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Review article

Ruptured abdominal aorto-iliac aneurysms: Diagnosis, treatment, abdominal compartment syndrome, and role of simulation-based training

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ABSTRACT

Ruptured abdominal aortic aneurysms (rAAA), with or without iliac involvement, are a life-threatening scenario with high mortality even after surgical therapy. Several factors have contributed to improving perioperative outcomes in recent years, including the progressive use of endovascular aortic repair (EVAR) and intraoperative balloon occlusion of the aorta, a dedicated treatment algorithm with centralization of care to high-volume centres, and optimized perioperative management protocols. Nowadays, EVAR is applicable in the majority of scenarios even in the emergency setting. Among the factors that influence the postoperative course of rAAA patients, abdominal compartment syndrome (ACS) is a rare but life-threatening complication. As its early clinical diagnosis is often missed but crucial to initiate an emergent surgical decompression therapy, dedicated surveillance protocols and transvesical measurement of the intraabdominal pressure are key for prompt diagnosis and immediate treatment of ACS. Further improvement of rAAA patients' outcome may be achieved by the implementation of simulation-based training (of both technical and non-technical skills for surgeons as well as all involved healthcare personnel in multidisciplinary teams) and by transfer of all rAAA patients to specialized vascular centres with advanced experience and high caseload.

1. Introduction

Abdominal aortic aneurysm (AAA), with or without iliac involvement, has a prevalence of 2-11% in the population aged >65 years [1]. Indeed, it is one of the leading causes of death in men >65 years if not treated electively above a certain diameter [1]. Detailed guidelines on the diagnosis and treatment of aorto-iliac aneurysms have been elaborated by the US-American Society for Vascular Surgery (SVS) and the European Society for Vascular Surgery (ESVS), and are resumed in Tables 1 and 2.

The most feared complication of AAA is rupture, which can be broadly divided into two main scenarios, namely free rup-

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Table 1 – Recommendations of the European Society of Vascular Surgery (ESVS), 2019
Level of evidence (LoE): **A: Data derived from multiple randomised clinical trials or meta-analyses; B: Data derived from a single randomised clinical trial or large non-randomised studies; C: Consensus of opinion of the experts and/or small studies, retrospective studies, and registries.** Classes of recommendations (CoE): **I: Evidence and/or general agreement that a given treatment or procedure is beneficial, useful, and effective; II: Conflicting evidence and/ or a divergence of opinion about the usefulness/efficacy of the given treatment or procedure; IIa: Weight of evidence/opinion is in favour of usefulness/efficacy; IIb: Usefulness/efficacy is less well established by evidence/opinion; III: Evidence or general agreement that the given treatment or procedure is not useful/effective and, in some cases, may be harmful.**

Recommendations of the European Society of Vascular Surgery (ESVS), 2019	CoR	LoE
In hemodynamically stable patients with suspected rAAA, prompt thoraco-abdominal CTA is recommended as the imaging modality of choice.	**I**	**B**
In hemodynamically unstable patients with suspected rAAA, prompt thoraco- abdominal CTA, allowing assessment for endovascular repair, should be considered before transferring the patient to the operating room.	IIa	B
In patients with rAAA, a policy of permissive hypotension, by restricting fluid resuscitation, is recommended in the conscious patient.	**I**	**B**
Local anaesthesia should be considered as the anaesthetic modality of choice for endovascular repair of rAAA whenever tolerated by the patient.	IIa	B
Aortic balloon occlusion for proximal control should be considered in hemodynamically unstable rAAA patients undergoing open or endovascular repair.	IIa	C
In patients undergoing endovascular repair for rAAA, a bifurcated device, in preference to an aorto-uni-iliac device, should be considered whenever anatomically suitable.	IIa	C
Selection of patients with rAAA aneurysm for palliation based entirely on scoring systems or solely on advanced age is not recommended.	III	B
In all patients undergoing open or endovascular treatment for rAAA, monitoring of intra-abdominal pressure for early diagnosis and management of intra-abdominal hypertension/abdominal compartment syndrome is recommended.	**I**	**B**
In the presence of abdominal compartment syndrome after open or endovascular treatment of rAAA, decompressive laparotomy is recommended.	**I**	**B**
In the management of open abdomen following decompression for abdominal compartment syndrome after open or endovascular treatment of rAAA, vacuum assisted closure system should be considered.	IIa	C
In patients with rAAA and suitable anatomy, endovascular repair is recommended as a first option.	**I**	**B**

ESVS: European society of vascular surgery; rAAA: ruptured abdominal aortic aneurysm; CTA: computer tomography angiogram; bold: classes of high recommendation

Table 2 – Recommendations of the Society of Vascular Surgery (SVS), 2017
Level of recommendation (LoR): **Grade I - strong: Practices where benefit clearly outweighs risk. These recommendations can be made by clinicians and accepted by patients with a high degree of confidence; Grade II - conditional: Benefits and risks are more closely matched and are more dependent on specific clinical scenarios. In general, physician and patient preferences play a more important role in the decision-making process in these latter circumstances.** Quality of Evidence (QoE): **A: high level of QoE, when additional research is considered very unlikely to change confidence in the estimate of effect; B: moderate level of QoE, when further research is likely to have an important impact on the estimate of effect; C: low level of QoE, when further research is very likely to change the estimate of the effect; Good practice statements: ungraded recommendations advising about performing certain actions considered by surgeons to be essential for patient care and supported only by indirect evidence.**

Recommendations of the Society of Vascular Surgery (SVS), 2017	LoR	QoE
We suggest a door-to-intervention time of <90 minutes, based on a framework of 30-30-30 minutes, for the management of the patient with rAAA.	GPS	-
An established protocol for the management of rAAA is essential for optimal outcomes.	GPS	-
We recommend implementing hypotensive haemostasis with restriction of fluid resuscitation in the conscious patient.	**I**	**B**
We suggest that patients with rAAA who require transfer for repair be referred to a facility with an established rupture protocol and suitable endovascular resources.	GPS	-
If it is anatomically feasible, we recommend EVAR over open repair for treatment of a rAAA.	**I**	**C**

SVS: Society of vascular surgery; LoR: Level of recommendations; QoE: Quality of Evidence; GPS: Good Practice Statement; EVAR: endovascular aortic repair; rAAA: ruptured abdominal aortic aneurysm; CTA: computer tomography angiogram; bold: Level of high recommendation ture and contained rupture, depending on whether the surrounding tissues exercise a compression on the rupture site that contains the ongoing blood loss. It may be further classified as either intraperitoneal rupture or retroperitoneal rupture, depending on whether there is the creation of hemoperitoneum or retroperitonal hematoma. Rupture into the inferior vena cava or the duodenum are rare manifestations, usually burdened by dramatic mortality. In case of rupture, more than 50% of patients may die before reaching the hospital [2,3]. Even after prompt surgical treatment of a ruptured abdominal aortic aneurysm (rAAA), mortality can still be as high as 30-35% [4–8]. However, in recent years, improvement in early mortality rate and long-term survival have been observed [9–13]. These developments have been mainly driven by several factors including the progressive use of endovascular aortic repair (EVAR) and improved perioperative and postoperative care protocols amongst others. Moreover, having an algorithm in place for emergency settings as proposed by SVS could play a role, as well as centralization of care to centres of excellence with high caseload [2]. Simulation-based training has also been suggested by some authors as an effective tool that may further improve the management of rAAA patients.

Once patients survive the initial event and surgical therapy, abdominal compartment syndrome (ACS) can complicate the postoperative course. It is mainly caused by the non-removed hematoma, particularly after EVAR, and can be worsened or precipitated by inadequate perioperative fluid management. Whenever it occurs, ACS is usually burdened by dramatic morbidity and mortality, therefore prompt diagnosis and immediate management remain mandatory

This narrative review article was intended to provide a brief yet comprehensive overview of current recommendations for diagnosis and therapy of rAAA as well as of ACS, and discuss the role of simulation-based training in the management of rAAA patients.

2. Diagnosis

Rupture is often the only and first symptom of an AAA. Typical symptoms of rupture are hypotension, abdominal and/or back pain, and an abdominal pulsating mass. However, this triad may occur in only about 50% of cases with a rAAA [14]. If a rAAA is suspected by clinical presentation or an abdominal ultrasound examination with evidence of an AAA, computed tomography angiography (CTA) of the aorta as quickly as possible is the diagnostic method of choice, as also recommended in the current ESVS guidelines [14–16]. Typical CTA findings of contained rupture of an AAA with a large retroperitoneal hematoma are demonstrated in Fig. 1. Besides the exclusion of possible differential diagnoses, CTA (performed with thin slices from the neck to the groins with at least two angiographic phases) forms the basis for planning EVAR and should be performed whenever possible [17–20]. Even in cases of hemodynamic instability, it should be aimed for and is feasible in most cases [14].

If a patient is too unstable to undergo CTA, he can be taken directly to the operating room (OR) for stabilisation using an aortic occlusion balloon (AOB) or quick aortic cross-clamping after open-surgical exposure. After stabilisation with the AOB, intraoperative angiography can be performed for EVAR evaluation, although this is not as accurate as CTA as it will miss critical anatomical details such as the presence of intraluminal thrombus [21]. Use of intravascular ultrasound (IVUS) may be helpful in these circumstances to implement the diagnostic accuracy.

Ultrasonography plays a minor role in the emergency diagnosis of rAAA because the sensitivity for a retroperitoneal hematoma is low [22]. However, it can certainly be used for an initial overview and AAA detection. In any case, it is advocated that an emergency algorithm for referral and diagnosis should be in place to improve the outcome of patients suspected of having a rAAA [2]. A door-to-intervention time of less than 90 minutes is recommended, where time zero is the first medical contact sought by the patient or his caregiver [2].

3. Treatment

3.1. *Perioperative management*

In patients with rAAA, permissive hypotension is recommended until proximal control of the aorta is achieved. The systolic blood pressure should be between 70-90 mmHg [14,23-25]. A restrictive regimen for infusion of clear fluids and transfusion of blood products with slightly hypotensive blood pressure levels may prevent thrombus dislocation with recurrent bleeding due to iatrogenic coagulopathy [26–28]. Although there is no comparative study of hypotensive vs normotensive blood pressure levels, this approach has been documented to be safe and is widely accepted for management of patients with rAAA [28–32]. In order to avoid hypertension, patients may receive intravenous nitroglycerin, esmolol, sodium nitroprusside, and pain medication. The overall aim of immediate pharmacologic measures is to re-establish or maintain perfusion of vital organs all while minimizing the risk of uncontained rupture [2].

If general anaesthesia is required, it should be induced immediately before the incision (usually after disinfecting and draping the patient and once the surgeons are ready for cut or after inserting an AOB). Induction of general anaesthesia and muscle relaxation may result in acute vasodilation and decreasing abdominal wall tension, which may cause circulatory collapse [14]. This risk is much lower with EVAR as it can be performed under local anaesthesia [33].

In principle, intraoperative systemic anticoagulation should also be given in the case of rAAA in order to prevent thrombembolic events (during aortic cross-clamping or after insertion of large-bore sheaths in the femoral vessels). Before administration of intravenous heparin, however, close attention should be paid to any pre-existing oral anticoagulation that may have not been paused in emergency situations, and to the current coagulation parameters of the patient. It is usually recommended to administer standard anticoagulation after proximal control or, in any case, after complete aneurysm occlusion with EVAR [14].

The role of pro-thrombotic drugs to reduce blood loss especially in open aortic repair (OAR) is not yet well investigated, and available evidence is scarce. A first randomised clinical trial on the effects of tranexamic acid, a synthetic derivate

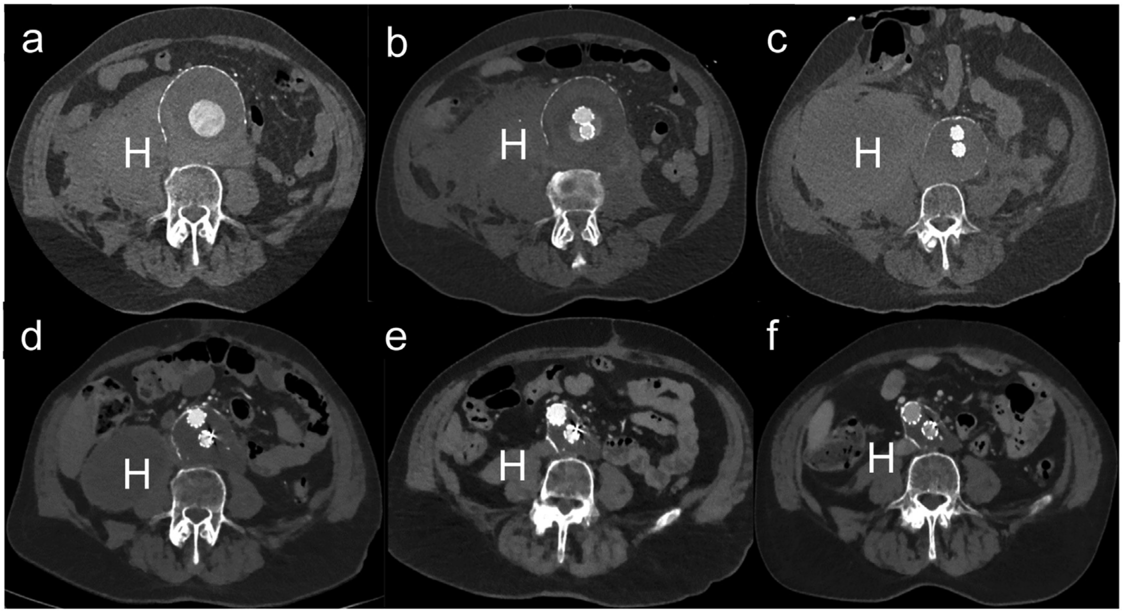

Figure 1 – Computed tomography angiographies (CTA) of a hemodynamically stable 79-year old patient presenting with a contained rupture of an abdominal aortic aneurysm and large hematoma (H) in the right retroperitoneal space (a). Immediate CTA after endovascular aortic repair (4hrs after the initial CTA) revealed hematoma growth due to a deranged coagulation (b) which lead to an abdominal compartment syndrome few hours later treated with decompressive laparotomy and abdominal vacuum therapy (c). Intraoperative aneurysm sac incision revealed no endoleakage. The retroperitoneal hematoma was not evacuated due to the persistent deranged coagulation and large retroperitoneal area affected. The hematoma shrinked spontaneously during further follow-up (d: after 2.5 months; e: after 1 year; f: after 2 years) without the need for evacuation or drainage.

of the aminoacid lysine with antifibrinolytic effects, demonstrated no reduction of intraoperative blood loss. Post-hoc analyses, however, revealed a significant reduction of postoperative blood loss, although the net difference of 40 ml might not be clinically relevant [34].

3.2. *Proximal aortic control*

Proximal aortic control is the most essential and crucial step in rAAA management to stop the ongoing blood loss and avoid circulatory collapse [2]. Proximal control can be achieved both endovascularly as well as surgically. In OAR, this can be achieved by infrarenal, suprarenal or supratruncal aortic cross-clamping, whereby the clamp must be moved to the infrarenal region as soon as possible. The aortic occlusion balloon (AOB) is an endovascular approach, which can be used before/during EVAR or as an alternative to conventional cross-clamping for OAR [35]. Indications for an AOB are circulatory collapse, hemodynamic instability, or anatomic limitations that make rapid, open access and cross-clamping difficult [33,36]. The AOB can be inserted under local anaesthesia under fluoroscopy, via a long sheath using either a transfemoral or transbrachial route, and inflated in to the supraceliac aorta [2,14]. We usually use the Reliant Stent Graft Balloon Catheter (Medtronic plc, Dublin Ireland) with a guidewire, fluoroscopic guidance and a 40 cm long 12 French flexible sheath (Flexor Introducer, Cook Medical) for transbrachial access or a 14 French, 45cm long stiff sheath for transfemoral access (Performer Introducer, Cook Medical). When the AOB is in position, general anaesthesia can be induced if required. The balloon can be removed once the aortic stent-graft is placed for EVAR and re-inflated in the stent-graft main body if required [36]. Current data suggest a positive effect of using AOB, as mortality rates show lower mortality in studies with higher rates of AOB [37]. In addition, the study by Raux et al. showed that intraoperative mortality was lower using AOB as compared to conventional cross-clamping [21]. However, in-hospital mortality was not different, which likely reflects the severity of clinical presentation [21]. Comparing transfemoral and transbrachial access routes, in the authors' opinion, the transbrachial approach offers some technical advantages, especially the option for gradual reperfusion with a step-by-step AOB deflation maintaining a stable balloon position and preventing potentially disturbing catheters in the operating field.

3.3. *Endovascular repair*

If the anatomy is suitable, EVAR should be the treatment of choice, which is already performed in more than 60% of cases in the contemporary era [2,14]. Furthermore, due to the minimally invasive technique and possible use of local anaesthesia, there is minimal physiologic derangement that contributes to better outcomes after EVAR for rAAA patients [14,38]. The necessity to convert to open surgery is reported to be uncommon [39,40]. The unfortunate downside of the increased implementation of EVAR may be represented by the growing number of secondary interventions for EVAR failures, where both endovascular and open repair are challenged by complex anatomic scenarios, as these may offset the early benefit.

A wide range of stent-grafts is available, enabling endovascular repair of even complex aortic morphologies such as iliac and/or hypogastric artery involvement (thanks to purposely designed iliac branch devices), narrow aortic bifurcations, or juxtarenal/suprarenal aneurysms (branched or fenestrated devices that can be physician-made or off-the-shelf; parallel grafts in rare cases or as a bailout procedure) [41–45]. To achieve high quality even in emergencies, the stent-graft chosen should be one that the surgeon is familiar with [14]. It is generally recommended to use bifurcated over monoiliac stent-grafts (Figure 1). Monoiliac stent-graft should be reserved for exceptional cases, extremely unstable patients or complex anatomies [2,14]. To prevent complications such as bowel ischemia care should be taken to ensure that at least one hypogastric artery remains perfused [14]. Therefore, in case of concomitant iliac artery involvement or aortoiliac aneurysms, iliac branch devices may be preferred over hypogastric artery embolization especially in young and fit patients (provided they are immediately available and physicians have enough skills). Nevertheless, hypogastric artery embolization can be a good and fast option to prevent later blood backflow from the pelvis with persistent bleeding from the aortic rupture site. If an AOB has been inserted for proximal aortic control, it can be removed after placement of the main body before release. A detailed description of this technique was published earlier [46]. If CTA was performed under permissive hypertension, 30% oversizing should be done when measuring the stent-graft to avoid the intra- or postoperative occurrence of a type Ia endoleak [47,48]. We recommend repeating CTA immediately postoperatively for precise control. While type I and type III endoleaks are still an indication for treatment, type II endoleaks can be further observed in the case of hemodynamic stability and stable haemoglobin values [49].

Usually, an ultrasound-guided percutaneous transfemoral access for EVAR should be aimed for even in emergency settings as it is faster than a surgical cut-down. Closure of these large bore holes can be performed using specially designed vascular closure devices. They can be divided into suture-based devices such as the ProGlide (Abbott Vascular, Abbott Park, Illinois) and plug-based devices such as the MANTA (Teleflex, Wayne, Pennsylvania), which does not require a preclosure technique. Both will usually achieve equal results in terms of access site-related vascular complications [50].

3.4. *Open repair*

Once proximal aortic control has been achieved by cross-clamping or AOB, OAR is performed as in the elective setting. Depending on the surgeon's preference and training, a transperitoneal or retroperitoneal approach can be chosen. We usually prefer the transperitoneal approach as it allows better and faster access to the aortic neck and both iliac arteries in the emergency setting. A Dacron or PTFE graft is used to replace the diseased aortic and/or iliac segment. The reconstruction of the aorta can be done by a tube or Y-graft depending on the anatomy [2,14,51]. Special attention must be paid in case of secondary ruptures after prior EVAR; several techniques can be employed (ranging from total to partial graft explantation), and suprarenal aortic cross-clamping is usually needed before the prior stent-graft can be safely removed. In our experience, the safest way to operate these secondary ruptures is to leave the main body in the aortic neck (and sometimes also the iliac legs), resect the prosthetic part in between, and to incorporate both the vessel wall and the remaining stent-graft into the anastomoses. Complete forceful removal, especially in the proximal aortic neck, may lead to juxta-/suprarenal aortic rupture/dissection due to stent-graft fixation systems (hooks, barbs, stents).

3.5. *Conservative therapy*

Conservative therapy plays no role in the curative treatment of rAAA, unless the patient is being considered for palliation. If a patient is diagnosed with rAAA, he must be operated on immediately because rAAA is not compatible with life [2,14]. However, palliative therapy with best supportive care and pain control can be initiated if survival chances are low due to poor general conditions or severe comorbidities. The decision to refrain from surgery and to switch to conservative/palliative care should be a shared decision between the patient and/or his caregivers, the vascular surgeon, the anaesthesiologist, and further healthcare personnel as required by individual circumstances. Although age in itself should not be the only parameter used for denying emergent surgical care, there is increased awareness that frailty assessment may play a role even in such dramatic clinical scenarios [52]. There are different scoring systems for assessing the mortality risk, but none of them could be found to be completely accurate [53,54].

3.6. *Clinical outcomes*

While mortality for OAR has long been as high as 50% or higher, it has been reduced to 25-41% over time due to improved perioperative management [14]. Mortality rates after EVAR vary widely and are reported to be as high as 13-53%. Nevertheless, mortality is generally lower after EVAR compared with OAR in observational studies [14]. In contrast, four available randomized controlled trials (Nottingham 2006, AJAX 2013, IMPROVE 2014 and ECAR 2015) showed no statistical difference in mortality comparing EVAR and OAR [6,35,55,56]. An individual patient meta-analysis of IMPROVE, AJAX and ECAR also failed to demonstrate a difference in 30- and 90-day mortality [57]. These different results between randomised controlled trials and observational studies are probably due to a selection bias that can be particularly pronounced in studies of emergency conditions. For safe planning, patients need to be stable enough to undergo CTA, so those who are planned for EVAR are usually more stable from the outset than those who receive OAR. The results of the randomised controlled trials, especially the IMPROVE trial, are based on an intention-to-treat principle, where patients are randomised before imaging and thus receive a different treatment than planned [6,14]. Nonetheless, the IMPROVE trial was able to demonstrate a net clinical benefit for EVAR at the three-year landmark analysis.

The clinical outcomes of rAAA also depend on the centre's experience and institutional caseload. Several studies have shown that transferring patients to a specialised vascular centre is safe and that high-volume hospital generally have lower mortality in both elective and emergency cases, especially after OAR [14,58-67].

4. Abdominal compartment syndrome

4.1. Definition

The occurrence of abdominal compartment syndrome (ACS) following the repair of rAAA is likely multifactorial. Nonetheless, several studies have shown dramatically increased mortality rates in patients requiring abdominal decompression [68,69]. These high rates have mainly been attributed to low postoperative awareness and delayed diagnosis, especially in the contemporary endovascular era. Currently, ACS is defined as sustained intraabdominal pressure (IAP) of >20 mmHg, with or without an abdominal perfusion pressure (APP) <60 mmHg, that is associated with new-onset clinically overt organ failure [70]. APP is defined as the difference between mean arterial pressure (MAP) and IAP, and it should be maintained at >60 mmHg. Following rAAA repair, patients are at particularly high risk of developing ACS due to several factors including (but not limited to) massive fluid shifts and aggressive resuscitation therapy, continued systemic coagulopathy, and retained retroperitoneal hematoma. A sustained pathologic elevation of IAP >12 mmHg is termed "intraabdominal hypertension". Indeed, it is relevant for clinicians not to focus exclusively on IAP, as ACS and end organ damage may also develop with IAP <20 mmHg in the setting of inadequate maintenance of MAP (and APP thereby). A general algorithm for management of ACS has been published in the ESVS 2019 guidelines on the management of aorto-iliac aneurysms [14].

4.2. Pathophysiology

General conditions associated with IAP and ACS may be categorised into two main groups: those that reduce the compliance of the abdominal wall, and those that increase the volume of intra-abdominal contents (mainly from an abnormal capillary leak and massive fluid resuscitation). There are conflicting data on the rate of ACS following OAR vs EVAR for rAAA. When measured as part of a routine protocol, as many as 20% of patients may show signs of ACS following OAR. In contrast, some studies demonstrate almost a 0% rate of ACS after EVAR, although these patients were the most stable, likely resulting in a selection bias with respect to the development of ACS. In fact, in other institutions where EVAR is the preferred approach for rAAA the rates of ACS have been shown to be similar to those reported with OAR at approximately 20% [71,72]. Development of ACS after EVAR seems to be largely influenced by physiological factors that include the need for an AOB, the presence of severe coagulopathy, massive transfusion requirements, prolonged hypotension <70 mmHg and the emergent conversion of modular bifurcated stent-grafts to aortouniliac devices [73,74]. These results may help to better identify high-risk patients for ACS who need more intensive monitoring. However, it is largely unknown whether these factors are causally implied or rather represent markers of more complicated clinical presentation. Nonetheless, a higher degree of suspicion may be warranted in rAAA patients presenting with one or more risk factors for IAP in order to allow for preventive measures and prompt diagnosis of ACS.

4.3. Diagnosis

Clinical signs may be vague and include increased abdominal pain/tenderness/distension, decreased urinary output, and exaggerated peak airway pressures in those patients who are mechanically ventilated. Implementation of routine surveillance protocols has been suggested and measurement of IAP should be done via a transvesical route (by measuring either continuous or intermittent bladder pressure). There are multiple methods and tools for measuring bladder pressure, the simplest is a three-way Foley catheter using the patient's urine as pressure medium. A minimum of 25 mL should be instilled into the bladder, and the patient should be in the supine position as bed elevation can erroneously increase IAP [75]. Unless proven contrary, new-onset organ dysfunction in the setting of IAP that is not otherwise explained by concomitant factors should be assumed as ACS unless proven contrary.

4.4. Management

Aggressive medical management is the first-line treatment for patients at high risk of or with impeding ACS. Major components include measures that aim to improve abdominal wall compliance (via analgesia, sedation, neuromuscular blockade, or any combination thereof). Intraluminal contents should be evacuated via nasogastric and/or rectal decompression, with use of prokinetic drugs as needed. Efforts should also be directed to correct clinically overt coagulopathy and electrolyte abnormalities. Intraabdominal space-occupying lesions can be identified by cross-sectional imaging and may be dealt with non-invasively through imaging-guided percutaneous drainage [76]. In patients with retroperitoneal hematoma and avoidance of decompressive laparotomy, less invasive approaches to midline laparotomy have been studied, such as lumbotomy or imaging-guided administration of thrombolytic drugs, for evacuation of the retroperitoneal space [77]. Managing fluid resuscitation can prove challenging owing to the delicate balance between providing enough circulating volume to maintain effective perfusion and not worsening the progression of ACS with too liberal administration practices. There is also uncertainty regarding the most appropriate type of resuscitative fluid; colloids have been suggested to minimise overall volume overload while maximising the movement of fluid into the intravascular space, while others argue that they will ultimately transfer to the third space, thereby worsening the patient's fluid status [78,79]. Diuretics should be employed judiciously in hemodynamically stable patients to help mobilise intracellular oedema, owing to their risk for worsening electrolyte abnormalities. In selected cases, renal replacement therapy can be utilised in patients with renal failure to remove excess fluid, usually with continuous haemofiltration/haemodiafiltration techniques to minimise the onset of sudden changes in patients' arterial pressure.

The only proven surgical option is decompressive laparotomy after EVAR or reopening of the abdominal closure after OAR (Fig. 1). In our centre, we always combine these procedures with an abdominal vacuum assisted closure system (negative pressure of 50-75 mmHg) for fluid absorption and wound adaption as also recommended by the ESVS guidelines [14]. Evacuation of the retroperitoneal hematoma is usually not necessary due to its absorption over time as exemplary shown in Fig. 1. The exact timing of decompressive laparotomy is disputed, although general guidelines suggest that the patient should be moved urgently to the OR for decompression when there is evidence of sustained IAP of >20 mmHg and/or end organ dysfunction. Some studies have suggested that decompression may be triggered at lower IAP thresholds on the assumption that by the time the patient's pressure has risen to > 20 mmHg, the damage will be much more severe so that decompression might potentially lead to massive reperfusion syndrome and worse outcomes [80]. It has been suggested that ACS could be approached even more aggressively with "prophylactic open treatment" at the time of the operation, which argues that all patients (or a subset of patients at higher risk for developing ACS) should be left open at their index operation to prevent the occurrence of ACS [72]. However, the current consensus remains that unless there are overt signs of developing (or impeding) ACS, such as a tense abdomen at the initial operation, there is no strong argument for routine prophylactic decompression [70]. Second-look assessment of bowel viability should be carefully performed whenever there are doubts for ongoing or impeding mesenteric ischemia. Indeed, decompression or the decision to leave the abdomen open at the initial operation may carry their own set of inherent risks, which need to be carefully balanced against the perceived benefits. The nature of the open peritoneal cavity may put the patient at risk for infection (which would be a catastrophic event in the setting of a vascular graft/stent-grafts) as well as ongoing insensible fluid and protein losses. An additional issue with a prolonged open abdomen is "freezing" of the abdominal wall, which, coupled with adhesions between this and the bowel, makes the closure more challenging to achieve as more time elapses until definitive reconstruction. Fortunately, there are various products available to aid in the closure, although this should be attempted as soon as clinically reasonable [81,82]. Finding a reliable test to predict the development of ACS remains an area of ongoing research, while some have argued a need for a randomised controlled trial of early vs delayed decompression [83].

4.5. *Prognosis*

Overall, ACS remains a devastating complication following open or endovascular treatment of rAAA that greatly affects patients' survival [72,73]. Owing to vague clinical presentation, a lower index of suspicion should be maintained to allow for prompt diagnosis, especially in patients with a higher-risk profile for ACS. While the mortality rate after decompression is high, it should be compared to that of nearly 100% if ACS is left untreated. Therefore, decompression should be promptly performed when deemed clinically necessary.

5. Role of simulation-based training: Current knowledge and future challenges

Emergency scenarios such as rAAA require the full attention and advanced experience of all involved healthcare professionals: vascular surgeons, anaesthesiologists, nurses from the emergency room/OR and - if required - interventional radiologists. This is especially important in the contemporary endovascular-first era because, for instance, not every scrub nurse (especially at night or during weekend shifts) may be familiar with endovascular procedures and devices. In sharp contrast with elective settings, structured and supervised intraoperative training of all surgeons and assisting nurses is usually more difficult to achieve and procedural mistakes may pose a risk to patients' survival. Therefore, simulation-based training has been discussed as a valuable option to achieve smooth, uncomplicated preoperative procedures and a quick, successful surgical solution. In-hospital emergent endovascular rAAA management involves three key steps that could be objectives of regular training: the preoperative management from the patient's arrival at the hospital until the groin puncture, the resuscitative endovascular balloon occlusion of the aorta, and the EVAR itself. Appropriate training measures can be divided into technical tuition of vascular surgeons (both in-training and those already trained) and assisting nurses (EVAR, resuscitative endovascular balloon occlusion of the aorta), and multidisciplinary team coaching.

Technical training for EVAR is usually performed using dedicated simulators such as the ANGIO Mentor Dual Slim (Simbionix/Surgical Science, Gothenburg, Sweden) or the VIST (Mentice, Gothenburg, Sweden). These portable simulators include haptic devices (simulating the patients' groins with introducers for guidewire insertion and balloons/stents implantation, as well as hybrid OR control devices), a laptop, display screens, and in-built EVAR modules. Stent-grafts from different manufacturers and with suprarenal or infrarenal fixation can be virtually implanted. The implementation of 3-dimensional aortic reconstructions from real CTA images using dedicated software such as Procedure Rehearsal Studio (Simbionix/Surgical Science, Gothenburg, Sweden) may even enable a virtual patient-specific rehearsal (PsR). Several improvements in simulator skills after repetitive training have been reported for novices as well as for experienced surgeons: the total procedure and fluoroscopy times, rate of endoleaks, as well as the applied amount of contrast media were reduced significantly and this could potentially enable faster procedures, less radiation exposure and re-interventions, and decreased risks of postoperative renal insufficiency [84–86]. Apart from repetitive training, several studies on single components of PsR with these simulators <24 hours of elective EVAR have also confirmed their benefits in actual clinical settings. Those included a significantly lower number of intraoperative errors, less angiograms for the visualisation of the distal and proximal landing zones, and a global trend towards decreased total procedural and fluoroscopy time as well as reduced contrast volume, with comparable or even higher technical success [87,88]. Furthermore, Pakeliani et al. reported that PsR was also feasible in emergent EVAR without any time delay compared with the locally established EVAR protocol [89].

Portable simulators can also serve for technical training in the appropriate use of resuscitative endovascular balloon occlusion of the aorta, but also porcine or silicone models and even perfused human cadavers were alternatively used in published reports [90]. A recent systematic review observed improved competence outcomes such as procedural time and knowledge tests after simulator-based training, but results in the clinical setting are still lacking [90].

More complex stationary simulators such as Orcamp (Orzone, Gothenberg, Sweden) include a mobile C-arm, operating table, control panels and multiscreen displays. In contrast to portable simulators, these fully immersive simulated angiosuites offer simultaneous technical and multidisciplinary hybrid OR team training [91].

Up to date, only one study has focused on multidisciplinary team training for preoperative procedures: Aho et al. recently presented their experience with a monthly, multidisciplinary EVAR simulation training in a real hybrid OR addressing >300 professionals (2015-2017, Helsinki, Finland) [92]. Nine to ten professionals took part in these 60-minute training sessions that included a briefing with the distribution of duties, the actual simulation beginning in the CT room and ending when the occlusion balloon was placed, and a debriefing where a video of the simulation was discussed and evaluated for individual improvement. Compared to the preceding two years, this training significantly reduced the “OR door to needle time” (65 vs 16 minutes, p=.000), and the 30-day mortality (44.8 vs 30.6%, p=.046). The confidence and knowledge on EVAR of the personnel investigated by preoperative and postoperative questionnaires also increased significantly.

Overall, the role of simulation-based training for emergent EVAR is still unclear, and current US-American and European guidelines do not even comment on it [2,14]. Potential benefits of repetitive training certainly exist, especially for novices, but the number of participants in relevant reports is small and, most importantly, it has not been definitively confirmed if (and how) such improvements of technical and non-technical skills can be fully adapted to the clinical setting [84–86]. For instance, important surgical aspects such as sterility and stent-graft preparation are difficult to implement with currently available simulation technologies/platforms. Improvement in clinical outcomes has been shown after PsR which, in contrast to simulator-based training, does not aim at improving general endovascular skills but at preparing for treating a particular patients [87,88]. In fact, PsR in emergency EVAR was feasible under study conditions and with a multidisciplinary team, but whether this can become a real-life routine in vascular centres is still questionable [89]. Simulators are expensive, and training with them requires the supervision of experienced surgeons, which is time-intensive, especially if more trainees are involved, and regular training is intended. On the other hand, team training seems to be at least equally important and is possible without special equipment. However, its organization, as proposed by Aho et al., is extremely challenging due to the high number of professionals that need to be involved and the fact that the hybrid OR has to be used outside of the regular working times [92]. In a perfect world with endless financial resources and without time constraints, simulation-based training of surgeons and multidisciplinary teams, with repetition of technical skills and rehearsal of non-technical components of care, would certainly play a bigger role and potentially lead to improved outcomes in rAAA patients. However, in real life, the available low evidence does not yet justify its regular and widespread implementation, or its replacement of traditional training methods.

6. Conclusions

Rupture of an AAA, with or without iliac involvement, remains a life-threatening event with high perioperative mortality. Several improvements in perioperative management, hemodynamic stabilisation with endovascular aortic balloon occlusion, and less invasive EVAR are some of the pivotal factors that have lowered its mortality in recent years. In the future, the implementation of regular simulation-based training of surgeons, nurses and multidisciplinary teams, as well as transfer of all rAAA patients to specialised vascular centres, might further improve the outcomes after rAAA.

Declaration of Competing Interest

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