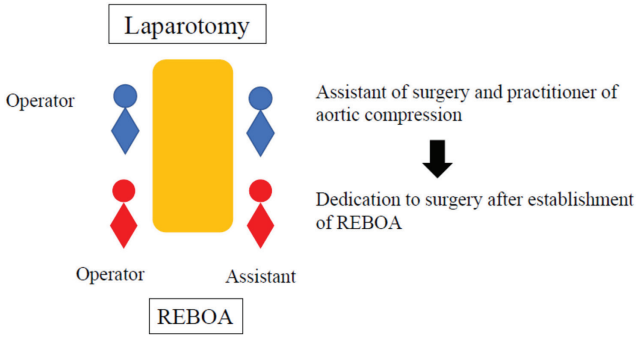

Figure 3 Conversion to REBOA from abdominal aortic compression/occlusion. Consider converting to REBOA before or even during laparotomy.

REBOA as an Adjunct to Definitive Hemostasis

Venous bleeding can be easily controlled by packing with gauze, but arterial bleeding cannot be controlled without ligation or angioembolization. Especially in retroperitoneal organ injuries and aortic injury, it is often difficult to reach and identify the bleeding site. The patient may have a compound injury. In such cases, REBOA can temporarily control arterial hemorrhage, making it much easier to reach and identify the bleeding site. In addition, it is useful for complex revascularization. Thus, REBOA can be used for resuscitation and temporary proximal control during hemostasis, which can be a major adjunct to definitive hemostasis.

CONTROVERSIAL ISSUES REGARDING REBOA AND RTACC

REBOA versus RTACC

Several studies, including two meta-analyses, have shown a reduction in mortality in the REBOA group compared with the RTACC group, suggesting the superiority of REBOA [26,27]. However, as a limitation, all meta-analyses were observational studies, not randomized controlled trials. In addition, the studies analyzed are not purely comparative due to overlap in cases and backgrounds. Some reports that the RTACC group had significantly higher chest AIS score and lower probability of survival (Ps) than the REBOA group [28]. Therefore, the target patients in the RTACC and REBOA groups are definitely different, so the difference in indications must be recognized [29].

Comparison by the Presence of Cardiac Arrest or Site of Injury

It has been reported that REBOA is superior when aortic occlusion is performed before cardiac arrest (AORTA2 study) [30]. As a limitation, 80% of the patients in the AORTA2 study were cardiac arrest patients, and the number of non-cardiac arrest patients who were actually compared was less than 30 in each group. The report by Matsumoto et al. [31] summarizes data from the Japan Trauma Data Bank, which is biased in terms of background and does not show the superiority of REBOA or RTACC.

Comparison by the Time Factor

It has been reported that the time to aortic occlusion is shorter with RTACC than with REBOA if arterial access is already achieved [6]. Therefore, RTACC should be chosen if the patient is already in impending cardiac arrest on admission. On the other hand, when arterial access is achieved, the time to aortic occlusion is significantly shorter with REBOA than with RTACC [6], appropriate recognition of patients who may require REBOA and early achieving of arterial access may improve prognosis [4].

As a comparison of other time factors, REBOA has been reported to have a shorter chest compression interruption time, higher end-expiratory partial pressure of carbon dioxide ($EtCO_2$), and a higher rate of return of spontaneous circulation [32]. In other words, the quality of resuscitation may be higher than that of RTACC. Of course, it should be noted that if thoracotomy is required for reasons other than resuscitation or open-chest cardiac massage, such as repair of chest injury, comparing REBOA with RTACC itself would be meaningless.

TECHNICAL ASPECTS OF RESUSCITATIVE THORACOTOMY

Resuscitative thoracotomy (RT) is performed to release cardiac tamponade, hemostasis and repair of cardiac injury, hemostasis of intrathoracic or chest wall bleeding, prevention of air embolism, open-chest cardiac massage, and cross-clamping the thoracic descending aorta (RTACC).

A suitable approach for these purposes is the left anterolateral thoracotomy. A skin incision is made by a scalpel in the left fourth or fifth intercostal space along the rib from the left margin of the sternum to the midaxillary line. Then, the upper rib margin is incised with Cooper's scissors, and the pleural wall is opened manually for rapid entry into the thoracic cavity. A finger is inserted into the thoracic cavity at that point, and using Cooper's scissors as a guide, the intercostal muscles and the parietal pleura are separated along the upper rib margin to open the chest without damaging the lung. Once the chest is opened, a thoracic retractor is applied to widen the incision. When only poor view could be obtained, the incision should be widened, but if widened dorsally and cut into the latissimus dorsi, it may result in excessive bleeding. When widening to the sternal side, be careful not to injure the internal thoracic artery.

In the event of cardiac arrest, immediately begin cardiac massage while making a sharp incision to open the pericardium, check for cardiac injury, and stop bleeding. Then, the inferior pulmonary ligament should be dissected, the descending aorta should be cross-clamped, and if necessary, the pulmonary hilum should be clamped. If there is bleeding from the chest wall, such as from intercostal arteries, stop the bleeding. If the patient has a right massive hemothorax, right cardiac injury, or aortic injury in the ascending arch, a left anterolateral thoracotomy followed by a right anterolateral thoracotomy and transverse sternal dissection should be performed to create a clamshell thoracotomy.

Following the algorithm for the indication of RT [33,34], RT should be performed for cardiopulmonary arrest patients with vital signs within 10 minutes for blunt trauma, 15 minutes for stab injury, and systolic blood pressure below 60 mmHg before arrival at the

hospital, and aortic occlusion should be performed. If cardiac contraction is present, aggressive resuscitation should be performed, including repair for cardiac injury, control of bleeding for intrathoracic or extrathoracic hemorrhage, and hilar clamping for air embolization. If there is no cardiac contraction but cardiac tamponade is present, open the pericardium and perform the cardiac repair. If there is no evidence of cardiac tamponade, stop resuscitation.

CONCLUSION

Each aortic occlusion technique has advantages and disadvantages. Trauma practitioners need to understand and utilize the rapid and appropriate method of occlusion. The aortic occlusion technique is a bridge to hemorrhage control, rather than a salvage technique. Early definitive hemostasis must be achieved, and occlusion is not the goal. Conversion to REBOA from RTACC can be a rapid and rational aortic occlusion procedure in traumatic cardiac arrest/impending cardiac arrest cases, especially in blunt trauma.

Ethics Statement

(1) All the authors mentioned in the manuscript have agreed to authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.
(2) The authors declare that they have read and abided by the JEVTM statement of ethical standards including rules of informed consent and ethical committee approval as stated in the article.

Conflicts of Interest

Yosuke Matsumura was a clinical advisory board member of Tokai Medical Products (2015–2017). The other authors declare that they have no conflicts of interest.

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