Original Article

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Effect of Severe Traumatic Hemorrhage on Large Arterial Diameter as Determined by Computed Tomography

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Background: The objective of this study was to investigate changes in the diameters of major arteries in trauma patients at the time of severe intravascular volume depletion.
Methods: Patients admitted from January 2008–June 2017 in extremis or in arrest who had an immediate computed tomography (CT) scan in the resuscitation period and at least one subsequent CT scan after hemodynamic stabilization and admission to the intensive care unit were included. Diameter in millimeters (mm) of the common carotid, subclavian, common iliac, external iliac, common femoral arteries, and aorta at the following locations were obtained: ascending, proximal descending, and mid-descending thoracic and supra-celiac, renal, and aortic bifurcation.
Results: Fourteen patients (93% male) were included. Mean injury severity score was 37 ± 8 and age 36 ± 18 years. Ten patients received a resuscitative endovascular balloon occlusion of the aorta and four patients received a resuscitative thoracotomy prior to the first CT. A maximum increase of the aorta of 63.6%, and 116.9% in the common carotid, subclavian, common iliac, external iliac, and common femoral arteries was observed. For patients aged 18–39 years, increases in diameter were statistically significant ($p < 0.05$) at all locations except the peri-renal aorta and left subclavian. Patients ≥40 years had a less robust change, with a significant diameter increase only with the proximal descending aorta ($p = 0.02$).
Conclusions: Large arterial diameters in the setting of severe hemorrhage are significantly reduced particularly in younger patients. This has significant implications for emergent placement of endovascular devices such as introducer sheaths, balloon catheters, and stent grafts where the determination of arterial diameter is critical.

Keywords: *Resuscitative Endovascular Balloon Occlusion of the Aorta; REBOA; Aortic Occlusion; Resuscitative Thoracotomy; Hemorrhagic Shock; Diameter*

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INTRODUCTION

The prevalence of endovascular and catheter-based interventions in trauma has been increasing, as evidenced by the paradigm shift in treatment of blunt thoracic aortic injuries (BTAI) from open surgical repair to thoracic endovascular repair (TEVAR) [1–3], as well as a significant increase in the usage of resuscitative endovascular balloon occlusion of the aorta (REBOA) [4,5]. The ability to predict and/or measure arterial diameter is critical in these contexts. A substantial transient decrease in arterial diameter, such as with hemorrhagic shock, may have important implications for emergent placement of endovascular devices, such as introducer sheaths, balloon catheters, and stent grafts. An underestimation of arterial diameter may lead to inappropriate stent sizing, which may increase the risk for complications such as endoleak, endograft malposition, migration, or collapse. The inflation diameter with balloon catheters required to occlude the aorta may be reduced, which may be significant especially in the setting of blind inflation. Lastly, decreased arterial diameters may potentially exacerbate the flow-limiting effects of indwelling introducer sheaths.

Hypovolemia from hemorrhagic shock and sympathetic activation from trauma results in a decrease in the diameters of the aorta and other large arteries; however, this phenomenon has yet to be adequately characterized. Porcine models of hemorrhagic shock have demonstrated that the diameter of the aorta can substantially decrease, up to 61%, and that the pulsatility (change in diameter between systole and diastole) of the aorta is also diminished [6,7], and may ultimately lead to the underestimation of these diameters at baseline. A few studies [8–10] have demonstrated that arterial diameters, as measured by computed tomography (CT) imaging acquired near admission, are reduced in comparison to subsequent CT imaging in humans. However, it remains unclear what the upper limits of this effect are on the diameters of the aorta and large arteries in trauma patients. In addition, there is a paucity of literature examining what the effects of aging or cardiovascular disease may be.

We sought to investigate this phenomenon by examining patients who underwent procedures typically reserved for patients in extremis such as REBOA or resuscitative thoracotomy. These patients likely represent a cohort of the most severely injured and potentially treatable patients.

METHODS

This retrospective case series was approved by the University of Maryland Medical Center Institutional Review Board. Patients, age ≥18 years old, admitted to the University of Maryland Shock Trauma Center, between January 2008 and June 2017, who underwent REBOA or resuscitative thoracotomy in the resuscitation area or were taken to the operating room emergently and had REBOA or thoracotomy were included. Patients who had a CT scan of the thorax and/or abdomen/pelvis immediately before or after intervention, as well as a subsequent CT, were included. The comparison CT, defined as the "baseline" or "reference" CT, was required to be obtained within 1 year of the CT obtained at the time of injury. Patients were excluded if they had a CT scan performed with the REBOA balloon partially or fully inflated. Demographics and hospital course data were collected from medical records.

All images were reviewed and vessel measurements were taken by a board-certified trauma radiologist with 25 years expertise in trauma imaging, who was blinded to the purpose of the study. Images were reviewed using IMPAX Software (AGFA Healthcare, Mortsel, Belgium). Two diameter measurements were taken at each location (one in the anterior–posterior dimension, and the other in the left–right or cranial–caudal dimension). Diameter measurements were taken of the left and right common carotid and subclavian arteries within 1 cm of their origins to the aorta/innominate artery. Measurements were taken of the ascending aorta (at the level of the manubrium-sternal joint), proximal descending thoracic aorta (just distal to the left subclavian artery origin), mid-descending thoracic aorta (at the level of the left pulmonary artery), supra-celiac aorta (immediately proximal to the origin of the celiac artery), peri-renal aorta (immediately adjacent to the renal arteries), and the aortic bifurcation (immediately proximal to the aortic bifurcation). The common iliac arteries were measured immediately proximal to the origin of the internal iliacs. The external iliacs were measured immediately adjacent to the origin of the inferior epigastric arteries. Lastly, the common femoral arteries were measured immediately proximal to the bifurcation of the superficial femoral and profunda femoris arteries. All measurements were taken using axial images except for the right subclavian artery, which required coronal imaging. No patients had significant tortuosity and/or angulation requiring reformatting of imaging to obtain appropriate diameter measurements perpendicular to the long axis of the vessels. Diameter measurements and comparisons were only included if it was possible to obtain measurements at both CT scan time points.

Patients were analyzed in total and divided into two groups, those aged 18–39 years and those over 39 years old. The diameters of the CT adjacent to the time of injury and reference CT were compared. The eccentricity of the arteries at each location was calculated and analyzed for potential changes. The value of eccentricity ranges from 0 (a perfect circle) to 1 (a straight line). Statistical analysis was performed using R Software (version 3.3.0, R Development Core Team, Vienna, Austria). A paired two-sample *t*-test was used for mean comparison of diameter and eccentricity changes between CT scans at both time points.

An unpaired one-sided *t*-test was used for mean comparison of the relative increase in arterial diameters between the younger (18–39 years) and older (≥40 years) age groups. For patients who underwent REBOA, the change in the common femoral artery that was accessed and manipulated was compared to the contralateral common femoral artery using a paired two-sided *t*-test. Fisher's exact test was used for proportion comparison of demographic characteristics between age groups. Statistical significance was defined as a *p*-value of 0.05 or less.

RESULTS

Fourteen patients were included. See Table 1 for a description of patient demographics and characteristics.

Table 1 Demographics and characteristics.

Variable	*Value*
n	14
ISS (mean ± standard deviation)	37 ± 8
Penetrating/blunt	57%, 43%
Gender	93% male, 7% female
Age (years)	36 ± 18
REBOA	*n* = 10
Resuscitative thoracotomy	*n* = 4
Time from admission to CT scan, median [inter-quartile range]	281 [191–673] minutes
Time from CT imaging near point of injury to comparison (baseline) CT	16 [10–28] days
Initial admission hemoglobin (mean ± standard deviation)	11.6 ± 1.8 g/dL
24 hour nadir hemoglobin	8.7 ± 1.9 g/dL
24 hour highest lactate	9.1 ± 5.1 mmol/L
Initial admission lactate	9.0 ± 5.2 mmol/L
24 hour nadir pH ABG	7.10 ± 0.18
24 hour nadir base deficit	−13.8 ± 6.8

The majority (93%) of patients were male. Mean injury severity score (ISS) was (± SD) 37 ± 8 and mean age was 36 ± 18 years. Three patients presented in cardiac arrest. For patients with a spontaneous rhythm, the admission systolic blood pressure was 97 ± 32 mmHg and heart rate was 113 ± 23. An additional three patients subsequently developed cardiac arrest in the resuscitation bay before operative intervention. Patients suffered severe hemorrhage as evidenced by their low hemoglobin laboratory values on admission and the lowest values within the first 24 hours of admission. The demographic and injury characteristics of the patients age 18–39 years old were similar to that of the patients 40 years old or over with the exception that the majority (60%) of patients in the older group had a history of hypertension compared to no patients in the 18–39 year-old group ($p = 0.03$).

As seen in Table 2, there was a significant increase in arterial diameters in the aorta and large arteries between the initial/admission CT scan and the reference CT scan. The mean increase in diameter size ranged from 1.4 (right subclavian) to 2.7 millimeters (mm) (mid-descending thoracic aorta), with a maximum increase of the aorta (ascending aorta) of 8.1 mm and up to a maximum of 5.2 mm (left common carotid) in the other arteries. The maximum increase of the aorta (at the aortic bifurcation) was 63.6%, and the maximum increase of the other arteries ranged between 48.1 and 116.9%. While many patients had significant increases in the diameters of the various arteries, some had minimal to no change and in some cases, there was even a small decrease in size.

Changes in arterial diameters were compared between younger (aged 18–39 years) and older (aged ≥40 years) patients, as seen in Table 3. The patients in the younger group had large, statistically significant, increases in their arterial diameters at almost all levels (except the left subclavian and peri-renal aorta, $p = 0.056$ and 0.093, respectively). In contrast, patients in the older group had a less dramatic increase, with statistical significance only being achieved in the proximal descending thoracic aorta. When compared, the younger group had a statistically significant larger increase in their arterial diameters at several locations, including the right common carotid, right subclavian, bilateral common iliac, and left common femoral arteries. The substantial difference between the two age groups in changes of arterial diameter from the initial/admission CT to the reference CT can be further visualized in Figure 1. Figure 1 also highlights the distribution of the diameter measurements and the degree of eccentricity for each group and CT measurement time point. Overall, most measurements of the arteries revealed some eccentricity with slight changes from the reference CT; however, no consistent pattern of increasing or decreasing eccentricity was identified across the different locations.

For all patients undergoing REBOA with complete data for both common femoral arteries ($n = 6$), there was no significant difference between the manipulated/accessed common femoral artery compared to the artery that was not accessed (23.9% vs. 19.7% increase, respectively; $p = 0.62$). Interestingly, younger patients (18–39 years, $n = 3$) did have a larger increase in arterial diameter on the side that was accessed vs. not accessed (54.4% vs. 37.7%, respectively; $p = 0.14$).

DISCUSSION

Large arterial diameters in the setting of severe hemorrhage are dramatically reduced, particularly in younger patients. The findings of a statistically significant and consistent decrease in diameter throughout the various locations of the aorta at the time of hemorrhage and injury, with an attenuated effect in older patients, have not been previously demonstrated [9,10]. In addition, the mean and maximum changes in the aorta of our series are greater than the cohorts of patients previously described [9,10], and may serve

Table 2 Arterial measurement characteristics for all patients.

	N (n = 14)	*M1*	*M2*	*Mean difference (mm)*	*Difference (% increase)*	*Range (%)*	*p-value*
Right common carotid	12	6.9 ± 1.3	8.3 ± 1.7	2.2 ± 1.3	31.6 ± 34.8	−24.7–103.2	0.04
Left common carotid	12	6.8 ± 1.2	8.3 ± 1.4	1.9 ± 1.4	26.5 ± 35.0	−15.2–116.9	0.02
Right subclavian	12	6.6 ± 1.2	7.9 ± 1.6	1.4 ± 1.2	20.3 ± 23.4	−6.9–79.1	0.01
Left subclavian	13	8.6 ± 1.2	9.7 ± 1.7	1.7 ± 1.2	14.9 ± 23.1	−12.9–58.0	0.04
Ascending aorta	13	25.1 ± 3.9	27.0 ± 3.4	2.4 ± 2.2	8.5 ± 10.9	−10.0–31.6	0.02
Proximal descending aorta	13	20.2 ± 3.0	22.7 ± 2.5	2.6 ± 2.0	13.8 ± 12.2	−1.6–29.2	0.001
Mid- descending thoracic aorta	13	19.2 ± 3.0	21.6 ± 2.5	2.7 ± 1.9	13.6 ± 14.1	−10.9–37.0	0.003
Supra-celiac aorta	13	18.2 ± 3.8	19.8 ± 2.3	2.4 ± 1.6	11.7 ± 16.9	−10.8–50.6	0.03
Peri-renal aorta	11	15.8 ± 3.1	17.2 ± 2.4	1.9 ± 1.5	11.4 ± 16.0	−7.0–48.3	0.03
Aorta at aortic bifurcation	11	14.4 ± 3.1	16.2 ± 1.9	2.5 ± 2.0	16.0 ± 23.0	−13.1–63.6	0.057
Right common iliac	10	10.3 ± 3.5	10.9 ± 2.1	2.4 ± 1.4	12.2 ± 28.8	−25.1–52.0	0.52
Left common iliac	11	9.8 ± 3.1	11.0 ± 1.5	2.6 ± 1.2	18.8 ± 28.7	−23.1–57.9	0.19
Right external iliac	7	6.6 ± 1.6	8.9 ± 1.3	2.4 ± 1.2	39.7 ± 27.7	−1.7–76.8	0.004
Left external iliac	10	7.0 ± 2.2	9.2 ± 1.7	2.5 ± 1.6	38.9 ± 33.1	−13.6–91.8	0.006
Right common femoral	8	7.8 ± 3.1	8.7 ± 1.5	1.9 ± 1.4	6.8 ± 31.2	−27.5–78.7	0.30
Left common femoral	10	7.8 ± 2.6	8.9 ± 1.6	1.6 ± 1.0	22.3 ± 19.8	−5.4–48.1	0.12

M1: Admit CT measurement (mean ± std. dev. mm). M2: Comparison CT measurement (mean ± std. dev. mm).

Table 3 Arterial measurement characteristics for patients aged 18–39 years and patients age ≥40 years.

	Difference (% increase) 18–39 years	*N (n = 9)*	*p-value (18–39 years M1 vs. M2)*	*Difference (% increase) ≥40 years*	*N (n = 5)*	*p-value (≥40 years M1 vs M2)*	*p-value comparison 18–39 vs. ≥40*
Right common carotid	37.3 ± 33.9	8	0.013	1.1 ± 24.4	4	1.000	0.044
Left common carotid	36.0 ± 38.3	8	0.018	7.5 ± 18.4	4	0.497	0.098
Right subclavian	30.8 ± 21.7	8	0.001	−0.7 ± 5.3	4	0.702	0.009
Left subclavian	18.6 ± 25.1	9	0.056	6.3 ± 18.0	4	0.596	0.199
Ascending aorta	10.3 ± 12.1	9	0.047	4.4 ± 7.3	4	0.291	0.195
Proximal descending aorta	16.7 ± 13.7	9	0.004	7.2 ± 4.3	4	0.018	0.104
Mid-descending thoracic aorta	16.3 ± 15.7	9	0.013	7.5 ± 8.2	4	0.111	0.160
Supra-celiac aorta	16.9 ± 18.3	8	0.024	3.3 ± 11.4	5	0.758	0.085
Peri-renal aorta	16.3 ± 20.3	6	0.093	5.4 ± 6.5	5	0.182	0.139
Aorta at aortic bifurcation	25.8 ± 21.9	6	0.017	4.1 ± 20.1	5	0.951	0.062
Right common iliac	37.3 ± 14.1	5	0.004	−12.9 ± 9.7	5	0.083	<0.001
Left common iliac	34.5 ± 18.3	6	0.005	−0.2 ± 28.7	5	0.553	0.019
Right external iliac	48.6 ± 24.9	5	0.003	17.5 ± 27.2	2	0.541	0.101
Left external iliac	51.6 ± 31.5	5	0.012	26.2 ± 32.7	5	0.225	0.123
Right common femoral	33.5 ± 29.4	5	0.026	−2.0 ± 22.2	3	0.647	0.062
Left common femoral	33.3 ± 13.7	5	0.002	11.3 ± 19.8	5	0.357	0.038

as a guide to the potential upper limit of change in arterial diameters. These findings deserve consideration when performing endovascular interventions within these patient populations.

The observations of decreased arterial diameters in the setting of intra-arterial volume depletion are likely a function of arterial compliance. The aorta is very compliant, especially in younger patients, and significant changes in diameter occur between systole and diastole [11]. Numerous studies have demonstrated that the compliance of the aorta and large arteries decreases with age, and may be related to cardiovascular disease [12–14]. We hypothesize that the finding that older patients have a less dramatic decrease in arterial diameters secondary to trauma and hemorrhage is likely related to decreased arterial compliance secondary to the effects of aging including cardiovascular disease.

Some endograft-specific complications may be related to under or over-sizing the stent based upon the initial admission CT (which frequently can be the only CT available). If a CT scan is performed on a severely injured patient on admission, the measurements may be underestimated in comparison to a healthy state and therefore the endograft stent may be under-sized, lead-

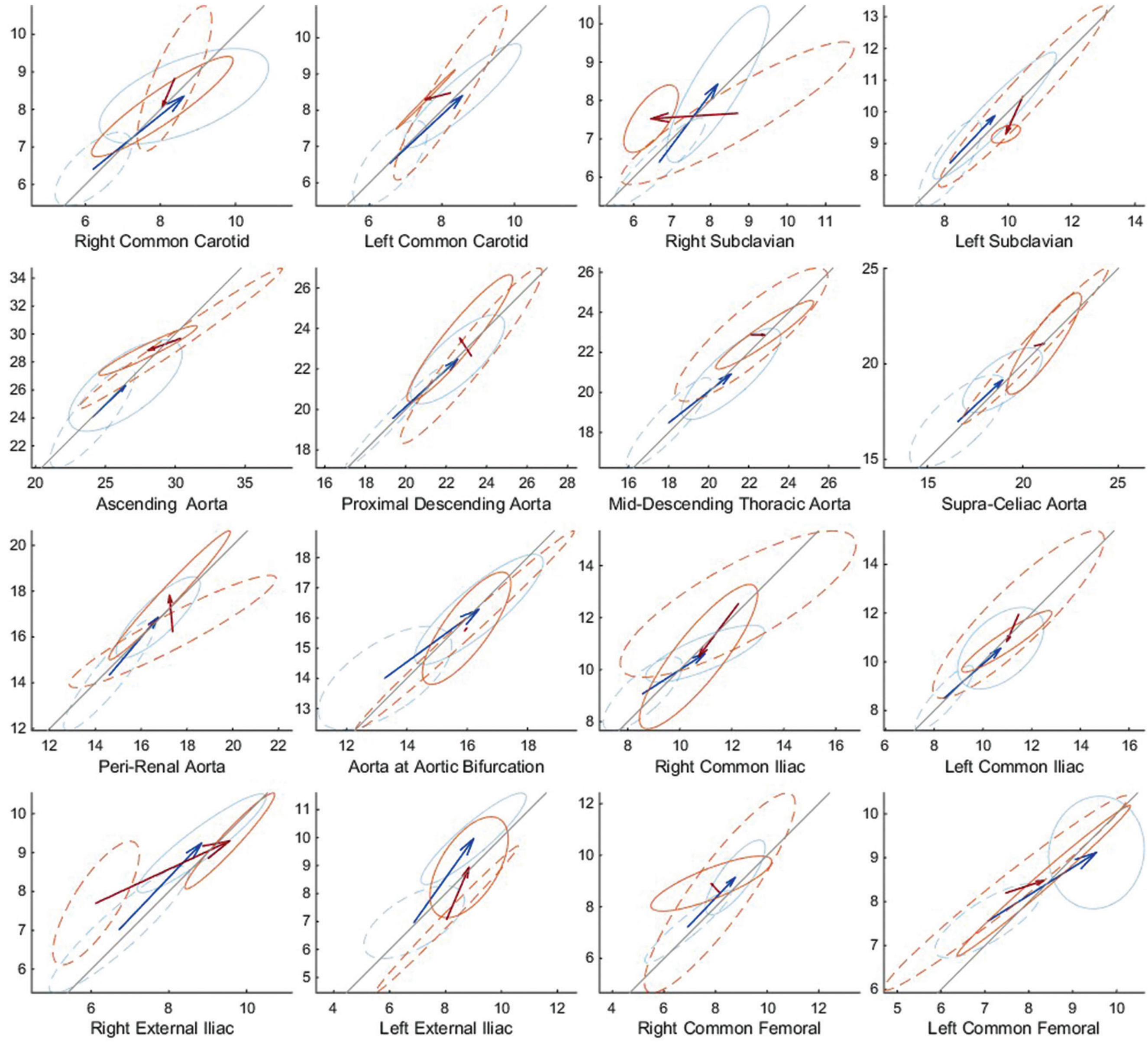

Figure 1 Changes in arterial diameters from the initial CT and reference CT are depicted. Each ellipsoid represents the two-dimensional Gaussian distribution (1 standard deviation) of arterial diameters made at the initial (dashed line) and reference (solid line) CTs. Patients aged 18–39 years are represented in light blue, and patients aged ≥40 years are represented in orange. The average increases for each group are represented by arrows starting at the centroid of the initial CT and ending (arrowhead portion) at the centroid of the reference CT. The axes are measured in millimeters. For all locations except the right subclavian artery, the *Y* axis is the anterior–posterior arterial diameter and the *X* axis is the right–left arterial diameter. For the right subclavian, the *Y* axis is the cranial–caudal arterial diameter and the *X* axis is the anterior–posterior arterial diameter. The solid gray lines depict equal diameter measurements of both axis and therefore represent an eccentricity of 0 (perfect circle). Overall, most measurements of the arteries revealed some eccentricity which slightly changed with the reference CT; however, no consistent pattern of increasing or decreasing eccentricity was identified across the different locations.

ing to potential complications. Given the findings of our series, it is clear that not all patients undergoing endovascular repair should have their endograft stents oversized to the same degree, based upon their admission CT scan, and the potential change in arterial dimensions is significantly greater than previously thought. Further imaging modalities such as intravascular ultrasound (IVUS) in the operating room just prior to endograft placement can give a more accurate aortic diameter [17,18]. The use of IVUS in the resuscitation bay prior to REBOA is not a feasible or safe option.

Arterial access and the management of arterial sheaths may be affected by a decrease in arterial diameters. The presence of an arterial sheath obstructs (at least partially) the arterial lumen and limits flow distal to the sheath. A study examining the degree of obstruction to the external iliac artery caused by introducer sheaths in endovascular aneurysm repairs (EVAR) demonstrated that the sheaths caused a mean functional stenosis of 70% [19], and cases of lower extremity ischemia secondary to the presence of an introducer sheath in the common femoral artery have been reported in the EVAR literature [19,20]. According to Poiseuille's law, the amount of flow through a pipe is related to the radius to the fourth power and therefore the decrease in diameters of the common femoral and external iliac arteries may dramatically increase the degree of flow limitation to the lower extremity. In addition, although our findings did not reach statistical significance, we suspect that the mere act of manipulating and accessing the common femoral artery may cause a further reduction of arterial size, especially in younger patients. Lower extremity ischemia in the setting of hemorrhage and severe trauma secondary to prolonged usage (28 hours) of a sheath in the common femoral artery has been described in a patient who underwent REBOA [21]. Anecdotally, we have encountered a patient (18-year-old female in profound hemorrhagic shock) in whom a 7 French sheath was totally occlusive of the common femoral artery at time of sheath removal after performing REBOA. Given these findings, our experience has led us to remove arterial sheaths as soon as possible, typically in the index operation or shortly thereafter once coagulopathy has improved.

The inflation diameter with balloon catheters required to occlude the aorta may be reduced in patients suffering from hemorrhage, which is especially important in relation to blind inflation. Adequate inflation of balloon catheters, such as for REBOA, is imperative to avoid potential complications of over-inflation including arterial injury or balloon rupture [22,23]. In addition, blind inflation in REBOA is typically performed in moribund patients before arrival to the operating room [5]. The amount of volume to achieve aortic occlusion in this setting may be less than previously thought, and is the focus of ongoing clinical investigations. Morphometric analyses have guided clinical estimates for inflation volumes for aortic occlusion; however, these images and measurements were collected from euvolemic patients. This data may help refine clinical protocols and procedure specifications.

Limitations

This study has several limitations. The study is a retrospective case series with a relatively small number of patients included. The CT imaging analyzed was not ECG gated, and therefore represents a confounding variable that we could not control for. The inability to control for exactly when the images were captured during the cardiac cycle is likely responsible for some variance in measurements and it is apparent in the findings that in some comparisons the arterial diameters were slightly larger during hemorrhage than during the reference imaging.

CONCLUSION

The diameters of major arteries, especially in younger patients, are temporarily decreased by severe trauma and hemorrhage. This has significant implications for emergent placement of endovascular devices such as introducer sheaths, balloon catheters, and stent grafts where the determination of arterial diameter is critical.

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