International Urogynecology Journal (2019) 30:401–407
https://doi.org/10.1007/s00192-017-3542-x

ORIGINAL ARTICLE

3D vascular anatomy of the presacral space: impact of age and adiposity

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Received: 25 August 2017 / Accepted: 6 December 2017 / Published online: 3 January 2018

Abstract

Introduction and hypothesis Defining patient characteristics that alter vascular anatomy at the sacrum is critical for avoiding life-threatening bleeding at the time of sacrocolpopexy. We tested the hypothesis that in thinner/older women, the bifurcations of the aorta and inferior vena cava (IVC) are lower relative to S1 resulting in less space accessible for suture/mesh placement, placing this group at increased risk of major vascular injury.

Methods In a retrospective cross-sectional study, CT scans were used to make 2D measurements and a 3D model of the aorta/IVC, intervertebral disc space, and bony anatomy using segmentation and modeling software. For analysis, Spearman's and Pearson's correlation, Student's *t* test and the Mann-Whitney *U* test were used along with multivariate analysis of variance.

Results Of eligible women who had undergone abdominal/pelvic CT, 107 were included. The median locations of the aortic and IVC bifurcations utilizing 2D analysis were at the inferior L4 and middle L5 vertebral body, respectively. In 10.2% of patients, the IVC was located at the L5-S1 disc space or lower; however, 3D modeling of this space which allowed assessment of the area below the S1 "drop off" showed that the amount of accessible space for suture/mesh placement was not decreased. Utilizing 2D analysis there was no statistically significant independent correlation between age or adiposity and the aortic or IVC bifurcation. Patients who were both elderly and thinner had a lower aortic bifurcation ($p = 0.005$) and a trend towards a lower IVC bifurcation ($p = 0.082$).

Conclusions In 10.2% of women, the IVC bifurcation descended at or below the L5-S1 disc space, suggesting that this group of women is at increased risk of major vascular injury. Patients who were both thin and elderly had lower bifurcations, but there was no difference in accessible surface area for suture placement on 3D analysis. 3D modeling improved visualization of the anatomy beyond the S1 "drop off" and may provide a future tool for surgical planning once predictors of high-risk anatomy are defined.

Keywords Aortic bifurcation · Sacrocolpopexy · Sacral promontory · Mesh

This work was presented at the Annual Scientific Meeting of the American Urogynecologic Society (AUGS), Denver, CO,27 September to 1 October, 2016, and at the Society of Gynecologic Surgeons (SGS) Annual Meeting, San Antonio, TX, 26 to March, 2017.

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Introduction

The sacral promontory is a critical landmark [1] during sacrocolpopexy (SCP) surgery to repair pelvic organ prolapse. Mesh is generally placed at or around the sacral promontory (S1) [1–3], with descriptions ranging from the L5-S1 to S3-4 vertebral levels. A systematic review [4] found that mesh was placed at the location of the sacral promontory in two studies, the area just below the promontory in three, the level of S1-2 in one, and at or below the sacral promontory in one. The longitudinal ligament of the spine is stronger at the sacral promontory or above rather than below [1], and at S1 compared to than at S2 [5]. Life-threatening vascular injury has been reported to occur during 0.4–2.6% of minimally invasive SCP procedures [6, 7]. While the middle sacral vessels are a critical landmark, these vessels are relatively easy to secure to maintain hemostasis. On the other hand, injury to the major vessels that border the promontory can be catastrophic, with venous injuries considered more dangerous, and the left common iliac vein (LCIV) [6] is the great vessel most commonly injured. Injury to the great vessels requires intraoperative consultation with a vascular surgeon, which may delay repair and place the patient at risk of major morbidity and even death. Understanding factors that alter the anatomy of the great vessels at the sacrum and increase the risk of injury is critical to optimizing the outcome in women undergoing SCP.

The aortic bifurcation is typically reported as occurring at the level of L4 [8–10] ranging from L3 to S1. The inferior vena cava (IVC) bifurcation typically occurs at the level of L5 with reported locations from L3 to S1 [9, 11, 12]. The IVC bifurcation is most often one or two segments below the aortic bifurcation [13]. The LCIV lies medially to the left common iliac artery. There is conflicting and limited evidence on the effects of age and adiposity on the location of the bifurcation of the great vessels [9, 13, 14]. Changes to the aorta (age and atherosclerosis cause enlargement and elongation of the aorta) [15, 16] and spine (loss of height due to decreased disc space, osteopenia) related to age and disease may result in a caudal shift of the aortic and IVC bifurcations that increase with age. Older thinner women are at increased risk of these changes [9, 13–17].

The aim of this study was to explore both traditional 2D and computational 3D modeling as tools to improve our understanding of sacral anatomy particularly with regard to the great vessels. The advantage of 3D modeling, in direct contradistinction to 2D imaging, is that the region of S1 caudal to the promontory (i.e. at and below the angulation of the sacrum) can be completely visualized. In addition, we aimed to determine the impact of age and adiposity on the position of the great vessels. We hypothesized that increased age and lower weight is associated with lower aortic and IVC bifurcations and thus less surface area accessible for suture placement.

Materials and methods

This retrospective, cross-sectional study was approved by the University of Pittsburgh Medical Center (UPMC) Institutional Review Board (IRB PRO15060607). UPMC Stentor (a radiology archiving and processing group) was used to query CT scans in an anonymized database. Consecutive women who had undergone abdominal/pelvic CT with and without contrast for hematuria from January 2007 to September 2015 were eligible for inclusion. Women with bone hardware, significant spinal disease (compressed disc, disc fracture, scoliosis), or aortic dilatation or aneurysm were excluded. The CT scans were then analyzed using Seg 3D 2.2.1 (NIH/NIGMS CIBC Center, Salt Lake City, UT), 3D Slicer 4.5 (Brigham and Women's Hospital, Boston, MA), and Paraview 5.2 (Kitware Inc., Clifton Park, NY). The measuring investigator (A.A.B.) was a physician trained and experienced in radiologic data collection, aware of the study design and objectives, and blinded to the patient's age and percent adiposity at the time of data collection. Age was provided after data collection using an anonymized database held by the Stentor group.

For measurements, we focused on the L5 to S2 region of the spine. Each vertebral body was divided equally into three segments (each one third of the vertebral height; Fig. 1), and each segment and intervertebral disc space from L5 to S2 was assigned a corresponding number (i.e. 9 is the superior, 10 is the middle, and 11 is the inferior segment of the L5 vertebral body, and 12 is the L5-S1 intervertebral disc space). The aortic and IVC bifurcations were defined as the point at which the abdominal aorta separates into the left and right common iliac arteries and the left and right common iliac veins, respectively. The aortic and IVC bifurcations were measured in relation to the vertebra and were strictly 2D measurements as observed in the coronal plane. Abdominal adipose tissue (adiposity) was assessed in each patient using a validated CT method [18], with an x-ray attenuation histogram created for adipose tissue which has been shown to be highly correlated ($r = 0.93$) with body mass index (BMI) and the sequela of obesity [19–22]. A fat percentage was calculated for each patient using the ratio of subcutaneous adipose tissue to total tissue. Adiposity ≤40% was chosen on the basis that it was the thinnest tertile of our sample population.

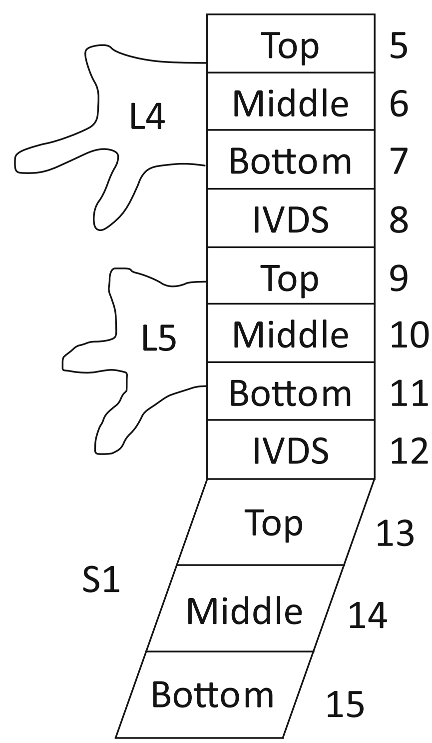

Fig. 1. Segmentation of vertebral bodies L4, L5 and S1 and the intervertebral disc spaces for measurement of aortic and IVC bifurcations (*IVDS* intervertebral disc space)

The arteries and veins were segmented to a maximum width of 3 cm on both sides from the midline, beginning at the level of the top of the L5 vertebral body to the bottom of S2 vertebral body. Similarly, the bone and vertebral disc anatomy from the top of the L5 vertebral body to the bottom of S2 was segmented to a width of 3 cm from the midline. An isosurface (a three-dimensional representation) of this segmentation was exported to 3D Slicer where the Hausdorff distance (a measure of the distance between two subsets of the segmentation, i.e. vessels versus boney anatomy) was calculated using a plug-in named Model-to-Model Distance (Francois Budin, University of North Carolina). A model with the mapping of the Hausdorff distance was then exported to Paraview for visualization (Fig. 2) and calculation of the percentage of lumbosacral surface area within 1 cm of the overlying vascular anatomy. The area, in 3D, that was more than 1 cm away from vascular anatomy and within 3 cm of the midline was defined as "accessible surface area" on the sacrum for suture/mesh placement for the purposes of this study. Unlike the measure of the level of bifurcation described above, these measurements were calculated in 3D, and unlike 2D measurements, allowed quantification of the surface area at and beyond the steep angle that occurs over the sacral promontory. Note that since the focus of this study was on the great vessels, "accessible surface area" in this study refers to the area not obstructed by the great vessels; it did not include the ureters, smaller sacral vessels, or nerves.

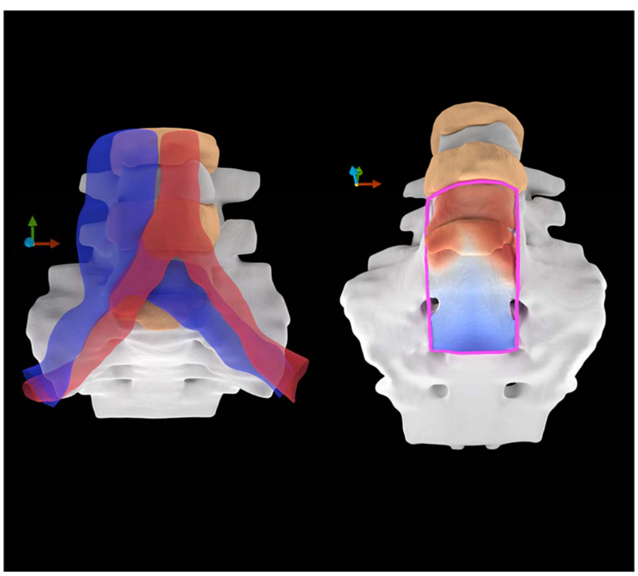

Fig. 2. *Left* 3D model of the great vessels overlying the sacral promontory as observed from an anterior to posterior perspective *Right* Color map of the resulting Hausdorff distance calculated between the vasculature and the lumbosacral spine with cooler colors representing further distance from the vasculature. Note that the perspective of the right image is rotated about the medial–lateral axis for better visualization of the sacrum. Rendered in Blender 3D software (www.blender.org)

For analysis of the effects of age and percent adiposity on the sites of aortic bifurcation, linear regression models were fitted to the data using SPSS version 21 (IBM Corp., Armonk, NY). Spearman's rank test was used for correlation statistics because the data were not normally distributed, and a monotonic relationship was assessed. When data were normally distributed, Spearman's and Pearson's analysis showed similar results. Ordinal data such as the location of the 2D bifurcation scores are reported as medians; otherwise mean values are used. The data were then evaluated comparing patients who were both thinner (defined as ≤40% adiposity, which corresponded to the thinnest one third of our patients) and older (≥65 years, the oldest one third) to those who were heavier and younger (i.e. the highest one third of adiposity, i.e. ≥47% adiposity, and the youngest one third of age, i.e. ≤51 years). Probability values were calculated for means using Student's *t* test and for medians using the Mann-Whitney *U* test. Multivariate analysis of variance was performed to examine the potential effect of age on the relationship between obesity and bifurcation location and the potential effect of obesity on the relationship between age and bifurcation location, respectively. A power calculation was performed using anchoring data from previous work on the location of the bifurcations of the great vessels [10] demonstrating that a sample size of 36 was needed to reject the null hypothesis that there is no difference in bifurcation location relative to S1 with a power of 80% at a two-sided significance level of $p = 0.05$.

Results

Of the eligible women who had undergone abdominal/pelvic CT, 107 were included in the study. Four were excluded, two with significant scoliosis (≥10° scoliosis curve), and two with spinal fusion (identified by the presence of spinal hardware). The median age of the subjects was 58 years, with a range of 24–88 years. The mean percent adiposity was 43.5 ± 13.6%. For the 2D coronal plane analysis, the median location of the aortic bifurcation was the inferior third of the L4 vertebral body, with a range from the middle segment of the L3 vertebral body to the inferior segment of the L5 vertebral body. The aortic bifurcation was located at the L5 vertebral body in 27.1% of patients. The median location of the IVC bifurcation was the middle segment of the L5 vertebral body, with a range from the superior segment of L4 to the superior segment of S1. In 81.3% of patients ($n = 87$) the bifurcation was at the level of the L5 vertebral disc. However, in 0.9% ($n = 1$) the IVC bifurcation was at the level of S1, and in 9.3% ($n = 10$) it was at the level of the L5-S1 intervertebral disc or lower, with the LCIV passing over the sacral promontory, indicating increased risk of injury.

There was a strong statistically significant positive correlation ($r_S = 0.74, p < 0.01$) between the location of the aortic bifurcation and the location of the IVC bifurcation. There was no significant

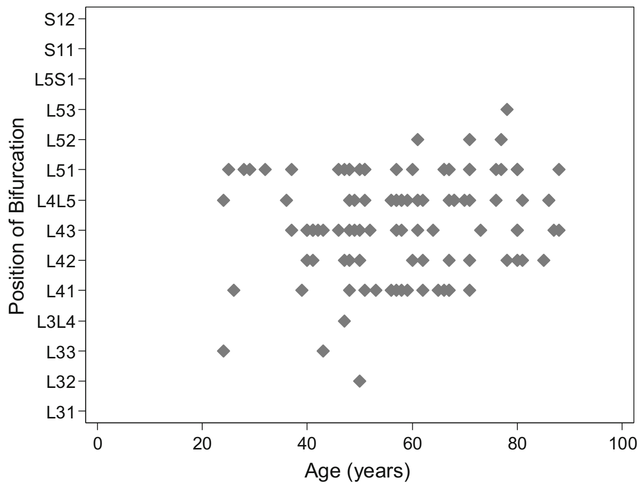

Fig. 3. Relationship between the location of the aortic bifurcation and age. There was no significant correlation ($r_S = 0.14$, $p = 0.16$)

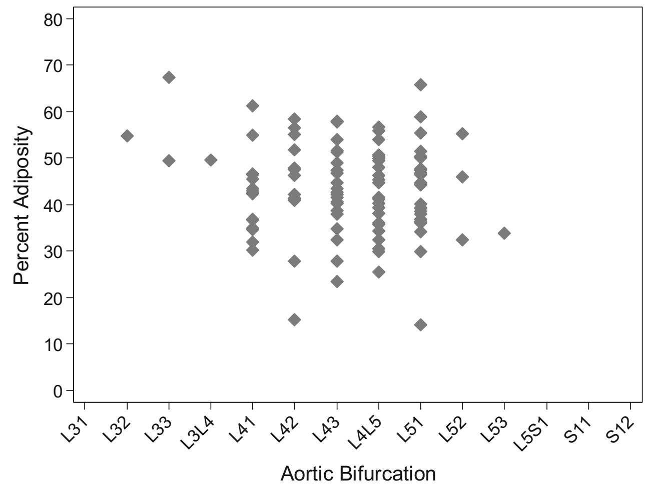

Fig. 5. Relationship between percent adiposity and location of the aortic bifurcation. There was no significant correlation ($r_S = -0.08$, $p = 0.42$)

correlation ($r_S = 0.14$, $p = 0.16$) between the location of the aortic bifurcation and age (Fig. 3). Similarly, there was no significant correlation between the location of the IVC bifurcation and age ($r_S = 0.05$, $p = 0.63$; Fig. 4). There was no significant correlation between percent adiposity and the location of the aortic bifurcation ($r_S = -0.08$, $p = 0.42$; Fig. 5) or the IVC bifurcation ($r_S = -0.09$, $p = 0.34$; Fig. 6).

A comparison between the patients who were both thinner (≤40% adiposity) and older (≥65 years old; $n = 14$) and those who were in the heaviest and youngest tertile ($n = 18$) showed a significant difference ($p = 0.022$) in the locations of the aortic bifurcation, with a lower median level for the thinner/older patients: median 8.43 (corresponding to the L4-5 intervertebral disc space) and median 6.72 (corresponding to the inferior segment of the L4 vertebral body), respectively. Similarly (although just beyond statistical significance), the older/thinner patients had a lower IVC bifurcation: median 10.5 (corresponding to the middle/inferior L5 segment) and median 9.33 (corresponding to the superior L5 segment), respectively ($p = 0.082$).

Controlling for adiposity, the multivariate analysis showed no significant correlation between age and the location of the aortic bifurcation (although the relationship approached significance; $p = 0.0922$), or, controlling for age, between adiposity and the location of the aortic bifurcation ($p = 0.1774$). Controlling for adiposity, the multivariate analysis showed no significant correlation between age and the location of the IVC bifurcation ($p = 0.3964$) or, controlling for age, between adiposity and the location of the IVC bifurcation ($p = 0.1977$). In addition, there were no significant differences between patients who were older (age ≥65 years) and thinner (<40% adiposity) and those who were younger and heavier.

The 3D computational analysis showed a mean accessible surface area of 65 ± 11.8% (note that the difference from 100% represents the area obstructed by the great vessels), and there was no significant correlation between age and accessible surface area

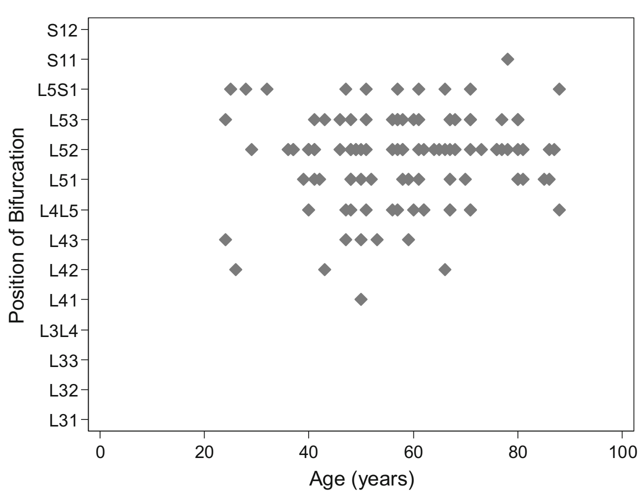

Fig. 4. Relationship between the location of the IVC bifurcation and age. There was no significant correlation ($r_S = 0.05$, $p = 0.63$)

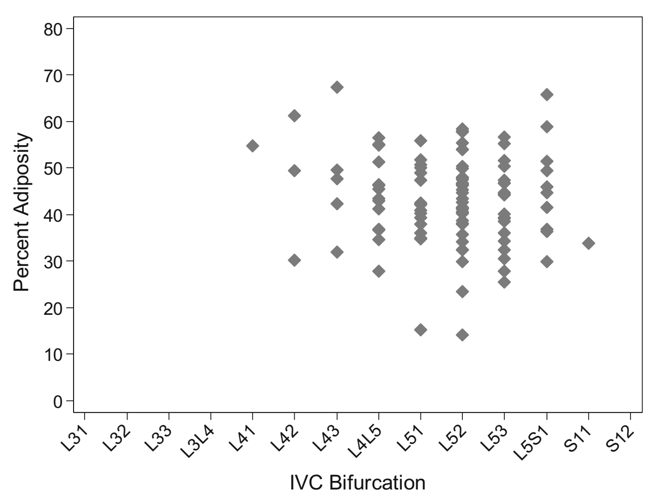

Fig. 6. Relationship between percent adiposity and location of the IVC bifurcation. There was no significant correlation ($r_S = -0.09$, $p = 0.34$)

($r_S = 0.07$, $p = 0.46$). or between adiposity and accessible surface area ($r_S = -0.02$, $p = 0.83$),. Further, the significantly lower bifurcations for thinner/older patients versus heavier/younger patients measured in the coronal plane (2D) had no measurable impact when examining the percent accessible surface area in 3D (64.93% vs. 65.45%,respectively, $p = 0.83$).

Discussion

The location of the bifurcation of the great vessels plays an important role in surgical dissection and placement of sutures and mesh in SCP. Although rare, injury to major vascular structures in the presacral space can result in life-threatening bleeding requiring vascular surgical intervention. The most important findings of this study were that in the majority of patients, the aortic bifurcation (mean inferior L4) and the IVC bifurcation (mean middle L5) when viewed in 2D in the coronal plane occurred above the L5-S1 intervertebral disc space. However, in 10% of patients the IVC bifurcation was at the L5-S1 intervertebral disc space or lower, placing the LCIV over the sacral promontory (right of midline) and portending a more complicated surgical dissection and increased risk of vascular injury. Our results failed to prove our hypothesis that age and adiposity are independently associated with a lower position of the aortic and IVC bifurcations; however, we did find that the bifurcation of the great vessels was lower in a subpopulation of women who were both ≥65 years of age and had an adiposity of ≤40%. Of these 14 patients, three had bifurcations at the L5-S1 intervertebral disc space or lower. Close examination of the data revealed that age and adiposity were not good predictors of the position of the great vessels, demonstrating that further characterization of the population at risk of injury is critical.

Previous research has found conflicting evidence on variation in the location of the aortic bifurcation in relation to age: one study showed that there is no variation in the location of the aortic bifurcation in relation to age [13], while another showed a highly significant downward shift with increasing age (especially in women) [9]. With each increasing decade of age, there is a descent equal to 17.5% of the vertebral height [9]. Another study [15] similarly showed a downward shift associated with both older age and lower BMI. Aging and atherosclerosis have been proposed as potential causes of a caudal shift in the aortic bifurcation, with aging of the lumbar spine associated with vertebral disc compression as well as decreased bone mineral density (BMD), which can lead to decreased vertebral height that in turn can lead to vertebral column shortening. Higher BMI is associated with greater BMD [23, 24]. Previous work [14] has shown a downward shift in the aortic bifurcation with lower BMI (in addition to older age). Our study indicates that patients who are both thinner and older may have lower bifurcations. Further work is needed to characterize the 10% of the population with potentially high-risk anatomy.

Interestingly, in further characterizing this population based on 3D image analysis, we found that the accessible surface area for placement of suture and mesh was not decreased in spite of finding a lower position of the bifurcations when measured in 2D in this subpopulation. Our 3D model offers significant advantages over a simple 2D CT scan of the vascular anatomy. This is particularly relevant to the fact that the sacrum orients posteriorly, and nearly 90° in some patients, relative to the great vessels as they descend into the pelvis. Thus, a small difference in 2D coronal measurement is nearly negligible relative to the accessible surface as defined by our 3D measurement. This can be appreciated in Fig. 2 in which an anterior view provides more of the 2D perspective (left), but rotating the pelvis in 3D about the medial-lateral axis reveals the large area on the sacrum that is still accessible because it deviates posteriorly relative to the direction of the great vessels. Collectively, these findings suggest that while the location of suture placement and route of dissection may be altered due to the location of the bifurcation of the great vessels, there is still potentially significant accessible space for suture placement more caudally/posteriorly from the promontory. For surgeons who operate strictly at the promontory and do not extend their dissection below the angulation of S1 in minimally invasive SCP, this portion of the sacrum may not be available. Safe access to this area laparoscopically may require the use of an angled laparoscope (30° and 45°).

It should also be noted that our study was not powered to assess differences in accessible surface area in 3D. In fact, a much larger sample size (a post-hoc sample size calculation of 16,382 subjects) would have been required to detect a difference. It is also possible that our method of measuring distance between two anatomical structures (with the inherent data limitations of the thickness of the CT scan slices that may lead to small changes in structures being missed) was not sensitive to small differences that can be appreciated surgically. It is also important to understand that the definition of "accessible" strictly referred to the distance between the bones/cartilage and great vessels. Other critical structures such as the ureter and nerves were not incorporated into our model [11, 25]. We also did not include the middle sacral vessels as it is our practice to identify and cauterize both the artery and the vein if they are in the path of planned suture placement.

The limitations of our study include the lack of accessible demographic information. The UPMC imaging population is ethnically homogeneous, with a majority Caucasian population; however, information on race, tobacco use, and concomitant illness such as atherosclerotic illnesses might have helped the evaluation of generalizability as well as additional correlations. Although we adjusted for all significant differences between the groups in a multivariate analysis, the possibility of unmeasured confounders cannot be excluded. In addition, we were limited by the application of the x-ray attenuation histogram created for adipose tissue to calculate a fat percentage. While this method has been heavily studied, validated and shown to accurately predict the complications of obesity in both animal and human studies [19–22], we believe that this is the first report of its use in surgery. Further studies are needed to validate its application in surgery.

The strengths of our study include findings that suggest no linear correlation but a relationship for the extremes of age and adiposity on the location of the great vessels, a significant surgical relationship for those performing SCP or spine surgery. Furthermore, the use of 3D computational analysis provided a novel approach to exploring these anatomic relationships. The surface area of the presacral space and the 3D relationship with the overlying vascular anatomy has never been previously explored, and our approach helps to advance the understanding of this important surgical anatomy and can be expanded to include other structures that may affect dissection and suture placement. Blinding the investigator collecting bifurcation measurements from age and obesity data helped decrease bias. Future studies are needed to determine how other factors such as race, smoking, and atherosclerotic diseases may affect this relationship. With a better understanding of these risk factors and the anatomic relationships, we can study the efficacy of algorithms for preoperative imaging and modeling to reduce the incidence of vascular injury.

Based on our results and the inability to link an easily identified demographic factor (age, adiposity) to lower bifurcations, we cannot suggest at this time that surgeons should use age or adiposity independently in considering who to image/model prior to suggesting SCP. Future studies are needed with demographic and clinical data to further define the 10% of women with potentially difficult anatomy that may make dissection and placement of sutures at the sacral promontory more technically challenging and dangerous. Once these women at high risk of major vascular injury are more accurately characterized, they can be identified prior to surgery. Incorporation of a detailed 3D computational model of the anatomy of a patient at high risk into preoperative planning could help surgeons anticipate difficult dissections and avoid complications.

Acknowledgements The authors acknowledge Leslie Meyn for her support with statistical analysis. Leslie Meyn is an employee of and is compensated by the University of Pittsburgh Medical Center.

Compliance with ethical standards

Conflicts of interest None.

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