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Respiration-Induced Deformations of the Superior Mesenteric and Renal Arteries in Patients with Abdominal Aortic Aneurysms

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Abstract

Purpose—This study was performed to quantify respiration-induced deformations of the superior mesenteric artery (SMA) and left and right renal arteries (LRA and RRA) in patients with small abdominal aortic aneurysms (AAA).

Materials and Methods—Sixteen men with AAAs (73 ± 7 years) were imaged with contrast-enhanced magnetic resonance angiography during inspiratory and expiratory breath-holds. Centerline paths of the aorta and the visceral arteries were acquired by geometric modeling and segmentation techniques. Vessel translations, and changes in branching angle and curvature due to respiration were computed from the centerline paths.

Results—With expiration, the SMA, LRA, and RRA bifurcation points translated superiorly by 12.4 ± 9.5 , 14.5 ± 8.8 , 12.7 ± 6.4 mm ($P < 0.001$) and posteriorly by 2.2 ± 2.7 , 4.9 ± 4.2 , 5.6 ± 3.9 mm ($P < 0.05$), respectively, and the SMA translated rightward by 3.9 ± 4.9 mm ($P < 0.01$). With expiration, the SMA, LRA, and RRA angled upwards by $9.7 \pm 6.4^\circ$, $7.5 \pm 7.8^\circ$, and $4.9 \pm 5.3^\circ$, respectively ($P < 0.005$). With expiration, the mean curvature increased by 0.02 ± 0.01 , 0.01 ± 0.01 , 0.01 ± 0.01 mm⁻¹ in the SMA, LRA, and RRA, respectively ($P < 0.05$). For both inspiration and expiration, the RRA curvature was greater than in other vessels ($P < 0.025$).

Conclusions—With expiration, the SMA, LRA, and RRA translated superiorly and posteriorly due to diaphragmatic motion, inducing upward angling of vessel branches and increase in curvature. In addition, the SMA exhibited rightward translation with expiration. The RRA was significantly more tortuous, but deformed less than the other vessels during respiration.

Introduction

Aortic endograft branch devices and stents may be implanted into the superior mesenteric artery (SMA) and renal arteries. For example, some aortic endograft designs implanted to

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repair abdominal aortic aneurysms (AAA), may include branch devices to help anchor the device (1–3), and stent grafts for thoracoabdominal and juxtarenal aortic aneurysms may include fenestrated branches to avoid sealing the visceral vessels while covering the aneurysm (4–6). In addition, the growing use of snorkel/chimney techniques has greatly increased the implantation of devices into the SMA and renal arteries. Although the initial technical and clinical success rates of these endovascular interventions are high (7,8), the long-term durability of these aortic and branch endografts has not been fully evaluated. Potential complications include migration, endoleak, loss of patency, and device fracture (9–18).

Long-term device performance may be influenced by in vivo vessel motion, which includes the cyclic deformation associated with respiration (17,19). Vascular deformations of abdominal aortic branches due to respiration may result from mobile abdominal organs and relatively fixed vessel ostia. The renal arteries have been reported to deform significantly during respiration due to mobile kidneys in healthy volunteers (19,20), so respiration-induced motion of the SMA may occur since other organs, such as the duodenum, translate significantly (21,22). Moreover, characterization of respiration-induced deformations of the SMA, LRA, and RRA in patients with AAAs would be especially relevant for AAA endograft design and evaluation.

This study quantifies the three-dimensional (3D) geometry of the SMA, LRA, and RRA in patients with small AAAs, and investigates the deformations of these vessels occurring during respiration.

Materials and Methods

Patient recruitment and image acquisition

Sixteen men (age 73 ± 7 years, range 61–84 years) with small AAAs (maximum lumen diameter 3.6 ± 0.6 cm, range 2.6–4.4 cm) were consented and recruited under a protocol approved by the Institutional Review Board. Subjects were imaged with contrast-enhanced MRA in the supine position with a 1.5-T GE Signa MR scanner (GE Medical Systems, Milwaukee, WI, USA). A 3D fast gradient echo MRA sequence was used in conjunction with MultiHance gadolinium (Bracco Diagnostics, Inc., Milan, Italy), injected via the left antecubital vein at a 0.1 mmol/kg dose. A test bolus was administered to determine the delay between the injection and the peak image enhancement of the abdominal aorta (23). MRA images were acquired during an inspiratory breath-hold, followed by an acquisition during an expiratory breath-hold. Imaging parameters included: 3.0–3.3 ms repetition time, 0.7–0.8 ms echo time, 25° flip angle, 80 slices with 3-mm thickness and 1.5-mm overlap, and $40 \times 40 \times 12$ cm³ volumetric field of view with 512×192 acquisition matrix per slice (reconstructed to 512×512). Resultant voxel size was $0.8 \times 0.8 \times 1.5$ mm³.

Construction of 3D model and centerline paths

The MRA images were utilized for constructing lumen models and centerline paths of the abdominal aorta, SMA, LRA, RRA, and bifurcated renal branches with use of custom software (Fig. 1) (24–27). From the MRA images, vessel paths were created manually, and lumen cross sections were segmented with a 2D level set segmentation technique. Segmented contours of vessels were lofted to form a single lumen model. True centerline paths were drawn by connection of centroids of the segmentation contours, and smoothing with an optimized number of Fourier modes (24).

Quantification of vessel geometry

The true centerline paths were used to quantify metrics of vessel morphology including the position of branch and vessel bifurcation points, vessel branching angle from the abdominal aorta, curvature, and peak curve angle of the SMA, LRA, and RRA. These metrics were quantified for inspiration and expiration, and they were subtracted to compute the deformations from inspiration to expiration.

The vessel branch point was defined as the ostia of the branch from the abdominal aorta, and the bifurcation point was defined as the first bifurcation on the branch vessel. Branch-to-bifurcation distance was the straight distance between the branch and bifurcation points (Fig. 2a). Branching angle was defined as the angle between the abdominal aorta and the SMA, LRA, or RRA. A branching angle greater than 90° indicates a downward tilt, and a branching angle less than 90° indicates an upward tilt (Fig. 2b). Curvature was defined as the inverse of the radius of a circumscribed circle around three centerline path points separated by distances of a vessel radius (Fig. 2c). Curvature was quantified from 5 to 30-mm distal to the branch point at every 0.1 mm on the centerline path. Mean curvature was computed by averaging curvature values over the same vessel segment. Proximal peak curvature was defined as the value of local maximum curvature located closest to the branch point. Maximum curvature changes were computed as the maximum point-to-point curvature difference from inspiration to expiration within the proximal 30 mm of each vessel. Proximal peak curve angle was defined as the angle of curvature at the proximal peak (Fig. 2d).

Statistical analysis

We reported average population data as mean $\pm$ standard deviation. Two-tailed paired t-tests were performed for comparisons. Statistical significance was defined as $P < 0.05$ for single comparisons and adjusted by Bonferroni-Holm correction for multiple comparisons (28).

Results

Ostia position and translation

With expiration, all vessels translated superiorly and posteriorly. Branch and bifurcation points translated superiorly significantly ($P < 0.001$), and the bifurcation points translated posteriorly significantly ($P < 0.01$). Posterior translation of the SMA bifurcation point was significantly less than those of the LRA and RRA ($P < 0.025$). In the SMA, the branch and bifurcation points translated significantly leftward ($P < 0.05$) and rightward ($P < 0.01$), respectively, with greater translation of the bifurcation point ($P < 0.005$). Rightward translation of the SMA bifurcation point was significantly greater than that of the RRA ($P < 0.005$), and non-significantly greater than that of the LRA ($P = 0.08$). The branch-to-bifurcation distance decreased significantly in the SMA ($P < 0.01$) and LRA ($P < 0.01$), and non-significantly in the RRA ($P = 0.1$). Reduction of the branch-to-bifurcation distance was significantly greater in the SMA than that of the LRA and RRA ($P < 0.01$) (Table 1). Note that while vessel translations did not occur in the same direction in all patients, statistical significance was achieved as reported in Table 1. An example of translation of the SMA, LRA, and RRA from inspiration to expiration is illustrated in Figure 3.

Angle change

With expiration, all vessels angled upward with a significant decrease of branching angle ($P < 0.005$). In the SMA, the reduction of branching angle was greater than that of the LRA and RRA, but the difference was not significant ($P = 0.3$ for LRA and $P = 0.05$ for RRA). For both inspiration and expiration, the proximal peak curve angle was greater in the RRA as

compared to the SMA and LRA ($P<0.005$). With expiration, all vessels exhibited increases of proximal peak curve angle ($P<0.05$) (Table 2).

Curvatures

The curvature corresponding to each point on the centerline was averaged for all 16 subjects within the proximal 5 to 30 mm of each vessel (Fig. 4). The mean curvature of the RRA was significantly greater than that of the SMA ($P<0.001$) and LRA ($P<0.025$ at inspiration, $P<0.05$ at expiration). With expiration, all vessels exhibited increases of mean curvature ($P<0.05$). The increase of mean curvature was greatest in the SMA, but it was not significantly different from the LRA ($P=0.1$) or RRA ($P=0.03$). The proximal peak curvature of the RRA was significantly greater than that of the SMA and LRA, for both inspiration and expiration ($P<0.005$). With expiration, all vessels exhibited increases of proximal peak curvature ($P<0.05$). The maximum curvature change was greater in the LRA, though not statistically significantly, as compared to the SMA ($P=0.05$) and RRA ($P=0.03$) (Table 2).

Maximum changes

The greatest bifurcation point translation among the 16 subjects exceeded 30 mm in the SMA and LRA. The greatest change of branching angle exceeded 20° in the SMA and LRA. The greatest change in proximal peak curve angle exceeded 20° in the LRA (Table 3).

Peak-curvature location

With expiration, the proximal peak location was shifted to the proximal direction, significantly in the RRA ($P<0.01$), and non-significantly in the SMA ($P=0.6$) and LRA ($P=1.0$). The maximum curvature change occurred more distally in the RRA (18.5 ± 7.7 mm from the branch point) as compared to the SMA (16.9 ± 7.3 mm from the branch point) and LRA (16.7 ± 7.5 mm from the branch point), but the difference was not statistically significant (Table 4).

Discussion

Notable translation of the SMA, LRA, and RRA was observed in all subjects during respiration. With expiration, the bifurcation point of all vessels translated superiorly and posteriorly with greater magnitude as compared to those of the branch points. With expiration, branch-to-bifurcation distance reduced significantly in the SMA and LRA with expiration. Moreover, with expiration, all vessels exhibited upward angling and increases of mean curvature, proximal peak curvature, and proximal peak curve angle (Tables 1 and 2). We opine that this visceral artery translation was induced by the movement of pancreas, duodenum, and kidneys with respect to the static abdominal aorta. Previous studies documented that visceral organs translate due to diaphragmatic motion during respiration. For example, with deep breathing, the pancreas and kidneys may translate up to 80 mm (20–22). Also, Draney et al. observed significant kidney translation with breathing and a correlation with renal artery translation (19). These organ and vessel translations in turn induce angling and bending of the SMA, LRA, and RRA.

The SMA and renal arteries exhibited distinctively different geometries and deformations due to respiration. The SMA exhibited the lowest curvature whereas the RRA exhibited the highest curvature for both inspiration and expiration (Fig. 4 and Table 2). During respiration, the SMA translated rightward significantly, which was not observed in the renal arteries. The rightward translation of the SMA bifurcation point was about 10.3-fold greater than that of the RRA. Moreover, the SMA translated posteriorly less in magnitude compared to the renal arteries (Table 1). We believe that the different geometries of these vessels, as well as their relationship with the visceral organs, contribute to their deformation

differences. The SMA branches off anteriorly from the abdominal aorta and extends inferiorly, at which point a number of vessels branch off transversely from the SMA to supply the duodenum and pancreas. These vessels may pull the distal SMA transversely as the pancreas and duodenum translate during respiration. Because the uncinate process of the pancreas and the left renal vein are located posterior to the SMA, the SMA may not translate posteriorly as much as the renal arteries. The RRA branches off anteriorly from the abdominal aorta and extends past the inferior vena cava (IVC) posteriorly, which explains the notable tortuosity of the proximal segment of the RRA. Moreover, the IVC may mechanically support the RRA, which may lead to less deformation due to respiration as compared to the LRA and SMA.

Although this study was conducted with explicit quantification techniques (24,25), there are several limitations. Our results are limited by the quality of the MRA images and motion artifacts introduced during image acquisitions (29,30). Our selection of imaging parameters may not be sufficient to detect the changes of vessel morphology smaller than 1 mm. Since all of our metrics were computed from the vessel centerline paths, path smoothing may limit the exact representation of vessel geometry if it was kinked or tortuous. Also, vessel calcification was not imaged, and the amount of calcification may contribute to vessel stiffness and deformations. Moreover, due to the fact that the MRAs were acquired in the supine position, our results do not consider visceral artery motions in different postures. Guzzetta et al. documented significant kidney translation and renal artery angulation due to postural changes (31); therefore the deformations quantified in this study would likely be influenced by body posture and gravity. Our subject population was limited to a small sample size, single gender (male), narrow age range, and small AAA diameters. Female AAA patients and patients with larger AAAs may exhibit different visceral artery dynamics.

Since this study is limited to the deformations of the native arteries without implanted devices, it is unclear how the presence of devices would affect these deformations. However, visceral vessel translation and deformation could affect the short and long-term performance of branched endografts. We observed up to 20° bending within 10–25 mm of the branch ostia (Tables 3 and 4), and branched endografts often employ branch devices that exceed 20 mm in length (32). Devices inhabiting this naturally-deforming section of vessel may experience less displacement than native arteries due to the mechanical support of the implanted device (33), however, dramatic kinking or bending may occur distal to the implanted device in order to accommodate the pulling of the pancreas and kidneys. Furthermore, focal vascular deformations distal to implants may augment arterial injury, thus increasing the possibility of intimal hyperplasia and restenosis, adversely affecting patency.

In conclusion, we quantified respiration-induced motion of the SMA, LRA, and RRA in small AAA patients. With expiration, the SMA, LRA, and RRA translated superiorly and posteriorly, inducing upward angling of vessel branches and increases of curvature. At the same time, the SMA translated significantly rightward with greater magnitude as compared to the renal arteries. The RRA exhibited more tortuous geometry in the proximal region near the aorta compared to the SMA and LRA, possibly due to the position of the IVC. These results may provide valuable information for device design and evaluation.

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Abbreviations

AAA	abdominal aortic aneurysm
SMA	superior mesenteric artery
LRA	left renal artery
RRA	right renal artery
IVC	inferior vena cava
MRA	magnetic resonance angiography
3D	three-dimensional

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Figure 1.

Image acquisition, model generation, and centerline paths extraction. (a) Magnetic resonance angiography (MRA) images were acquired from each subject during inspiratory and expiratory breath-holds. (b) MRA images were loaded into custom software, and vessel paths were constructed. The vessels of interest included the abdominal aorta, superior mesenteric artery (SMA), and left and right renal arteries (LRA and RRA). (c) To segment the lumen boundaries of each vessel, 2D level set segmentations were performed along the vessel paths. (d) Segmentation contours were lofted to form a lumen surface. (e) Lumen models for inspiration and expiration MRA images were generated. (f) Mathematical centroids were computed for the segmentation contours of (c). (g) Centerline paths were

constructed by connecting the set of centroids with interpolated cubic splines, and smoothed by optimized Fourier smoothing. (h) The extracted centerline paths were used to quantify deformation of the SMA, LRA, and RRA from inspiration to expiration.

Figure 2.

Illustrations of the position of vessel branch and bifurcation points, branching angle, curvature, and curve angle of the superior mesenteric artery (SMA), and left and right renal arteries (LRA and RRA). (a) The branch point is at the ostia of the vessel branch from the abdominal aorta. The bifurcation point is where the vessel bifurcates. Movements of these points were measured in left-to-right (R), anterior-to-posterior (P), and inferior-to-superior (S) directions from inspiration to expiration. Branch-to-bifurcation distance is the straight distance between these points. (b) The branching angle θ is the angle between two vectors, d_a , along the centerline path of the abdominal aorta, and d_b , along the path of the vessel, each the length of the average diameter of the aorta, SMA, LRA, or RRA (depending on the location of the vector). (c) Curvature at point P_i is the inverse of the radius, R , of a circumscribed circle on the centerline path. The circle was formed by P_i and adjacent points P_a and P_b , chosen such that the arclength between P_a to P_i and P_b to P_i is the average vessel radius. (d) The curve angle at point P_i , Φ , is the angle between two vectors, $\overrightarrow{P_a P_i}$, connecting P_a to P_i , and $\overrightarrow{P_i P_b}$, connecting P_i to P_b . The proximal peak curve angle of a vessel was measured at the point of local maximum curvature located closest to the branch point of each vessel.

Figure 3.

Lumen morphology of one subject during inspiration (light grey) and expiration (dark grey) in coronal, axial, and sagittal views. The abdominal aorta is depicted during expiration (dark grey). Note morphological changes of the superior mesenteric artery (SMA) and left and right renal arteries (LRA and RRA) due to respiration.

Figure 4.

Curvatures, averaged across sixteen subjects, plotted during inspiration (light grey solid line) and expiration (dark grey solid line), as well as their difference (Exp. - Insp. with black dashed line) shown with standard deviation (light grey area), for the superior mesenteric artery, and left and right renal arteries. The curvature is plotted for the vessel segment 5 to 30 mm distal of the branch point.

Table 1

Three-dimensional translation of branch and bifurcation points in the SMA, LRA, and RRA from inspiration to expiration.

	SMA	LRA	RRA
<i>Branch point</i>			
Left-to-Right (mm)	$-1.0 \pm 1.6^{\ddagger*}$	-0.5 ± 1.2	$0.2 \pm 1.2^{\ddagger}$
Anterior-to-Posterior (mm)	0.2 ± 1.2	0.4 ± 1.4	$0.9 \pm 1.6^*$
Inferior-to-Superior (mm)	$3.3 \pm 2.2^{\ddagger*}$	$2.4 \pm 1.9^{\ddagger*}$	$2.9 \pm 1.8^*$
<i>Bifurcation point</i>			
Left-to-Right (mm)	$3.9 \pm 4.9^{\ddagger*}$	0.8 ± 3.1	$0.4 \pm 3.7^{\ddagger}$
Anterior-to-Posterior (mm)	$2.2 \pm 2.7^{\ddagger*}$	$4.9 \pm 4.2^{\ddagger*}$	$5.6 \pm 3.9^{\ddagger*}$
Inferior-to-Superior (mm)	$12.4 \pm 9.5^*$	$14.5 \pm 8.8^*$	$12.7 \pm 6.4^*$
<i>Both</i>			
Branch-to-bifurcation distance (mm)	$-5.7 \pm 5.6^{\ddagger*}$	$-1.5 \pm 2.0^{\ddagger*}$	$-0.7 \pm 1.8^{\ddagger}$

Values are mean $\pm$ standard deviation. SMA, LRA, and RRA indicate superior mesenteric artery, left renal artery, and right renal artery, respectively.

$\ddagger$ indicates significant difference between SMA and LRA.

$\ddagger^*$ indicates significant difference between SMA and RRA.

$*$ indicates significant changes due to respiration.

Significance threshold ($P < 0.05$) was adjusted by Bonferroni-Holm correction for multiple comparisons between SMA and LRA and between SMA and RRA. No statistical significance was found between LRA and RRA for any of the metrics.

Table 2

Branching angle, proximal peak curve angle, and curvatures in the SMA, LRA, and RRA at inspiration and expiration, and the change from inspiration to expiration.

		SMA	LRA	RRA
<i>Angles</i>				
Branching angle (°)	Inspiration	119.2±11.0	114.9±14.3	122.3±14.9
	Expiration	109.6±13.6	107.4±13.0	117.4±17.0
	Exp. – Insp.	-9.7±6.4 [*]	-7.5±7.8 [*]	-4.9±5.3 [*]
Proximal peak curve angle (°)	Inspiration	13.6±6.2 [‡]	18.6±10.5 [§]	30.9±12.3 ^{‡§}
	Expiration	20.9±4.8 [‡]	24.8±10.5 [§]	35.7±12.8 ^{‡§}
	Exp. – Insp.	7.3±4.8 [*]	6.2±7.0 [*]	4.8±4.3 [*]
<i>Curvatures</i>				
Mean curvature (mm ⁻¹)	Inspiration	0.03±0.02 [‡]	0.05±0.02 ^{‡§}	0.07±0.02 ^{‡§}
	Expiration	0.05±0.02 [‡]	0.06±0.01 [‡]	0.08±0.02 [‡]
	Exp. – Insp.	0.02±0.01 [*]	0.01±0.01 [*]	0.01±0.01 [*]
Proximal peak curvature (mm ⁻¹)	Inspiration	0.05±0.02 [‡]	0.07±0.04 [§]	0.13±0.05 ^{‡§}
	Expiration	0.07±0.02 [‡]	0.10±0.03 ^{‡§}	0.15±0.06 ^{‡§}
	Exp. – Insp.	0.02±0.02 [*]	0.03±0.04 [*]	0.02±0.02 [*]
Maximum curvature change (mm ⁻¹)	Exp. – Insp.	0.05±0.02	0.07±0.03	0.04±0.03

Values are mean ± standard deviation. SMA, LRA, and RRA indicate superior mesenteric artery, left renal artery, and right renal artery.

[‡] indicates significant difference between SMA and LRA.

[‡] indicates significant difference between SMA and RRA.

[§] indicates statistical significance between LRA and RRA.

^{*} indicates significant changes due to respiration.

Significance threshold (P<0.05) was adjusted by Bonferroni-Holm correction for multiple comparisons between SMA and LRA, SMA and RRA, and LRA and RRA.

Table 3

Greatest changes of bifurcation point location, branching angle, and proximal peak curve angle due to respiration in the SMA, LRA, and RRA.

	SMA	LRA	RRA
<i>Translation of bifurcation point</i>			
Left-to-Right (mm)	10.9	9.0	12.9
Anterior-to-Posterior (mm)	5.6	12.5	16.2
Inferior-to-Superior (mm)	31.9	34.3	25.2
Branch-to-bifurcation distance (mm)	-19.1	-5.1	-4.0
<i>Angle change</i>			
Branching angle (°)	-23.0	-23.5	-13.9
Proximal peak curve angle (°)	15.2	22.3	12.0

Values are maximum changes from inspiration to expiration among 16 patients. SMA, LRA, and RRA indicate superior mesenteric artery, left renal artery, and right renal artery, respectively. Negative branching angle change indicates the upward angulation from inspiration to expiration. Positive change of the proximal peak curve angle indicates the increase of tortuosity from inspiration to expiration.

Table 4

The location of the proximal peak curvature at inspiration, expiration, and the change from inspiration to expiration as well as the location of the maximum curvature change in the SMA, LRA, and RRA.

		SMA	LRA	RRA
Location of the proximal peak curvature (mm)	Inspiration	11.7±2.1	11.4±4.3	13.4±2.2
	Expiration	11.3±2.5	11.4±3.0	12.7±1.8
	Exp. – Insp.	-0.4±2.9	0.0±2.1	-0.6±0.8 *
Location of the maximum curvature change (mm)	Exp. – Insp.	16.9±7.3	16.7±7.5	18.5±7.7

Values are mean ± standard deviation. SMA, LRA, and RRA indicate superior mesenteric artery, left renal artery, and right renal artery.

* indicates significant changes due to respiration.

No statistical significance was found between the branch vessels.