Original Article

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Approximation of Pediatric Morphometry for Resuscitative Endovascular Balloon Occlusion of the Aorta

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Background: Resuscitative endovascular balloon occlusion of the aorta (REBOA) may be beneficial in the management of traumatic and iatrogenic vascular and solid organ injuries in children, but requires an understanding of vessel diameter at the access site and landing zones. We adapted the Broselow Tape method to estimate aortic and femoral artery diameters for this purpose.

Methods: Computed tomography scans from trauma and non-trauma pediatric patients at a level 1 trauma center were reviewed for vascular dimensions at aorta Zone I, Zone III, and the common femoral artery (CFA). Vessel size was measured by two providers using a vascular software suite with a 10% interobserver comparison. Height was used to create linear regression equations for each location and calculate ranges for each Broselow Tape category.

Results: We reviewed scans from 110 patients ages 2–14 years with less than 8% interobserver variability. Of these, 64% were male and 46% were trauma patients. Height-based regression equations were closely correlated with vessel diameter: Zone I (mm) = [0.093 ± 0.006 · height (cm)] + 0.589 ± 0.768; $R^2 = 0.714$, $p < 0.001$; Zone III (mm) = [0.083 ± 0.005 · height (cm)] – 0.703 ± 0.660; and $R^2 = 0.728$, $p < 0.001$; CFA (mm) = [0.043 ± 0.003 · height (cm)] + 0.644 ± 0.419; $R^2 = 0.642$, $p < 0.001$. These equations, along with the minimum and maximum length for each Broselow Tape color, were used to define color-coded normal ranges for each REBOA landing zone and access site.

Conclusion: Knowledge of the access vessel and occlusion zone diameters in pediatric patients is crucial for future research and application of REBOA in this population. Furthermore, an adapted Broselow Tape including these measurements would assist in appropriate sheath and balloon catheter selection in emergent settings.

Keywords: *Pediatric REBOA; aortic morphometry; trauma; balloon occlusion resuscitation; Broselow tape*

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INTRODUCTION

There is growing translational data and clinical support for the use of resuscitative endovascular balloon occlusion of the aorta (REBOA) for the resuscitation of adult trauma patients with abdominal and pelvic hemorrhage [1–10]. While additional research is required to fully understand the utility of REBOA in different patient populations, REBOA may be beneficial in the management of traumatic and iatrogenic vascular and solid organ injuries in children. Using data from the Japan Trauma Data Bank, Norii et al. [11] published the first report on pediatric REBOA use, demonstrating equivalent survival rates to adults in 54 pediatric REBOA patients ranging from 5 to 17 years of age. Although clinical use has now begun, there remain no studies describing the morphometric variability between pediatric patients as applied to the selection of appropriate aortic occlusion catheters.

Ninety percent of pediatric trauma results from blunt traumatic mechanisms [12,13]. Solid organ injury is the most common abdominal injury following blunt trauma and requires operative intervention in 4% of cases while direct vascular injuries from penetrating mechanisms requiring intervention are even more rare, comprising only 1% of all trauma cases [14–16]. Both sources of hemorrhage in pediatric populations may be amenable to aortic occlusion to minimize blood loss and profound shock. Additionally, REBOA may have application in hazardous pediatric surgical cases such as large abdominal or sacral tumor excision, either for prophylactic use or following iatrogenic injury. However, broad anatomical differences exist across the pediatric age range, affecting vessel diameters, lengths, and locations of key branch vessels, negating the potential for a "one balloon fits all" approach.

The potential for iatrogenic vessel injury within the aorta or at the site of vascular access is a significant concern given changes in aortic and femoral size throughout childhood. Inherently, this represents a challenge for exploring REBOA use in this population. We sought to ameliorate these anatomical concerns by defining the typical balloon occlusion zone and access site vessel diameters in a representative pediatric population and adapting these values to the Broselow Tape method used commonly during pediatric resuscitations [17,18].

METHODS

Computed Tomography Imaging Analysis

Our cohort included any pediatric patient (age 2–14 years) evaluated with intravenous (IV) contrasted computed tomography (CT) imaging of the abdomen in the University of California Davis Medical Center (UCDMC) Emergency Department for abdominal pain or appendicitis between July 2015 and June 2017. A cohort of age and sex-matched patients who underwent IV contrasted CT scan of the abdomen for trauma from the same time period were then identified. The age, sex, height, weight, and systolic blood pressure (SBP) within 2 hours of CT imaging were included for analysis. Body mass index (BMI) and body surface area (BSA) were calculated [19]. Exclusion criteria included lack of height measurement and lack of adequate extent or clarity of imaging. Additionally, patients with systolic hypotension as determined by age-adjusted norms were excluded to avoid the effect of shock on compliant vessels. Hypotension was defined as SBP <70 mmHg plus age times 2 for children 2–9 years of age and SBP <90 mmHg for patients 10 and older [20].

CT scans were performed on one of four CT scanners (three 64-slice, one 16-slice) with IV contrast administered per standard UCDMC radiology protocols.

Each CT was analyzed using TeraRecon 3D (TeraRecon Inc., Foster City, CA). The recorded measurements included: aortic diameter at the superior endplate of the T10 vertebral body, immediately superior to the celiac artery origin, inferior to the lowest primary renal artery, and at the aortic bifurcation. Common femoral artery (CFA) diameter was obtained just proximal to the deep femoral artery. The imaging was analyzed by two senior vascular surgery residents (MS/AW). Ten percent of cases were interpreted by both residents to provide an interobserver comparison.

The collection of CT imaging and patient data was performed under UCDMC IRB # 935667-2.

Data Analysis

The data was collected and analyzed using Excel (Microsoft, Redmond, WA) spreadsheets. Descriptive statistics were used to define the cohort demographics including age, sex, height, weight, and trauma vs non-trauma. Zone I diameter was defined as the mean aortic diameter between the superior endplate of the T10 vertebral body and just superior to the celiac axis. Zone III measurement was defined as the mean aortic diameter between the lowest renal artery and the aortic bifurcation. Measured left and right CFA diameters were averaged for each patient. Height, weight, BMI, and BSA were individually plotted against Zone I, Zone III, and CFA diameters and analyzed using linear regression lines. Pearson's correlation coefficient (R^2) was calculated for each variable. Height was used to create simple linear regression equations and the standard error for slope and intercept was calculated. Residual plots were also examined.

Creation of Broselow Tape Ranges

A Broselow Tape (CareFusion, 2011 Version A) was used to measure the minimum and maximum lengths for each color. These values were entered into the linear regression equations to define the Broselow category minimum and maximum vessel diameter for each zone and the CFA using one standard deviation. The calculation of sheath size recommendations was based on the recommended ratio of catheter outer diameter to arterial luminal diameter (OD/AD ratio) of ≤50% [21].

RESULTS

Cohort Description

We identified 227 trauma and non-trauma patients with CT scans of the abdomen and pelvis with contrast. Of these 107 were excluded due to lack of height data and 10 scans were excluded due to poor or inadequate image quality, leaving 110 scans for analysis. No patients were excluded for hypotension. There were 51 scans for trauma (46%) and 59 scans for non-trauma (54%) complaints. The patients were mostly male (64%) with a median age of 9 years (range 2–14 years).

Linear Regression Analysis

Vessel diameter data was plotted against the variables of height, weight, BMI, and BSA to produce scatter plots. A best-fit linear regression line was applied to each plot and the coefficients of determination were examined. The highest Pearson correlation coefficients for Zone I, Zone III, and CFA diameters were identified for the independent variables of height (R^2 = 0.7144, 0.7275, and 0.6420, respectively), BSA (R^2 = 0.7276, 0.7200, and 0.6335, respectively), and weight (R^2 = 0.6569, 0.6382, and 0.5676, respectively). BMI was poorly correlated (R^2 = 0.3175, 0.2979, and 0.2749, respectively). The scatter plots and regression lines for height are presented in Figure 1. The linear regression equations, their associated standard error, and correlation coefficients are as follows: Zone I (mm) = [0.093 ± 0.006 · height (cm)] + 0.589 ± 0.768; R^2 = 0.714, $p < 0.001$; Zone III (mm) = [0.083 ± 0.005 · height (cm)] – 0.703 ± 0.660; R^2 = 0.728, $p < 0.001$; CFA (mm) = [0.043 ± 0.003 · height (cm)] + 0.644 ± 0.419; R^2 = 0.642, $p < 0.001$.

The scatter plots and regression lines for weight, BMI and BSA are presented in Figure 2 for comparison.

Broselow Tape Adaptation

As height was among the highest correlating factors and the goal was to produce a representative vessel diameter range for each length range on the Broselow tape, the regression line equations for height were selected for extrapolation. The vessel diameter ranges for Zone I, Zone III, and CFA can be found in Figure 3 in a color-coded format to match the corresponding Broselow color. Included in section C of this figure is the suggested CFA access sheath sizes which would not result in a greater than 50% OD/AD ratio including a 1 French (Fr) buffer to account for the added thickness of the sheath material. These are represented as a range with the smaller sheaths being appropriate at the low end of the height range and larger diameter sheaths suggested for the upper end of the height range.

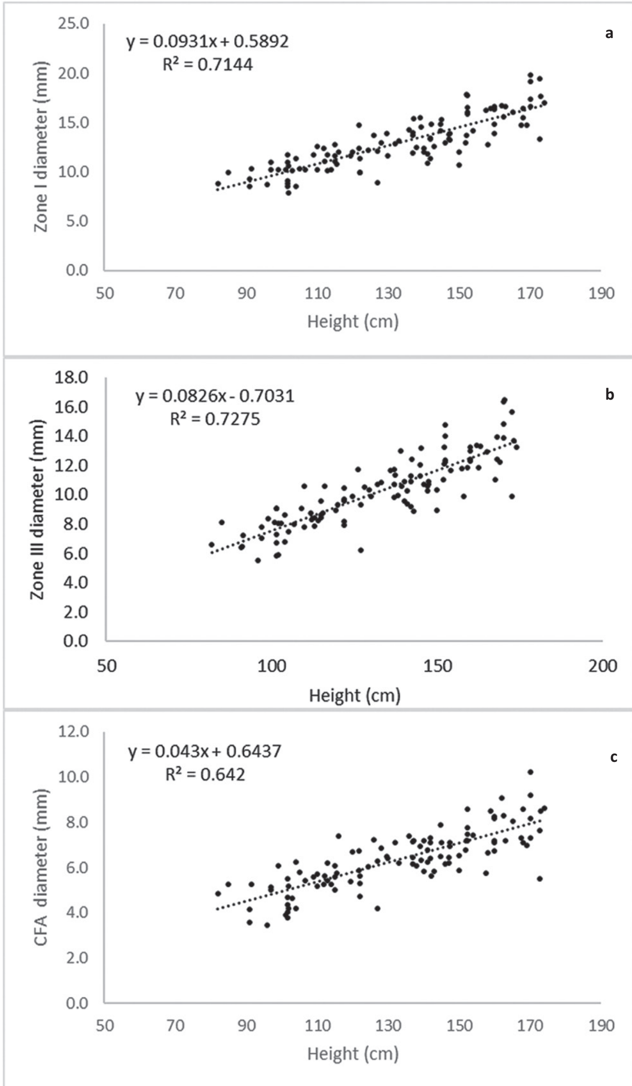


Figure 1 Scatter plots and linear regression lines comparing height with vessel diameter. (**a**) Zone I, (**b**) Zone III, (**c**) and CFA; $p < 0.001$ for all.

Interobserver Comparison

Thirteen patients (11.8%, 7 trauma, 6 non-trauma) were selected at random for dual interpretation. There was less than 8% variability between the readers for measurement of each diameter (Zone I 7%, Zone III 8%, and CFA 7%).

DISCUSSION

Broselow Adaptation

The Broselow Tape is a widely used tool to estimate weight, drug dosing, endotracheal tube diameter, and

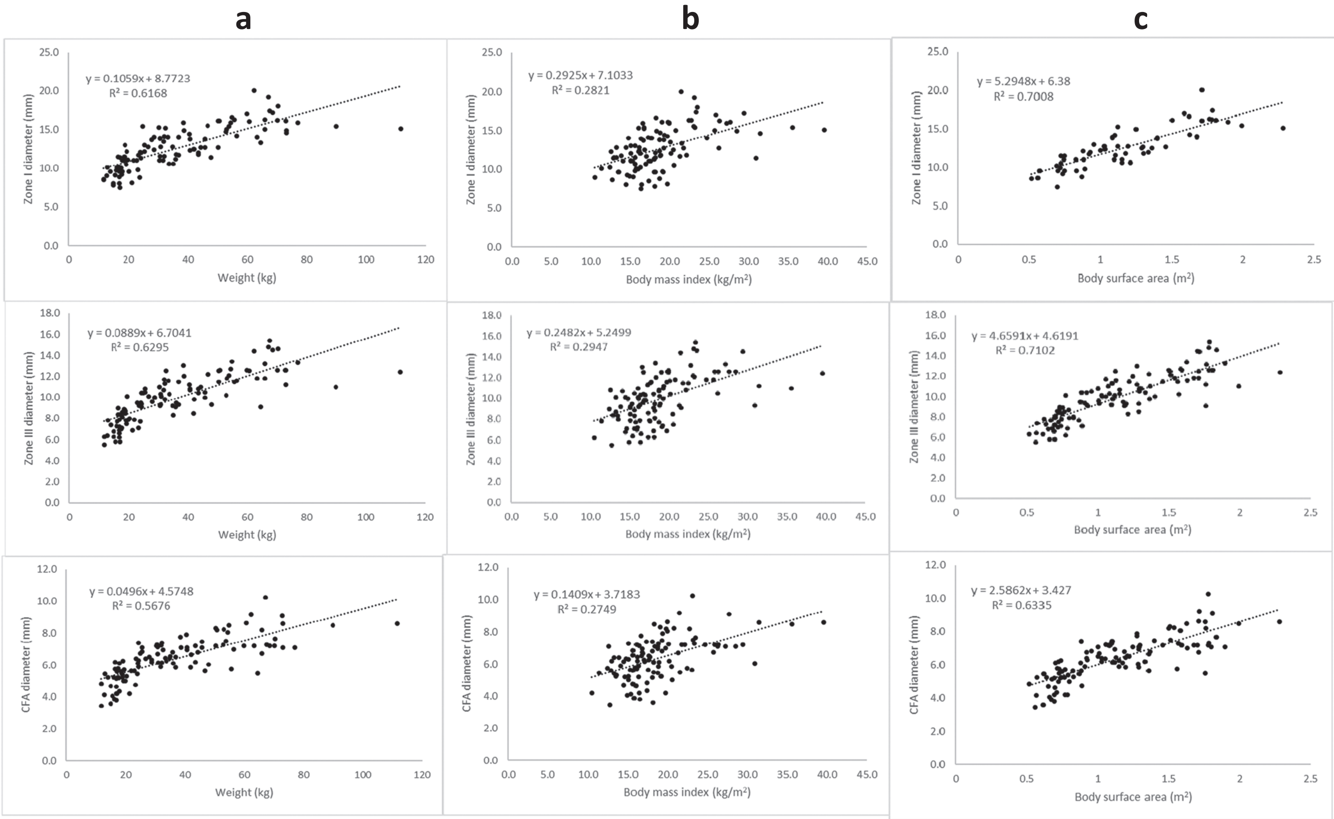


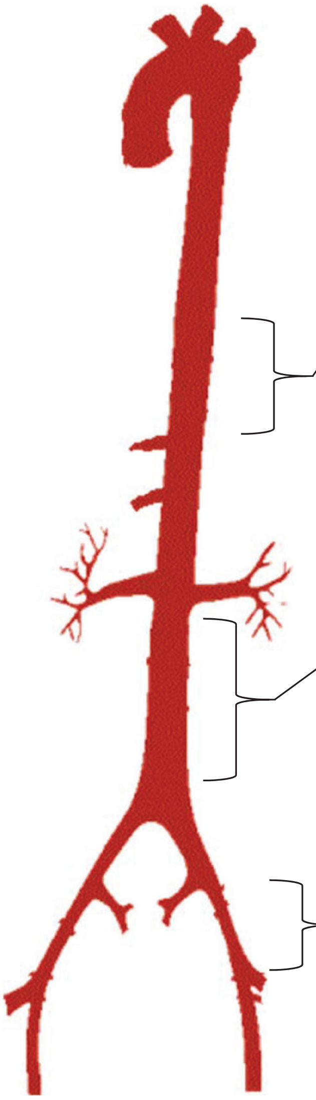
Figure 2 Scatter plots and linear regression lines comparing (**a**) weight, (**b**) body mass index, and (**c**) body surface area with vessel diameter at Zone I, Zone III, and CFA.

other emergent interventions based on the length of an injured child before an initial weight can be obtained [17,18,22]. Anatomical considerations for the use of REBOA in a pediatric patient include aortic and femoral artery diameters as well as distances between the femoral access point and occlusion zones. For the purposes of REBOA, the regions of greatest importance include the supraceliac aorta cephalad to the diaphragm (Zone I) and the infrarenal aorta (Zone III). Sandgren et al. [23] determined that CFA diameter and BSA parallel each other for both males and females up until 25 years of age. Although very accurate when height and weight measurements are readily available, BSA is inherently difficult to estimate in emergent settings, supporting the use of tools such as the Broselow Tape to guide rapid intervention. While the determination of BSA and BMI based on height and estimated weight will not be perfect for all patients, it can provide an estimate to select occlusion balloons in an emergency. In our regression analysis, height, weight, and BSA carried similar correlation to vessel diameter.

Common Femoral Artery Access Considerations

CFA access is frequently performed in children for cardiac catheterization or extracorporeal membrane oxygenation (ECMO). Cardiac catheterization utilizes smaller diameter access sheaths (3.3 Fr to 6 Fr) compared with ECMO which starts at 12 Fr and often requires additional distal perfusion access. In a series of 21 pediatric patients treated with femoral venous-arterial ECMO, 52% developed limb ischemia despite the use of distal perfusion catheters in a portion of patients, a figure in line with previous reports of 30–50% [24–26]. In contrast, cardiac catheterization via femoral artery access has much lower rates of ischemic complications (3.8%) suggesting that the smallest possible access sheaths will provide the lowest rate of arterial injury and thrombotic complication [27].

In infants and small children, CFA diameters are expected to be small resulting in a higher risk of adverse events such as arterial injury and limb ischemia. Alexander et al. [21] reviewed 486 catheterizations in children (median age 22 months) in which 33 patients experienced loss of pulse (LOP) in the ipsilateral extremity post-procedure. The only independent risk factor for LOP was CFA diameter <3 mm. Additionally, the ratio of catheter outer diameter to arterial luminal diameter (OD/AD ratio) was identified as a predictor for LOP with OD/AD ratio of >50% leading to LOP in 17.2% of patients compared with 5.2% of patients with OD/AD ratio of ≤50%. For 4, 5, and 6 Fr sheaths, ideal CFA



a

Broselow Color	Zone I Diameter (mm)	
	Min	Max
Pink	3.9	6.8
Red	4.6	7.5
Purple	5.2	8.4
Yellow	6.1	9.6
White	7.1	10.8
Blue	8.2	12.1
Orange	9.3	13.0
Green	10.2	14.3

b

Broselow Color	Zone III Diameter (mm)	
	Min	Max
Pink	2.3	4.7
Red	2.9	5.4
Purple	3.5	6.2
Yellow	4.2	7.2
White	5.1	8.4
Blue	6.1	9.5
Orange	7.1	10.3
Green	7.8	11.4

c

Broselow Color	CFA Diameter (mm)		Introducer Sheath (Fr)
	Min	Max	
Pink	2.1	3.6	2-5
Red	2.4	3.9	3-5
Purple	2.7	4.4	4-6
Yellow	3.1	4.9	4-7
White	3.5	5.5	5-8
Blue	4.1	6.1	6-9
Orange	4.6	6.5	6-9
Green	4.9	7.1	6-9

Figure 3 Broselow category vessel diameters. (**a**) Zone I, (**b**) Zone III, and (**c**) common femoral artery including recommended access sheath sizes. Range represents calculated diameter for minimum and maximum height for each Broselow color ± one standard deviation.

diameter would be greater than 2.67, 2.34, and 4 mm, respectively. The risk of partial or near-complete occlusion of the CFA for the duration of REBOA intervention must be weighed against the potential lifesaving benefits and, when possible, access sheaths and devices should be selected to optimize the OD/AD ratio. Low profile devices deployable through 4 Fr access sheaths hold the most promise for implementing REBOA in very young children while minimizing the risk of arterial injury and thrombotic complications.

Utilization in a Pediatric Population

Defining clinical criteria for REBOA placement in children will be challenging, yet crucial. While physiologic indications for pediatric REBOA may eventually differ from that of adults (i.e. presenting SBP <90 mmHg), injury pattern indications and contraindications will likely remain constant with some additional unique indications such as sacral or coccygeal tumor resection [28]. It is unknown when a patient will be old enough to meet adult indications for REBOA, however, we can estimate the height at which the femoral artery would be of adequate diameter to safely accept a 7 Fr access sheath and deployment of the standard ER-REBOA (Prytime Medical, Boerne, TX) platform. A CFA diameter of 5.9 mm allows for a standard 7 Fr sheath with an outer diameter of 2.95 mm to be placed while maintaining <50% OD/AD ratio. This CFA diameter is expected at a height of 122 cm or approximately 4 feet which lies in the green Broselow Tape color group. The use of lower profile sheaths would allow for use in smaller patients. As of now, there are no trauma-specific devices which would serve the spectrum of pediatric sheath sizes needed. Future investigation will be required to identify acceptable off the shelf catheters for use in pediatric REBOA. In addition, it is yet to be seen whether intervention with REBOA in children is more beneficial as a prophylactic adjunct or whether it should be used after physiologic decline has manifested.

Limitations

A potential limitation of this study was the adaptation of height-based estimates to a population with accelerating obesity. Our analysis determined that height, weight, and BSA held comparatively close correlation with aortic and CFA diameters ($R^2 = 0.57–0.73$) as compared with BMI which was poorly correlated ($R^2 = 0.28–0.32$). These measurements were obtained from contrast imaging which was not necessarily protocolled for precise measurements of the vasculature. However, this modality is becoming commonplace for establishing normal vasculature morphometry [23,29–32]. There were no children under 2 years of age and CT scans for the Broselow colors below blue were either poorly powered or absent. It is possible that the vasculature growth curves below 2 years of age are markedly different, however previous work using angiograms and CT scans has come to similar conclusions that height, weight, and BSA correlate well with vasculature diameter, even in infants as young at 1 month of age [29]. Future studies may be able to further refine these estimates, but as CT imaging in the very young is generally avoided due to concerns for ionizing radiation, significant numbers of scans may be difficult to obtain.

CONCLUSION

Pediatric REBOA may be a useful adjunct in the management of life-threatening traumatic and iatrogenic bleeding. Height correlates closely with and can be used to estimate aortic zone and CFA diameters for use in emergent settings. By adapting a rapid system accounting for the anatomic differences associated with vascular development during childhood, this study provides a foundation for research, development, and execution of REBOA techniques in the pediatric population.

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