Minimal Aortic Injury: Mechanisms, Imaging Manifestations, Natural History, and Management

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Abbreviations: BTAI = blunt traumatic aortic injury, ECG = electrocardiographic, MAI = minimal aortic injury, SAI = significant aortic injury, SVS = Society for Vascular Surgery, TEVAR = thoracic endovascular aortic repair

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SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- Identify direct signs, indirect signs, and mimics of MAI at CT.
- Outline the pathophysiologic mechanisms, natural history, and current approach to the management of MAI.
- Discuss controversies and the future direction of definitions of the MAI spectrum.

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Over the last 2 decades, increased depiction of minimal aortic injury (MAI) in the evaluation of patients who have sustained trauma has mirrored the increased utilization and improved resolution of multidetector CT. MAI represents a mild form of blunt traumatic aortic injury (BTAI) that usually resolves or stabilizes with pharmacologic management. The traditional imaging manifestation of MAI is a subcentimeter round, triangular, or linear aortic filling defect attached to an aortic wall, representing a small intimal flap or thrombus consistent with grade I injury according to the Society for Vascular Surgery (SVS). Small intramural hematoma (SVS grade II injury) without external aortic contour deformity is included in the MAI spectrum in several BTAI classifications on the basis of its favorable outcome. Although higher SVS grades of injury generally call for endovascular repair, there is growing literature supporting conservative management for small pseudoaneurysms (SVS grade III) and large intimal flaps (>1 cm, unclassified by the SVS), hinting toward possible future inclusion of these entities in the MAI spectrum. Injury progression of MAI is rare, with endovascular aortic repair reserved for these patients as well as patients for whom medical treatment cannot be implemented. No consensus on the predetermined frequency and duration of multidetector CT follow-up exists, but it is common practice to perform a repeat CT examination shortly after the initial diagnosis. The authors review the evolving definition, pathophysiology, and natural history of MAI, present the primary and secondary imaging findings and diagnostic pitfalls, and discuss the current management options for MAI.

Online DICOM image stacks are available for this article.

Introduction

Blunt traumatic aortic injury (BTAI) is the second leading cause of trauma-related mortality, exceeded only by fall-related death from traumatic brain injury, and accounts for 10%–20% of fatal outcomes (1–3). The last several decades have seen significant advances in multidetector CT technology, allowing rapid acquisition of high-resolution near-isotropic images. These advances, in combination with widespread availability and utilization of CT angiography, have led to marked improvement in imaging depiction of BTAI (sensitivity of 95%–100%, negative predictive value of 100%) (4–6). The spectrum of BTAI depicted at multidetector CT angiography encompasses a wide range of injuries, from small intraluminal defects to full-thickness circumferential ruptures. BTAI is classified on the basis of the absence or presence of external aortic wall abnormality as minimal aortic injury (MAI) or significant aortic injury (SAI), respectively (Fig 1). While the presence of SAI often dictates immediate or prompt invasive measures, MAI usually does not require immediate intervention (7–11). Recent literature estimates MAI incidence to be

TEACHING POINTS

- BTAI is classified on the basis of the absence or presence of external aortic wall abnormality as minimal aortic injury (MAI) or significant aortic injury (SAI), respectively.
- The current definition of MAI is a "sub-centimeter intimo-medial abnormality with no external contour deformity." This includes small intimal tear and intramural hematoma. While small intimal tear (SVS grade I) has always been considered an MAI lesion, the relatively recent inclusion of intramural hematoma (SVS grade II) is strongly supported by newer management-based classification systems (eg, the Vancouver and Harborview classifications).
- The isthmus of the descending thoracic aorta is the most commonly involved site of MAI, involved in approximately two-thirds of patients with BTAI who present to the hospital. A smaller proportion of cases involve the ascending aorta (8%–27%), aortic arch (8%–18%), distal descending aorta, (11%–21%), and abdominal aorta (7%–22%).
- The two most common imaging findings of an intimal tear in MAI are a rounded or triangular intraluminal filling defect (10 mm or less in 80% of cases) or a thin focal intimal flap (seen in 15% of cases) attached to a vessel wall without external contour abnormality. These are most often found at the aortic isthmus and represent an SVS grade I injury. A small (1 cm or less in thickness) intramural hematoma is characterized by increased attenuation within the aortic wall due to hemorrhage from ruptured vasa vasorum or small intimomedial tears. It represents SVS grade II injury but is considered to be in the MAI spectrum by multiple surgical groups and constitutes 5% of all MAI cases.
- Significantly increased depiction of MAI owing to improved CT technology and increased utilization has allowed studies of larger cohorts to be conducted over the last several years. Investigators report spontaneous healing of MAI within the first 4–8 weeks, with only 10%–15% of cases persisting or progressing during the follow-up interval. Variation in the reported range of resolution (55%–85%) is largely due to short to mid-term follow-up data variation.

10%–30% of all BTAI that manifests at imaging, with the diagnosis based solely on multidetector CT findings (11–13).

Traditionally, MAI is defined as a subcentimeter intimal abnormality (thrombus or flap) without external contour deformity (14). Increasing experience with conservative management is expanding the boundaries of what can be called minimal on the basis of long-term stability or short-term resolution (11,15–17). Although the recommendations are not unanimous, localized intramural hematoma without external contour abnormality has now been accepted as part of several classifications as an additional manifestation of MAI (18–20). Both of these MAI patterns tend to have a good prognosis, with fewer than 10%–15% of cases showing progression at follow-up multidetector CT (7–12,19,21–25).

Advocacy for follow-up imaging is not unanimous, and no clear guidelines exist regarding the frequency and interval of follow-up (18). Moreover, recent reports on favorable outcomes after conservative management in cases of large intimal flaps (>1 cm) and small pseudoaneurysms (<1 cm) are fostering debate regarding optimal follow-up tactics, and some cases such as localized intramural hematoma are being considered by some surgeons as mild rather than significant aortic injury (18,25–28).

This review updates the reader on the current concepts of MAI diagnosis and management, with emphasis on imaging appearances, potential pitfalls, and natural history. It also provides insight into the evolving trends related to management and prognostication of MAI from the surgeon's perspective.

Definition, Mechanisms of Injury, and Pathophysiology

MAI was first suggested by Gavant et al (29) in 1995 and further defined by Malhotra et al (30) in 2001 as "a small intimal flap with minimal to no periaortic hematoma." The seminal paper from Azizzadeh et al (31) clearly defined an image-based grading system for BTAI on the basis of the anatomic extent of aortic wall involvement demonstrated at multidetector CT, as follows: intimal tear (grade I), intramural hematoma (grade II), pseudoaneurysm (grade III), and aortic rupture (grade IV). MAI was defined as a small intimal aortic abnormality with no external contour deformity (31). In 2011, this classification was adopted by the Society for Vascular Surgery (SVS) and began being used to help guide intervention (32).

The current definition of MAI is a "sub-centimeter intimo-medial abnormality with no external contour deformity" (18,24,25). This includes small intimal tear and intramural hematoma. While small intimal tear (SVS grade I) has always been considered an MAI lesion, the relatively recent inclusion of intramural hematoma (SVS grade II) is strongly supported by newer management-based classification systems (eg, the Vancouver and Harborview classifications) (18,20–22).

Overall, the majority of BTAIs occur in younger persons who have been involved in high-velocity motor vehicle collisions (3,33,34). Among scenarios in which BTAI has been reported, frontal collisions (60%–65%) are far more common than lateral impact collisions (21%–29%). These are followed by pedestrians being struck by motor vehicles, motorcycle collisions, and a fall from significant height, in decreasing order of frequency (3,33–36).

Although there are no clear pathophysiologic profile differences between MAI and SAI, a restrained frontal collision with use of seat belts and airbag deployment is most often linked to MAI (3,34,36). Conversely, SAI is more common with side-impact collisions and unrestrained passengers,

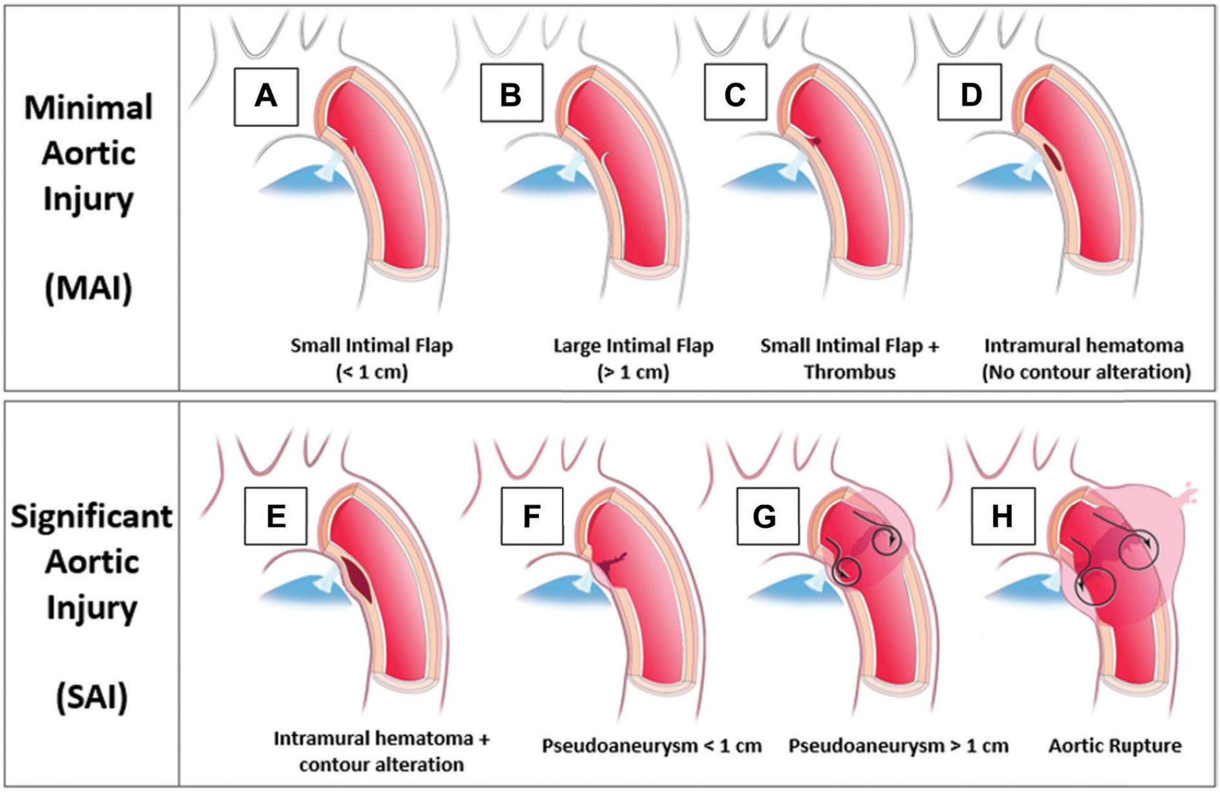


Figure 1. Different morphologic forms of BTAI at the aortic isthmus. Aortic injuries without outer aortic contour alteration are shown: *A,* small intimal flap (<1 cm); *B,* large intimal flap (>1 cm); *C,* small intimal flap with a small adherent thrombus; and *D,* intramural hematoma without contour deformity. While *A* and *C* are traditionally accepted MAI entities, the lesions in *B* and *D* have garnered strong support in favor of nonoperative management and are grouped together with traditional MAI entities in newer management-based classification systems. Aortic injuries with altered outer aortic contour include the following: *E,* intramural hematoma with contour deformity; *F,* contained rupture with small pseudoaneurysm (<1 cm, or occupying less than 50% of aortic circumference); *G,* large pseudoaneurysm (>1 cm, or occupying 50% or more of aortic circumference); and *H,* complete aortic rupture affecting all walls. It is important to note that even though *E* and *F* fall outside the confines of what is traditionally accepted as minimal, the trend toward empirical nonoperative management for these lesions indicates otherwise.

which allow greater and quicker impact on the unsupported torso (3,36,37).

Blunt injury to the deeply situated aorta results from shear stress at rigid points of fixation or at the transition sites between mobile and immobile segments of the aorta. The aorta is tethered by multiple vascular and nonvascular structures such as the aortic arch branches, ligamentum arteriosum, heart, intercostal arteries, and diaphragmatic crura. The known sites of transition between mobile and fixed segments include the aortic root, aortic isthmus, and diaphragmatic aortic hiatus.

Four injury mechanisms or forces have been described that may result in BTAI: *(a)* stretch effect due to opposing vertical tension from arch branches cranially and the heart and intercostal branches caudally; *(b)* shear effect due to tug and torsion applied at the sites of anchorage such as the isthmus; *(c)* pinch effect from external osseous compression of the aorta between the sternum and the spine; and *(d)* thump effect, which involves pressurization of the aortic blood column (Fig 2). Although the precise contribution of different forces is unknown, the current general theory of BTAI indicates convergence of multiple simultaneous injury forces (38,39).

The isthmus of the descending thoracic aorta is the most commonly involved site of MAI, involved in approximately two-thirds of patients with BTAI who present to the hospital (2,6,9,11,40,41). A smaller proportion of cases involve the ascending aorta (8%–27%), aortic arch (8%–18%), distal descending aorta, (11%–21%), and abdominal aorta (7%–22%) (Fig 3) (2,6,9,11,40,41). Aortic arch branches are the least common location for MAI. Instead, branch vessel injuries manifest more frequently with total luminal occlusion because of the smaller caliber and more muscular nature of these arteries (6,42).

In several autopsy series investigating BTAI, multiple simultaneous injuries were seen in 6%–18% of cases, and involvement of the abdominal aorta was seen in 5%–6% of cases (2,40,41). The injury morphologies and mechanisms affecting the abdominal aorta are overall quite similar to those seen in the thoracic aorta (43). Direct and indirect forces are implicated in the trauma. Direct force

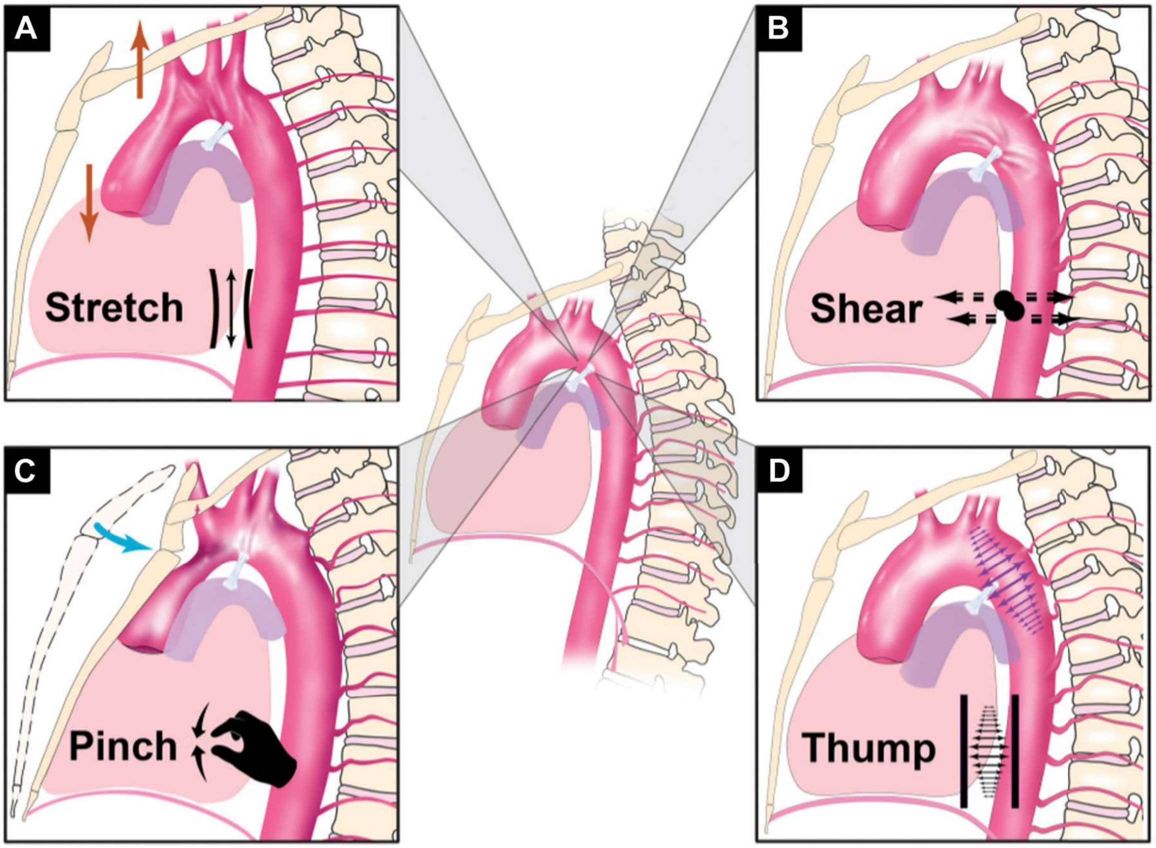


Figure 2. Illustration depicts the main injury forces in blunt aortic injury (including MAI) at the most common location, the aortic isthmus. These forces are often combined and described as follows: *A,* stretch effect with vertically distributed forces (arrows) by the cranial pull by the arch vessels with a hyperextended neck; *B,* shear force due to tugging (dashed arrows) at the site of aortic fixations; *C,* pinch effect due to osseous compression (blue arrow) of the aorta between the rigid sternocostal cage anteriorly and vertebral column posteriorly; and *D,* thump effect, which involves intravascular pressurization (double arrows) of the aortic blood column akin to a water hammer.

between a lap belt and the lumbar spine is thought to be a common mechanism, accounting for nearly half of the cases (44). Shear force, a major factor in thoracic aortic injury, has been shown to play a less important role in abdominal aortic injury and is exerted predominantly in the distal infrarenal aorta near the bifurcation (44,45).

Other than the aforementioned mechanisms of injury, patient factors can potentially influence the injury dynamics. Aortic position and configuration (eg, tortuosity or unfolding) and aortic wall compliance (eg, elasticity, compliance, or atherosclerosis) may contribute to different injury patterns. Most published mechanistic studies assume the transmission of forces in the healthy aorta of a young patient (38,39). It is plausible that the edges of calcific atherosclerotic plaques may act as points of shear vulnerability. However, no quality data exist to support this presumption. On the other hand, overall lower incidence (0.06%–7%) of aortic trauma in the pediatric population is presumably because of preserved thoracic elasticity, aortic configuration, and a lack of vascular atherosclerosis (46–48).

Imaging Evaluation of MAI

Imaging Modalities

Multidetector CT Angiography.—Multidetector CT angiography has become the standard for traumatic aortic evaluation, with sensitivity and specificity of 98%–100%, including in MAI (5). The examination is typically performed as part of a whole-body multidetector CT examination and includes concomitant evaluation for injuries in the abdomen and pelvis (49).

The conventional protocol includes two phases. Chest CT angiography is performed from the thoracic inlet to the caudal renal level. Next, additional abdominal and pelvic imaging is performed in the portovenous phase, starting just above the diaphragm and to the level of the proximal femurs.

Here, chest CT angiography performed with a section thickness of 3 mm or less is started by a bolus tracking and preceded by an injection of nonionic intravenous iodinated contrast material with a saline chaser. The rates of injection and volume of the contrast material and saline vary

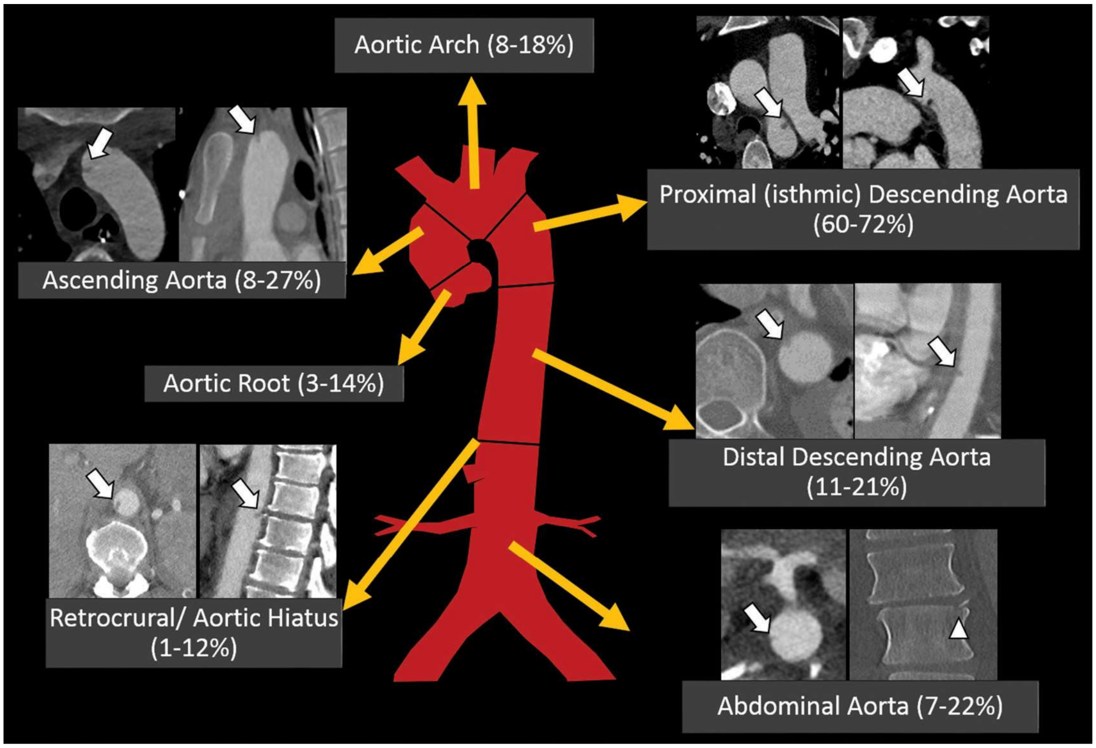


Figure 3. Illustration with image examples (axial images with relevant multiplanar reconstructions) shows the incidence of MAI by location. MAI lesions (white arrows) are subdivided by location (orange arrows) into aortic root (aortic annulus to sinotubular junction); ascending aorta (between sinotubular junction and origin of brachiocephalic artery); aortic arch (segment with all arch vessels); and descending aorta, which includes an isthmic segment (2 cm caudal to the left subclavian artery origin) and a distal segment to the level of the hiatus. Among these, the isthmic segment is affected the most by MAI. Injuries to the aorta at the hiatus and abdominal aorta are less frequent but are commonly associated with lumbar spine injury (arrowhead).

depending on the patient and vendor but generally are within 90–150 mL at 3–5 mL/sec for the contrast material bolus and approximately 30 mL at 4–5 mL/sec for the saline chaser. Imaging in the portovenous phase through the abdomen and pelvis is usually performed with a 70–75-second scan delay. Alternatively, a modified triphasic injection, single-pass, whole-body imaging protocol is described as well and is reported to provide better vascular and parenchymal opacification when compared with conventional two-phase trauma imaging (50).

Multiplanar reconstructions and maximum intensity projection images are vital and are highly recommended to help uncover a fair proportion of injuries that are not as apparent at axial imaging (5,51,52). Although not routinely used, electrocardiographic (ECG) gating at the end of diastole can aid in resolving pulsation and respiratory artifacts encountered in the initial assessment of aortic trauma at nongated multidetector CT and is typically used in imaging follow-up of MAI.

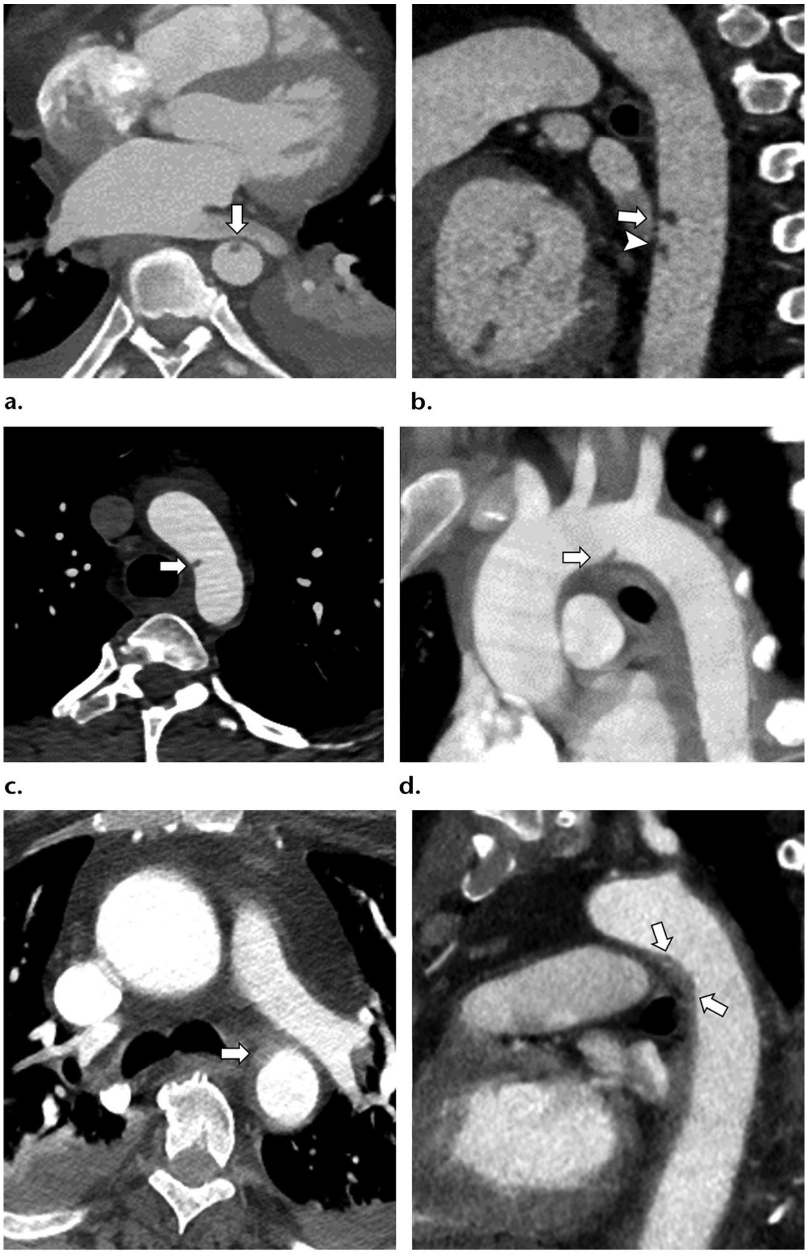
Invasive Imaging Modalities.—These include conventional percutaneous transcatheter angiography and transesophageal echocardiography (TEE). Both of these modalities are inferior to multidetector CT in sensitivity and specificity, especially in the evaluation of MAI because of the subtlety of the imaging findings. Use of TEE primarily for aortic injury screening is recommended only in preliminary intraoperative inspection for aortic injury when CT is delayed because of an emergent surgical exploration (49).

Imaging Findings

Overall, CT findings of BTAI can be subdivided into direct and indirect signs and associated injuries.

Direct Signs.—The two most common imaging findings of an intimal tear in MAI are a rounded or triangular intraluminal filling defect (10 mm or less in 80% of cases) or a thin focal intimal flap (seen in 15% of cases) attached to a vessel wall without external contour abnormality (Fig 1, *A*–*C*; Fig 4) (6,12,35,53). These are most often found at the aortic isthmus and represent an SVS grade I injury (2,6,9,11,40,41).

A small (1 cm or less in thickness) intramural hematoma is characterized by increased attenuation within the aortic wall due to hemorrhage from ruptured vasa vasorum or small intimomedial tears (Fig 1, *D*; Fig 4e). It represents SVS grade II injury but is considered to be in the MAI



a. b. c. d. e. f.

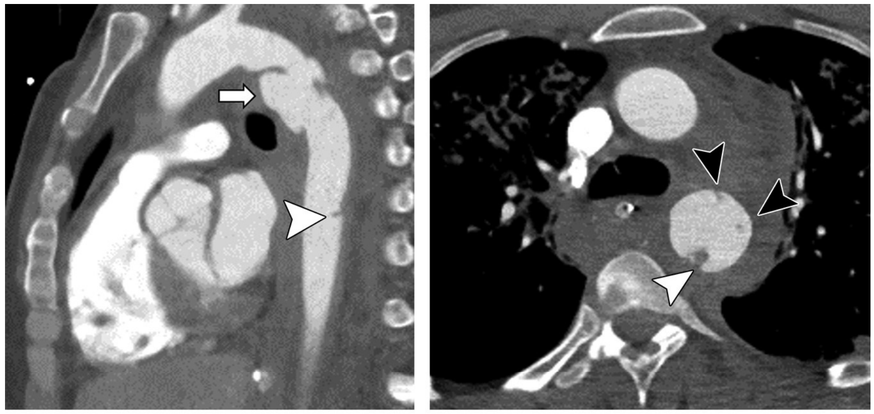
Figure 4. Different imaging subtypes of MAI. The most common imaging manifestations of MAI are a small triangular or rounded wall-adherent thrombus (arrow in **a** and **b**) and a small intimal flap (arrow in **c** and **d**). These could be multifocal MAI (arrowhead in **b**). A small intramural hematoma with characteristic increased attenuation within the wall (arrows in **e** and **f**) without external contour abnormality is the least frequent imaging finding. **(a, b)** Wall-adherent thrombus (attached to a nonresolvable intimal flap) in a 39-year-old man who presented to the emergency department after a restrained high-velocity motor vehicle collision. Axial **(a)** and sagittal **(b)** CT angiograms show multifocal small triangular or rounded wall-adherent thrombi (arrow) within the distal isthmic or descending aorta. The lesions resolved at subsequent imaging before discharge. *(A full DICOM image stack is available online.)* **(c, d)** Intimal flap in a 48-year-old woman who presented to the emergency department after a restrained motor vehicle collision. Axial **(c)** and sagittal **(d)** CT angiograms show a single subcentimeter linear intimal flap (arrow) at the level of the aortic arch. The flap remained stable at two subsequent CT angiography follow-ups performed at 3 days and 4 weeks. No further follow-up images were available. *(A full DICOM image stack is available online.)* **(e, f)** Localized intramural hematoma (seen in addition to an intimal flap, not shown here) in a 55-year-old man involved in an all-terrain vehicle (ATV) accident. Axial **(e)** and sagittal **(f)** CT angiograms show a localized intramural hematoma (arrows). Complete resolution occurred after pharmacologic treatment. *(A full DICOM image stack is available online.)*

spectrum by multiple surgical groups and constitutes 5% of all MAI cases (22,27,35).

A nonenhanced CT examination is rarely performed in the setting of trauma, but intramural hematomas are most easily identified at nonenhanced CT as a crescentic or circumferential region of increased attenuation within the aortic wall (Fig 1). It is important to note that MAI may be multifocal and can be associated with SAI adjacent to or at a different aortic location (Figs 4a, 5).

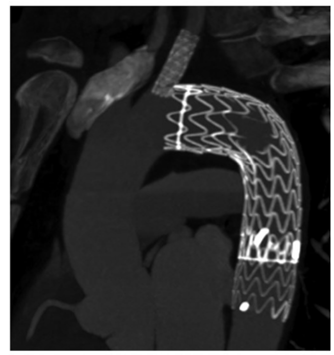
Several surgical groups advocate for inclusion of small pseudoaneurysm in the spectrum of mild nonoperative (similar to MAI) group of BTAI on the basis of its favorable outcome and survival (Fig 1, *F*; 4c) (26–28). A small pseudoaneurysm is usually defined as a contour abnormality occupying less than 50% of the aortic circumference (<1 cm in length) and occurring as a result of a partial tear of the aortic wall beyond the intima. These are commonly observed at the anteromedial aspect of the aortic isthmus. If they progress, aortic pseudoaneurysms have a tendency to enlarge in a transverse direction, and those at the isthmus are often eccentric due to flow-associated dynamics (Fig 1, *F, H*).

Indirect Signs.—Indirect signs associated with BTAI are most often seen with SAI rather than MAI. The most common indirect signs are periaortic and mediastinal hematoma, such that both were initially proposed as mandatory exclusion



a. b.

Figure 5. Concurrent MAI and SAI. **(a, b)** Sagittal **(a)** and axial **(b)** CT angiograms show a large isthmic pseudoaneurysm (arrow in **a**), which is an SAI (SVS grade III injury), with concurrent small intimal flaps (white and black arrowheads) at the distal descending aorta, which is an MAI (SVS grade I injury). Note the large volume of periaortic and mediastinal hemorrhage, which in combination with aortic injuries helped guide the treatment toward urgent thoracic endovascular aortic repair (TEVAR). **(c)** Coronal CT angiogram shows a stent-graft covering both of these injuries.



c.

criteria for the diagnosis of MAI (30,52,54). However, Forman et al (55) found frequent occurrence of periaortic hematoma in MAI (in 79% of cases), and thus it is now accepted that surrounding hematoma can be present in the setting of solitary MAI or in conjunction with SAI (Fig 5).

Two imaging findings that help differentiate hemorrhage from an alternate source such as small mediastinal veins, smaller branch arteries, or aortic vasa vasorum are *(a)* preserved fat plane between the hemorrhage and an intact aortic wall and *(b)* hemorrhage without significant mass effect (9,54,56). However, hemorrhage from aortic arch branches and bronchial and intercostal arteries might be large enough to cause mass effect on adjacent structures.

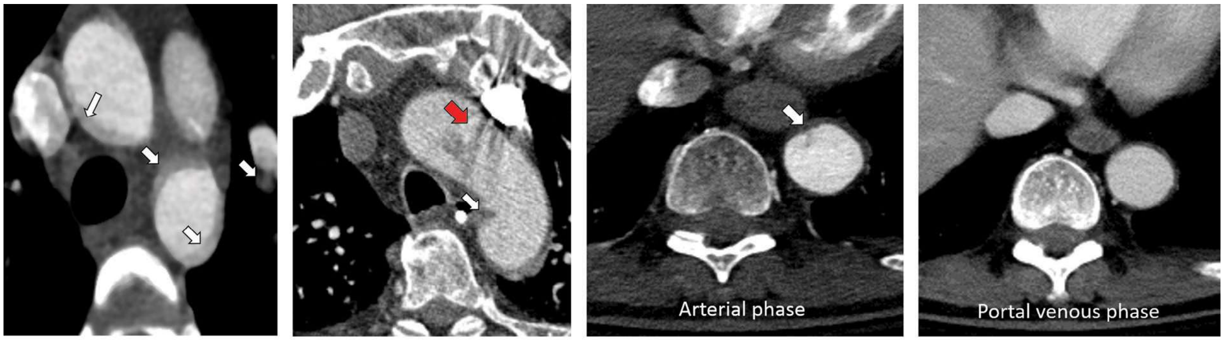
Associated Injuries.—The presence of certain injuries within the thorax is often representative of high-velocity impact, raising the suspicion for deep vascular injuries. Such injuries include fractures of the sternum, first three ribs, scapula, and thoracic spine, which are seen with MAI and SAI (3,14,43,44,55,56). While some studies describe a higher incidence of traumatic brain injury and long bone fractures with SAI and a higher association of isolated rib and spinal fractures with MAI, other studies find no particular injury pattern predictive of the degree of aortic injury (22,24,57). Although similar all-cause mortality is reported for SAI and MAI, this is confounded significantly by the presence of multiple additional severe injuries in these patients (24).

Imaging Pitfalls

The imaging interpretation of MAI can be challenged by a number of pitfalls (51,58). These can be conceptually separated into technical, morphologic, and pathologic mimics (Figs 6–8).

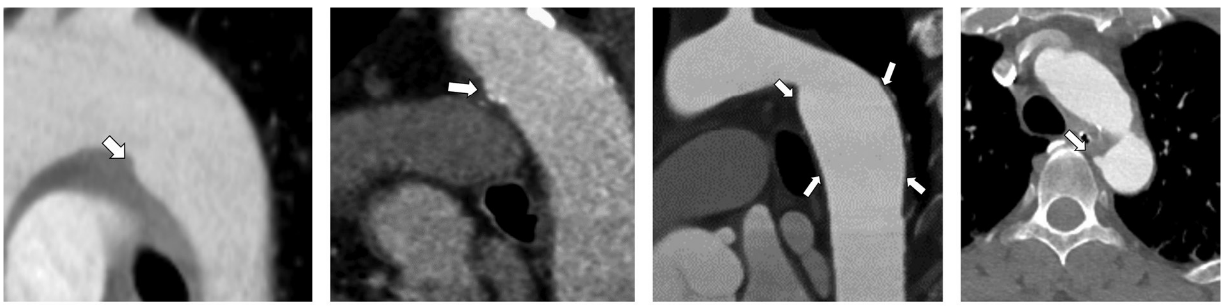
Technical Mimics.—Technical artifacts such as motion artifacts (respiratory motion and cardiac pulsation) and streak artifacts from injected intravenous contrast material can mask or simulate minimal intimal or small contour abnormalities (Fig 6a, 6b). ECG leads or catheters can also cause streak artifact. Mitigation of these artifacts can be achieved with optimal breath hold, cardiac gating, and repeat delayed imaging or repeated injection from the contralateral extremity, respectively (Fig 9).

Anatomic Mimics.—Three anatomic variants of the aortic contour at or around the ligamentum insertion can also be mistaken for small pseudoaneurysms: ductus diverticulum, aortic spindle, and branch vascular infundibula (at the bronchial, intercostal, and spinal arteries). A ductus diverticulum or ductus bump is a congenital variant appearing as a smooth convex bulge along the aortic undersurface at the point of ligamentum arteriosum attachment (Fig 7a). Frequently, a focal calcification at the ductus diverticulum origin is present, providing a helpful clue (Fig 7b).



a. b. c. d.

Figure 6. Technical mimics of MAI. **(a)** Axial multidetector CT image shows motion artifact (arrows) due to cardiac or respiratory motion, which is often obvious due to extension of the artifact beyond the aortic walls or blurred margins of pulmonary vessels or interstitium (not shown). **(b)** Axial multidetector CT image shows streak artifact (red arrow) from attenuating intravenous contrast material within the left brachiocephalic vein. Note the typical attachment of the ligamentum arteriosum at the medial side of the aortic isthmus (white arrow). **(c)** Axial arterial phase multidetector CT image demonstrates mixing artifact (arrow). **(d)** Axial portal venous phase multidetector CT image obtained through the abdomen during the same examination shows that the mixing artifact has been completely resolved.



a. b. c. d.

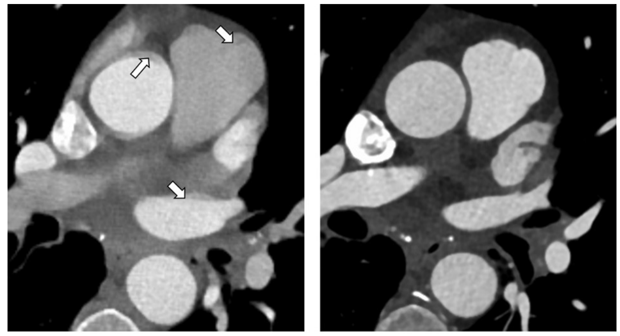
Figure 7. Anatomic mimics of MAI. **(a, b)** Sagittal multidetector CT images show ductus diverticulum without calcifications (arrow in **a**) and with small wall calcifications (arrow in **b**) with typical smooth convexity and congruity with the native aortic wall. **(c)** Sagittal multidetector CT image shows aortic spindle (arrows) with typical smooth and symmetric increase in the caliber of the aorta just below the isthmus. **(d)** Axial multidetector CT image depicts vascular infundibulum with its typical conical shape and a vessel emanating from its apex (arrow).

a. b. c.

Figure 8. Pathologic mimics of MAI. **(a)** Axial multidetector CT image obtained in an elderly patient demonstrates a noncalcified linear atheroma (arrow) in a frequently seen location adjacent to the wall calcifications. **(b, c)** Axial **(b)** and coronal **(c)** multidetector CT images obtained in an elderly patient show a round noncalcified atheroma (arrow) with diffuse circumferential atherosclerosis.

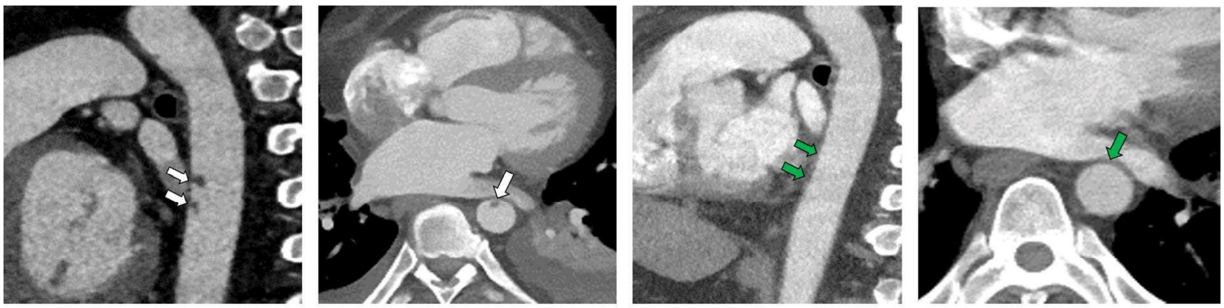
Aortic spindle is a mild fusiform dilatation of the aorta just distal to the isthmus (Fig 7c). Ductus diverticulum and aortic spindle result in smooth contour variations, forming obtuse margins with the normal aorta.

A vascular infundibulum appears more conical and has a small branch vessel emanating from its apex (Fig 7d). The third intercostal artery, also called the superior or highest intercostal artery, is often more prominent on the



a. b.

Figure 9. Troubleshooting cardiac motion with ECG-gated CT angiography of the aorta. CT angiography of the aorta can be performed with prospective or retrospective gating (the preferred method) in cases of significant artifact at the ascending aorta. This approach allows resolution of cardiac motion–produced blur or margin unsharpness (arrows in **a**). Axial CT angiograms obtained before **(a)** and after **(b)** gating demonstrate the resolution of cardiac motion artifact.



a. b. c. d.

Figure 10. MAI in a 55-year-old woman who was an unrestrained driver in a motor vehicle collision and presented with stable hemodynamic parameters. **(a, b)** Sagittal **(a)** and axial **(b)** CT angiograms show multifocal MAI (arrows) in the descending aorta. **(c, d)** Sagittal **(c)** and axial **(d)** multidetector CT angiograms obtained 4 weeks later demonstrate complete resolution of the imaging findings (arrows).

right compared with on the left, and its infundibula may be mistaken for a ductus remnant or isthmic injury (58).

Pathologic Mimics.—Noncalcified and partially calcified atheroma can also mimic MAI entities, specifically small intimal flap, small thrombus, or even controversial intramural hematoma, at multidetector CT evaluation of acute trauma (Fig 8). They less commonly present a diagnostic challenge with diffuse atheromatous aortic changes, but a lack of prior imaging in the setting of trauma can be challenging for differentiation in nondiffuse atherosclerosis. Requesting prior cross-sectional studies along with follow-up imaging and correlation for the signs of other injuries might aid management.

Natural History of MAI

Significantly increased depiction of MAI owing to improved CT technology and increased utilization has allowed studies of larger cohorts to be conducted over the last several years. Investigators report spontaneous healing of MAI within the first 4–8 weeks, with only 10%–15% of cases persisting or progressing during the follow-up interval (Fig 10) (7–12,19,21–25). Variation in the reported range of resolution (55%–85%) is largely due to short- to midterm follow-up data variation (7–12,19,21–25).

In addition, a recent systematic review of 74 studies of BTAI reported a progression rate of 3.4%, with a need to perform salvage therapy in only one out of 146 patients with MAI (10). Progression (defined as an increasing grade of the aortic injury) was found to be associated with other injuries, an overall higher degree of multitrauma, advanced age, and persistent symptoms such as chest pain or unstable blood pressure (10).

The location of MAI may play a role in the difference in resolution and the course. The vast majority of data collected about MAI are focused on thoracic aortic injury, with the most frequent location of MAI at the aortic isthmus. Although nonisthmic MAI is believed to manifest similarly, data specifically pertaining to the natural history of these injuries are limited.

A recent study by Sabra et al (59) showed that BTAI or MAI in the distal descending aorta tends to be a lower grade and requires intervention less frequently. These injuries were associated with higher mortality because of higher overall trauma severity, specifically when there was involvement of the spine (59). At the same time, Shalhub et al (45) found that six out of 28 abdominal MAIs (21.4%) involved the perirenal abdominal aorta, and all but one resolved completely at 72-hour multidetector CT follow-up (45).

To our knowledge, the interesting concept of downstream emboli from MAI injuries has been

Figure 11. Downstream emboli with MAI in a 14-year-old girl who was an unrestrained driver in a motor vehicle collision. **(a, b)** Sagittal **(a)** and axial **(b)** multidetector CT angiograms show an isthmic MAI manifesting as an intraluminal thrombus (arrow). **(c)** Coronal multidetector CT angiogram obtained through the abdomen shows multiple small left renal infarcts (arrowheads). The results of laboratory tests showed no associated renal dysfunction.

examined only by Gunn et al (35) (Fig 11). It is plausible that an intimal breach in a turbulent flow environment of the aorta can pose a risk for dislodgement of intimal thrombi, which can embolize to downstream capillary beds. The report by Gunn et al found new renal or splenic infarcts arising in four out of 23 cases of MAI (17%) (35). The full impact of this new area of evaluation of MAI on overall mortality is yet to be defined.

Current and Evolving Management of MAI

In 2011, the SVS designated a small intimal tear as grade I (minimal injury) and recommended "expectant management with serial imaging" (32). Intramural hematoma and pseudoaneurysm were considered surgical entities, representing grade II and III injuries, respectively (Fig 12).

While the classification scheme reflected progression of injury through the aortic wall, it did not address heterogeneity of the lesions by their size, morphology, and location, and it did not help guide treatment. Moreover, multiple definitions of BTAI were proposed with variable inclusion of injury morphology and arbitrary size limits based on surgeon and institutional thresholds (8,55). At least five different definitions of MAI exist in the contemporary literature, complicating detailed comparison of management and outcomes (8,11,30,35,55,60).

More recently, data from nonoperative management of grade II injuries (intramural hematoma) that could not be repaired emergently because of concomitant severe injuries have shown favorable spontaneous resolution with medical therapy, in turn leading to its wide acceptance with its inclusion in the MAI spectrum (18–20). Also, the SVS simplified their grading system in the most recent revision by combining grade I and grade II injuries as mild and leaving grade III (pseudoaneurysm) and grade IV (rupture) injuries separate as moderate and severe, respectively (18,19).

However, this change still does not address small pseudoaneurysms (usually less than 1 cm) that also are shown to be stable during follow-up and are unlikely to be linked with lesion-specific mortality (26–28). Currently the treatment algorithm suggests repair of all pseudoaneurysms regardless of size, given the potential for devastating complications resulting from expansion and rupture.

While most specialists treating aortic injury tend to follow the SVS guidelines, two other grading systems have been proposed. The Vancouver classification is aimed at improving the modest reproducibility of the SVS classification (20). The Harborview classification is aimed at aligning the injury grades with the current management algorithms (18). The management-focused approach of the Harborview classification system has made it the second most commonly used system (Fig 12) (24). Despite conceptual controversies concerning all three classification systems, MAI represents the lowest aortic injury grade with the most favorable prognosis.

The current recommendation for MAI is nonoperative management (7–12,19,21–25). The SVS guidelines for BTAI recommend expectant management with serial imaging for grade I injuries, while recommending that grade II–IV injuries be repaired operatively. These recommendations are based on the initial study by Azizzadeh et al (31), which demonstrated that most of these intimal injuries heal spontaneously (32).

In a recent retrospective study by Paul et al (23), 13 patients with MAI had zero aortic-related complications with nonoperative management, with an average of 1.6 follow-up CT angiographic studies per patient. Osgood et al (10) evaluated results of nonoperative management for

Society of Vascular Surgery Classification (Azzazideh et al.)		Vancouver Classification (Lemarche et al.)		Harborview Classification (Heneghan et al.)	
Year proposed - 2009 Most widely used		Year proposed - 2012 Proposed advantage - Better reproducibility		Year proposed - 2016 Proposed advantage - Tailored to guide management	
Grade	Description	Grade	Description	Grade	Description
I	Intimal tear/ Flap	I	Thrombus/Flap/IMH < 1 cm	Minimal	Thrombus/Flap/ IMH < 1cm w/o contour abnormality
II	Intramural hematoma (IMH)	II	Thrombus/Flap/IMH > 1 cm	Moderate	External contour abnormality or flap > 1 cm
III	Pseudo-aneurysm (PSA)	III	PSA without extravasation		
IV	Free rupture	IV	Contrast extravasation	Severe	Extravasation, Left subclavian artery hematoma > 1.5 cm

Figure 12. Classifications for BTAI that include MAI. The SVS classification (31) was introduced in 2009 and is based on the morphologic severity of aortic wall disruption. It remains the most widely used classification system. The Vancouver classification (20) (introduced in 2012) and the Harborview classification (18) (introduced in 2016) have incorporated additional details, such as size and stability, on nonoperative treatment of small pseudoaneurysm and intramural hematoma without external contour deformity, allowing improved patient selection for optimal treatment. The Vancouver classification has better reproducibility, and the Harborview classification is tailored to help guide management. *NA* = not applicable.

grade I and grade II injuries with a mean follow-up of 74 days, with 55% of cases resolving and 40% of cases demonstrating stability. A contemporary study by Spencer et al (22) with 11-year follow-up of 71 patients with BTAI identified 30 patients with grades I and II injuries. Two out of 16 patients randomized to the nonoperative management group showed progression of aortic injuries at follow-up CT, with none requiring operative intervention (22).

The nonoperative management strategy for MAI primarily consists of blood pressure and heart rate control. Effective and uninterrupted therapy has shown to drastically decrease the risk of progression from 12% to 1.5% (61). Patients are generally admitted to an intensive care or telemetry unit, where intravenous infusion of β-blocking agents, calcium channel blockers, or vasodilators (or a combination thereof) is administered to achieve a heart rate goal of less than 70–80 beats per minute and a systolic blood pressure goal of less than 110–120 mm Hg. A transition to oral agents is done as soon as possible. Antiplatelet therapy is also recommended for intimal injuries, especially those associated with thrombus. However, this must be done with consideration for the risk of bleeding from other associated injuries (10).

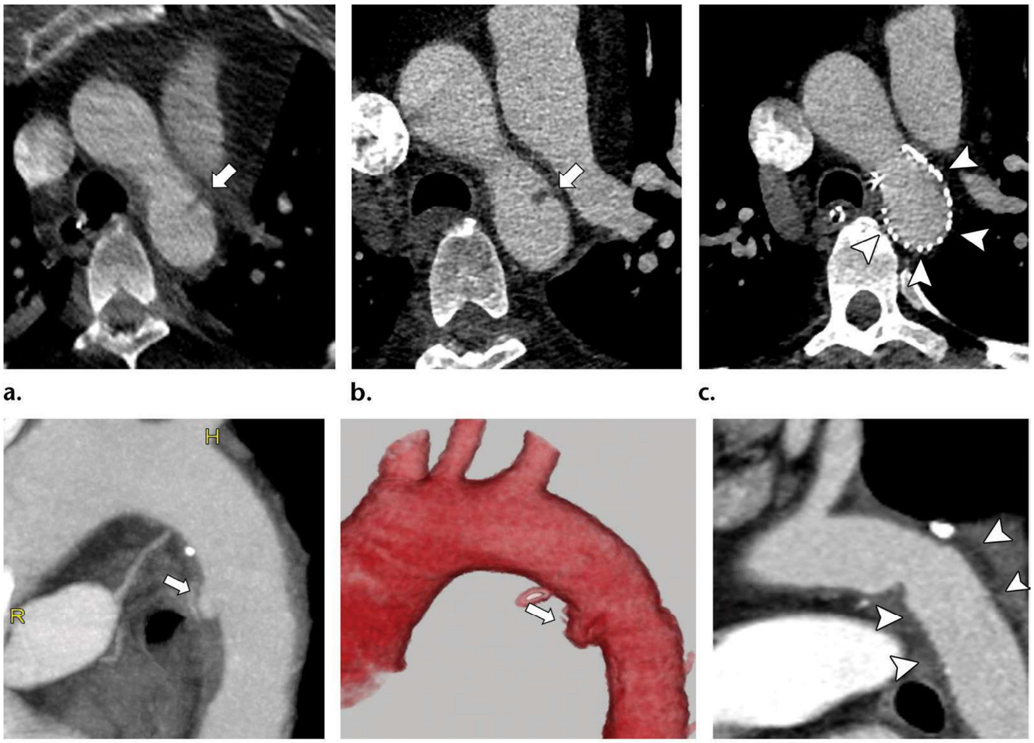
Repeat CT angiography is the key to evaluation of nonoperative management failure in MAI. However, there is no consensus on the timing of the repeat imaging, with most studies demonstrating an average of 1.6–2.7 follow-up CT angiographic examinations (10,18,21,23,35). Some advocate against imaging follow-up of MAI for grades I and II, while others suggest follow-up at 6 months, 12 months, and then annually for persistent but stable cases (8,9,17,25,62). Our practice is to repeat ECG-gated CT angiography at 48–72 hours postinjury and then again at 1 month. Should the imaging or clinical picture of the patient demonstrate progression of the grade of aortic injury, operative management may then be needed.

Treatment of MAI from the Surgical Perspective

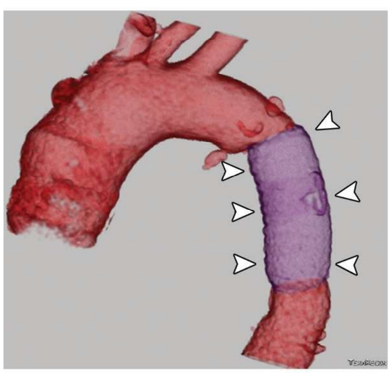
Very few scenarios exist in which surgical intervention is required for MAI. An example is when the patient has concomitant injuries that prevent lowering of the heart rate and blood pressure, such as severe cerebral or spinal injuries that require increasing cerebral or spinal perfusion pressures, respectively (16,63). In these cases, a coordinated discussion between associated specialists should occur to determine the best course of action. A minimally invasive thoracic endovascular aortic repair (TEVAR) can be performed by placing a stent-graft to cover the intimal injury and allow the elevated heart rate and blood pressure typically required to improve neurologic perfusion pressures (Fig 13).

TEVAR has almost completely replaced the open surgical approach in the last several decades, given its far superior mortality and morbidity profile (eg, low stroke and paraplegia rates) and high technical success (16,64). The complication rate from TEVAR in overall BTAI management is reported at 3%–18% (16,64). While urgent (performed in less than 24 hours) TEVAR is required for patients in an unstable condition with aortic lesions manifesting with external contour abnormalities (pseudoaneurysm regardless of the size, SVS grade III injury and

Figure 13. TEVAR management of MAI and small pseudoaneurysm. **(a–c)** Axial CT angiogram **(a)** in a 42-year-old man involved in a motor vehicle collision shows a small intimal flap (arrow). Axial CT angiogram **(b)** obtained 3 weeks later shows the small intimal flap (arrow) to be stable. However, the patient reported persistent chest pain, which prompted TEVAR stent-graft. Axial CT angiogram **(c)** shows the TEVAR stent-graft (arrowheads). The patient had complete resolution of symptoms after surgery. **(d–g)** Sagittal CT angiogram **(d)** and volume-rendered reconstruction **(e)** in a 37-year-old man show a small (<1 cm) pseudoaneurysm (arrow in **d** and **e**) that was associated with a small mediastinal hematoma (not shown) but was otherwise asymptomatic. The pseudoaneurysm underwent semielective TEVAR repair (based on SVS guidelines) on day 8. Sagittal CT angiogram **(f)** and volume-rendered reconstruction **(g)** depict the TEVAR stent-graft (arrowheads in **g** and **f**) that was placed without intraoperative or postsurgical complications.



a. b. c. d. e. f.



g.

complete aortic transection, or SVS grade IV injury), patients with grade I or II injuries may be chosen for delayed (performed after 24 hours) or semielective (performed after 15 days) repair, depending on the severity of concomitant injuries.

Pre-TEVAR CT angiography is used for appropriate sizing of the endograft. In acutely injured patients, stent-graft oversizing is limited to approximately 10% and certainly no greater than 20%. In a patient with acute trauma, if there is any concern for decreased intravascular volume contributing to undersizing of the true aortic diameter, then intravascular US can be used to help gauge diameter. However, undersizing is generally not a problem given that trauma remains a condition affecting primarily patients in younger age ranges with smaller native aortic diameters (65–67). A significant proportion of patients with MAI require coverage of the left subclavian artery ostium in order to stent the injury, with reported rates as high as 40%. However, this technique is usually well tolerated in this young patient demographic, owing to preserved collateral sufficiency (9,24,68). Periprocedural anticoagulation therapy with the associated risk of bleeding in patients with polytrauma is also proven to be low when using low-dose heparin as an anticoagulative agent (69).

Small Aortic Pseudoaneurysm and Large Intimal Flap

Currently, the SVS does not distinguish between small and large pseudoaneurysm and recommends endovascular repair regardless of size

(32). A growing body of literature suggests that small aortic pseudoaneurysms may be successfully nonoperatively managed on the basis of reported stability (26–28). Another controversial lesion is a large intimal flap without external aortic wall abnormality, and there are current debates about whether it belongs to a mild nonoperative type of injury or represents a moderate degree of aortic injury and should be repaired (18,25). However, most institutions, including our own, tend to perform delayed or semielective TEVAR of a pseudoaneurysm or large intimal flap on the basis of current SVS recommendations. This approach may change in the future as more data are collected and results from the Aortic Trauma Foundation national registry are finalized. As of January 2020, the registry has accrued 537 cases from multiple centers across North America, with the main goal of helping standardize patient selection for the most appropriate treatment (70).

Conclusion

MAI represents a mild form of BTAI with a favorable prognosis and is traditionally defined as a small intimomedial abnormality with no external contour irregularity, most commonly occurring at the aortic isthmus. The imaging spectrum of manifestations of MAI may expand in the future as more long-term data are collected regarding the course of and survival rates for several other traumatic aortic lesions. High-resolution multidetector CT with multiplanar reconstructions and awareness of imaging findings are essential for the diagnosis. Asymptomatic resolution of this imaging abnormality with conservative management is expected in the majority of patients. The consensus on the imaging follow-up timeline and the need for intervention in persistent cases is currently not defined.

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References

1. Arthurs ZM, Starnes BW, Sohn VY, Singh N, Martin MJ, Andersen CA. Functional and survival outcomes in traumatic blunt thoracic aortic injuries: an analysis of the National Trauma Databank. J Vasc Surg 2009;49(4):988–994.
2. Teixeira PGR, Inaba K, Barmparas G, Georgiou C. Blunt thoracic aortic injuries: an autopsy study. J Trauma 2011;70(1):197–202.
3. Fadl SA, Sandstrom CK. Pattern Recognition: a Mechanism-based Approach to Injury Detection after Motor Vehicle Collisions. RadioGraphics 2019;39(3):857–876.
4. Broder J, Warshauer DM. Increasing utilization of computed tomography in the adult emergency department, 2000-2005. Emerg Radiol 2006;13(1):25–30.
5. Steenburg SD, Ravenel JG, Ikonomidis JS, Schönholz C, Reeves S. Acute traumatic aortic injury: imaging evaluation and management. Radiology 2008;248(3):748–762.
6. Langa SM, Dlamini NNM, Pillay B. Spectrum of multidetector computed tomography imaging findings of thoracic vascular injuries secondary to blunt chest trauma: Correlation with vascular intervention and patient outcomes. SA J Radiol 2019;23(1):1709.
7. Sandhu HK, Leonard SD, Perlick A, et al. Determinants and outcomes of nonoperative management for blunt traumatic aortic injuries. J Vasc Surg 2018;67(2):389–398.
8. Rabin J, DuBose J, Sliker CW, O'Connor JV, Scalea TM, Griffith BP. Parameters for successful nonoperative management of traumatic aortic injury. J Thorac Cardiovasc Surg 2014;147(1):143–149.
9. DuBose JJ, Leake SS, Brenner M, et al. Contemporary management and outcomes of blunt thoracic aortic injury: a multicenter retrospective study. J Trauma Acute Care Surg 2015;78(2):360–369 [Published correction appears in J Trauma Acute Care Surg 2015;78(3):656.].
10. Osgood MJ, Heck JM, Rellinger EJ, et al. Natural history of grade I-II blunt traumatic aortic injury. J Vasc Surg 2014;59(2):334–341.
11. Jacob-Brassard J, Salata K, Kayssi A, et al. A systematic review of nonoperative management in blunt thoracic aortic injury. J Vasc Surg 2019;70(5):1675–1681.e6.
12. Harris DG, Rabin J, Crawford RS, et al. Incidence and outcomes of thoracic aortic injuries with regionalized care in a mature trauma system. Trauma 2019;21(1):55–60.
13. Payne RE, Nygaard RM, Fernandez JD, et al. Blunt aortic injuries in the new era: radiologic findings and polytrauma risk assessment dictates management strategy. Eur J Trauma Emerg Surg 2019;45(6):951–957.
14. Marro A, Chan V, Haas B, Ditkofsky N. Blunt chest trauma: classification and management. Emerg Radiol 2019;26(5):557–566.
15. Demetriades D, Velmahos GC, Scalea TM, et al. Blunt traumatic thoracic aortic injuries: early or delayed repair—results of an American Association for the Surgery of Trauma prospective study. J Trauma 2009;66(4):967–973.
16. Scalea TM, Feliciano DV, DuBose JJ, Ottochian M, O'Connor JV, Morrison JJ. Blunt Thoracic Aortic Injury: endovascular Repair Is Now the Standard. J Am Coll Surg 2019;228(4):605–610.
17. Harris DG, Rabin J, Starnes BW, et al. Evolution of lesion-specific management of blunt thoracic aortic injury. J Vasc Surg 2016;64(2):500–505.
18. Heneghan RE, Aarabi S, Quiroga E, Gunn ML, Singh N, Starnes BW. Call for a new classification system and treatment strategy in blunt aortic injury. J Vasc Surg 2016;64(1):171–176.
19. Fortuna GR Jr, Perlick A, DuBose JJ, et al. Injury grade is a predictor of aortic-related death among patients with blunt thoracic aortic injury. J Vasc Surg 2016;63(5):1225–1231.
20. Lamarche Y, Berger FH, Nicolaou S, et al. Vancouver simplified grading system with computed tomographic angiography for blunt aortic injury. J Thorac Cardiovasc Surg 2012;144(2):347–354, 354.e1.
21. Mosquera VX, González-Barbeito M, Marini M, et al. Evolution of conservative treatment of acute traumatic aortic injuries: lights and shadows. Eur J Cardiothorac Surg 2018;54(4):689–695.
22. Spencer SM, Safcsak K, Smith CP, Cheatham ML, Bhullar IS. Nonoperative management rather than endovascular repair may be safe for grade II blunt traumatic aortic injuries: an 11-year retrospective analysis. J Trauma Acute Care Surg 2018;84(1):133–138.
23. Paul JS, Neideen T, Tutton S, et al. Minimal aortic injury after blunt trauma: selective nonoperative management is safe. J Trauma 2011;71(6):1519–1523.
24. Quiroga E, Starnes BW, Tran NT, Singh N. Implementation and results of a practical grading system for blunt thoracic aortic injury. J Vasc Surg 2019;70(4):1082–1088.
25. Starnes BW, Lundgren RS, Gunn M, et al. A new classification scheme for treating blunt aortic injury. J Vasc Surg 2012;55(1):47–54.
26. Tanizaki S, Maeda S, Matano H, et al. Blunt thoracic aortic injury with small pseudoaneurysm may be managed by nonoperative treatment. J Vasc Surg 2016;63(2):341–344.
27. Gandhi SS, Blas JV, Lee S, Eidt JF, Carsten CG 3rd. Nonoperative management of grade III blunt thoracic aortic injuries. J Vasc Surg 2016;64(6):1580–1586.

28. Harris DG, Rabin J, Bhardwaj A, et al. Nonoperative Management of Traumatic Aortic Pseudoaneurysms. Ann Vasc Surg 2016;35:75–81.
29. Gavant ML, Menke PG, Fabian T, Flick PA, Graney MJ, Gold RE. Blunt traumatic aortic rupture: detection with helical CT of the chest. Radiology 1995;197(1):125–133.
30. Malhotra AK, Fabian TC, Croce MA, Weiman DS, Gavant ML, Pate JW. Minimal aortic injury: a lesion associated with advancing diagnostic techniques. J Trauma 2001;51(6):1042–1048.
31. Azizzadeh A, Keyhani K, Miller CC 3rd, Coogan SM, Safi HJ, Estrera AL. Blunt traumatic aortic injury: initial experience with endovascular repair. J Vasc Surg 2009;49(6):1403–1408.
32. Lee WA, Matsumura JS, Mitchell RS, et al. Endovascular repair of traumatic thoracic aortic injury: clinical practice guidelines of the Society for Vascular Surgery. J Vasc Surg 2011;53(1):187–192.
33. Tefft B. Rates of Motor Vehicle Crashes, Injuries and Deaths in Relation to Driver Age, United States, 2014-2015. AAA Foundation for Traffic Safety. https://aaafoundation.org/rates-motor-vehicle-crashes-injuries-deaths-relation-driver-age-united-states-2014-2015/. Published 2017. Accessed April 4, 2020.
34. Abu-Zidan FM, Eid HO. Factors affecting injury severity of vehicle occupants following road traffic collisions. Injury 2015;46(1):136–141.
35. Gunn MLD, Lehnert BE, Lungren RS, et al. Minimal aortic injury of the thoracic aorta: imaging appearances and outcome. Emerg Radiol 2014;21(3):227–233.
36. Stigson H, Gustafsson M, Sunnevång C, Krafft M, Kullgren A. Differences in long-term medical consequences depending on impact direction involving passenger cars. Traffic Inj Prev 2015;16(Suppl 1):S133–S139.
37. Katyal D, McLellan BA, Brenneman FD, Boulanger BR, Sharkey PW, Waddell JP. Lateral impact motor vehicle collisions: significant cause of blunt traumatic rupture of the thoracic aorta. J Trauma 1997;42(5):769–772.
38. Richens D, Field M, Neale M, Oakley C. The mechanism of injury in blunt traumatic rupture of the aorta. Eur J Cardiothorac Surg 2002;21(2):288–293.
39. Neschis DG, Scalea TM, Flinn WR, Griffith BP. Blunt aortic injury. N Engl J Med 2008;359(16):1708–1716.
40. Burkhart HM, Gomez GA, Jacobson LE, Pless JE, Broadie TA. Fatal blunt aortic injuries: a review of 242 autopsy cases. J Trauma 2001;50(1):113–115.
41. Feczko JD, Lynch L, Pless JE, Clark MA, McClain J, Hawley DA. An autopsy case review of 142 nonpenetrating (blunt) injuries of the aorta. J Trauma 1992;33(6):846–849.
42. Holdgate A, Dunlop S. Review of branch aortic injuries in blunt chest trauma. Emerg Med Australas 2005;17(1):49–56.
43. Michaels AJ, Gerndt SJ, Taheri PA, et al. Blunt force injury of the abdominal aorta. J Trauma 1996;41(1):105–109.
44. Roth SM, Wheeler JR, Gregory RT, et al. Blunt injury of the abdominal aorta: a review. J Trauma 1997;42(4):748–755.
45. Shalhub S, Starnes BW, Tran NT, et al. Blunt abdominal aortic injury. J Vasc Surg 2012;55(5):1277–1285.
46. Spouge AR, Burrows PE, Armstrong D, Daneman A. Traumatic aortic rupture in the pediatric population. Role of plain film, CT and angiography in the diagnosis. Pediatr Radiol 1991;21(5):324–328.
47. Hasjim BJ, Grigorian A, Barrios C Jr, et al. National Trends of Thoracic Endovascular Aortic Repair versus Open Thoracic Aortic Repair in Pediatric Blunt Thoracic Aortic Injury. Ann Vasc Surg 2019;59:150–157.
48. Trachiotis GD, Sell JE, Pearson GD, Martin GR, Midgley FM. Traumatic thoracic aortic rupture in the pediatric patient. Ann Thorac Surg 1996;62(3):724–731; discussion 731–732.
49. Demehri S, Rybicki FJ, Desjardins B, et al. ACR Appropriateness Criteria(®) blunt chest trauma: suspected aortic injury. Emerg Radiol 2012;19(4):287–292.
50. Yaniv G, Portnoy O, Simon D, Bader S, Konen E, Guranda L. Revised protocol for whole-body CT for multi-trauma patients applying triphasic injection followed by a single-pass scan on a 64-MDCT. Clin Radiol 2013;68(7):668–675.
51. Bruckner BA, DiBardino DJ, Cumbie TC, et al. Critical evaluation of chest computed tomography scans for blunt descending thoracic aortic injury. Ann Thorac Surg 2006;81(4):1339–1346.
52. Gavant ML. Helical CT grading of traumatic aortic injuries. Impact on clinical guidelines for medical and surgical management. Radiol Clin North Am 1999;37(3):553–574, vi.
53. Hsiang YN, Fragoso M, Lundkist A, Weis M. The natural history of intimal flaps caused by angioscopy. Ann Vasc Surg 1992;6(1):38–44.
54. Harris DG, Rabin J, Kufera JA, et al. A new aortic injury score predicts early rupture more accurately than clinical assessment. J Vasc Surg 2015;61(2):332–338.
55. Forman MJ, Mirvis SE, Hollander DS. Blunt thoracic aortic injuries: CT characterisation and treatment outcomes of minor injury. Eur Radiol 2013;23(11):2988–2995.
56. Hayes CW, Conway WF, Walsh JW, Coppage L, Gervin AS. Seat belt injuries: radiologic findings and clinical correlation. RadioGraphics 1991;11(1):23–36.
57. Mosquera VX, Marini M, Gulías D, et al. Minimal traumatic aortic injuries: meaning and natural history. Interact Cardiovasc Thorac Surg 2012;14(6):773–778.
58. Fisher RG, Sanchez-Torres M, Whigham CJ, Thomas JW. "Lumps" and "bumps" that mimic acute aortic and brachiocephalic vessel injury. RadioGraphics 1997;17(4): 825–834.
59. Sabra MJ, Dennis JW, Allmon JC, Gautam S, Habib J. Identification of unique characteristics and the management of blunt traumatic aortic injuries occurring at unusual locations in the descending thoracic aorta. J Vasc Surg 2019;69(1):40–46.
60. Fabian TC, Davis KA, Gavant ML, et al. Prospective study of blunt aortic injury: helical CT is diagnostic and antihypertensive therapy reduces rupture. Ann Surg 1998;227(5):666–676; discussion 676–677.
61. Hemmila MR, Arbabi S, Rowe SA, et al. Delayed repair for blunt thoracic aortic injury: is it really equivalent to early repair? J Trauma 2004;56(1):13–23.
62. Kidane B, Abramowitz D, Harris JR, DeRose G, Forbes TL. Natural history of minimal aortic injury following blunt thoracic aortic trauma. Can J Surg 2012;55(6):377–381.
63. Akhmerov A, DuBose J, Azizzadeh A. Blunt Thoracic Aortic Injury: Current Therapies, Outcomes, and Challenges. Ann Vasc Dis 2019;12(1):1–5.
64. Tang GL, Tehrani HY, Usman A, et al. Reduced mortality, paraplegia, and stroke with stent graft repair of blunt aortic transections: a modern meta-analysis. J Vasc Surg 2008;47(3):671–675.
65. Ceja Rodriguez M, Realyvasquez A, Galante J, Pevec W, Humphries M. Differences in Aortic Diameter Measurements With Intravascular Ultrasound and Computed Tomography After Blunt Traumatic Aortic Injury. J Vasc Surg 2016;64(2):P545.
66. Etheridge JC, Ahanchi SS, Dexter DJ, Cain BC, Collins JN, Panneton JM. The impact of intravascular ultrasound on outcomes of endovascular repair of blunt traumatic aortic injury. Trauma (United Kingdom) 2019;21(3):208–214.
67. Wallace GA, Starnes BW, Hatsukami TS, Sobel M, Singh N, Tran NT. Intravascular ultrasound is a critical tool for accurate endograft sizing in the management of blunt thoracic aortic injury. J Vasc Surg 2015;61(3):630–635.
68. McBride CL, Dubose JJ, Miller CC 3rd, et al. Intentional left subclavian artery coverage during thoracic endovascular aortic repair for traumatic aortic injury. J Vasc Surg 2015;61(1):73–79.
69. Kenel-Pierre S, Ramos Duran E, Abi-Chaker A, et al. The role of heparin in endovascular repair of blunt thoracic aortic injury. J Vasc Surg 2019;70(6):1809–1815.
70. Aortic Trauma Foundation. (@AorticTrauma) / Twitter n.d. https://twitter.com/AorticTrauma. Accessed March 4, 2020.