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Respiratory-Induced 3D Deformations of the Renal Arteries Quantified with Geometric Modeling During Inspiration and Expiration Breath-holds of Magnetic Resonance Angiography

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Abstract

Purpose—To quantify renal artery deformation due to respiration using magnetic resonance (MR) image-based geometric analysis.

Materials and Methods—Five males were imaged with contrast-enhanced MR angiography during inspiratory and expiratory breath-holds. From 3D models of the abdominal aorta, left and right renal arteries (LRA and RRA), we quantified branching angle, curvature, peak curve angle, axial length, and locations of branch points.

Results—With expiration, maximum curvature changes were $0.054 \pm 0.025 \text{ mm}^{-1}$ ($P < 0.01$), and curve angle at the most proximal curvature peak increased by $8.0 \pm 4.5^\circ$ ($P < 0.05$) in the LRA. Changes in maximum curvature and curve angles were not significant in the RRA. The first renal bifurcation point translated superiorly and posteriorly by $9.7 \pm 3.6 \text{ mm}$ ($P < 0.005$) and $3.5 \pm 2.1 \text{ mm}$ ($P < 0.05$), respectively in the LRA, and $10.8 \pm 6.1 \text{ mm}$ ($P < 0.05$) and $3.6 \pm 2.5 \text{ mm}$ ($P < 0.05$), respectively in the RRA. Changes in branching angle, axial length, and renal ostia locations were not significant.

Conclusion—The LRA and RRA deformed and translated significantly. Greater deformation of the LRA as compared to the RRA may be due to asymmetric anatomy and mechanical support by the inferior vena cava. The presented methodology can extend to quantification of deformation of diseased and stented arteries to help renal artery implant development.

Keywords

Renal artery; magnetic resonance angiography; geometric modeling; vascular implants; respiratory deformation

INTRODUCTION

Renal arteries are vulnerable to long-term complications regarding implantation of renal stents and aortic stent grafts. Renal stents, implanted to treat renal artery stenosis and resultant renovascular hypertension, commonly incorporate the ostial and proximal portions of renal arteries (1, 2). In addition, endovascular repair of juxtarenal, thoracoabdominal, and abdominal aortic aneurysms (AAA) may involve fenestration or anchoring with renal branch

devices (3, 4, 5, 6). Although the rate of operational success is high, recent reports on device failure including *in vivo* stent fracture, and in-stent restenosis and thrombosis have increased concerns about treatment with endoluminal devices (7, 8, 9, 10). As a possible contributor to stent fracture and restenosis, the dynamic motion of kidneys and deformation of renal arteries induced by respiration have been hypothesized to cause cyclic stent deformations (2, 10, 11). From inspiration to expiration, bending and angulation of the renal arteries have been observed, and these deformations may adversely affect renal stent performance (11). According to the FDA MAUDE database, the occurrence of renal stent fracture is two-fold greater in the left renal artery than the right renal artery (2). The dominance of the stent fractures on the left side implies that the left renal artery may deform more than the right renal artery; however, it is yet unclear how stent fractures are related to deformations of the renal arteries during respiration. Understanding respiratory-induced renal artery dynamics may help improve the design and evaluation of renal artery implants and aortic endografts with renal branch components.

Recently, several MRI studies have focused on performing systematic quantification of vessel geometry to understand complex *in vivo* artery motions and their possible correlation to disease progression and therapeutic complications. Cheng et al. quantified the deformation of superficial femoral arteries using MRA-based centerline paths as analytic representations of vessel geometry (12). Goergen et al. utilized MRI and 2D lumen segmentation techniques to quantify aortic geometry and motions in mice with AAAs (13). Choi et al. developed an explicit method to refine vessel centerline paths by employing centroid extraction from 2D lumen contours and optimized Fourier smoothing, and quantified dynamic deformations of the abdominal aorta, iliac arteries, superficial femoral arteries, and coronary arteries (14, 15).

In this study, we aimed to establish techniques to quantify *in vivo* three-dimensional (3D) motion and deformation of the renal arteries during respiration using MRA and 3D geometric modeling in healthy subjects. Draney et al. previously introduced MRA image acquisition during expiration breath-hold immediately after an acquisition during inspiration breath-hold (11). Based on these inspiratory and expiratory MRA images, we systematically extracted vessel centerline paths using a method developed by Choi et al., and quantified respiratory changes of arterial curvature, axial length, branching angle, and translation of renal branch points (14, 15). This study will provide a foundation for further quantification of renal arterial deformation in patients with vascular disease with and without endovascular implants.

MATERIALS AND METHODS

Image Acquisition

Five male subjects (age 57 ± 14 years, range 35–72) without known history of vascular disease were recruited under a protocol approved by the local Institutional Review Board, and informed consent was obtained from all subjects. Each subject was imaged with contrast-enhanced MR angiography in the supine position with 1.5-T GE Signa MR scanner (GE Medical Systems, Milwaukee, WI, USA). A body coil and a torso phased array coil were used for signal transmission and reception, respectively. 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. First, a test bolus, 3 cc of contrast and 15 cc of saline, was administered with 2-cc/s injection rate to determine the delay between the injection and the peak image enhancement of the abdominal aorta, such that the acquisition of the center of k-space could be timed to peak enhancement (16). With the estimated delay time, contrast was injected at a 0.2 mmol/kg dose with 2-cc/s injection rate, and the first phase was acquired during an inspiratory breath-hold. After, the scan was immediately

repeated for an expiratory breath-hold. The amount of contrast was determined based on body weight of each subject. Each phase acquisition lasted 30–40 seconds, which we determined to be the maximum duration the subjects could comfortably hold their breath. During inspiratory breath-hold, subjects were instructed to inhale deeply and hold during phase acquisition. During expiratory breath-hold, subjects were instructed to inhale, exhale to the limit, and hold. Respiratory bellow was used to monitor the breathing and breath-hold. The imaging parameters were optimized to achieve these low scan times as well as a volume of image slices to encompass the abdominal aorta, renal arteries, and kidneys with acceptable image quality. Imaging parameters included: 4.4 ms repetition time, 1 ms echo time, 25° flip angle, 1.7–2.1 mm slice thickness, and 34–40 cm field of view with 512×192 acquisition matrix (reconstructed to 512×512). The number of slices in image volume was 60–88. Resultant in-plane spatial resolution was 0.66–0.78 mm. Each volume of data was corrected with proprietary software (GE Medical Systems, Milwaukee, WI, USA) for known gradient nonlinearities to avoid image distortion in the slice direction.

Image-based Modeling and Extraction of Vessel Centerline Paths

The acquired MRA images were utilized for constructing lumen models and centerline paths of the abdominal aorta and renal arteries (Fig. 1). Using the software SimVascular (17), we constructed initial vessel paths for the abdominal aorta, and left and right renal arteries by hand-picking points in the lumen, and connecting these points with interpolated cubic splines. Along these initial vessel paths, we segmented the lumen boundaries of the vessels with a 2D level set segmentation technique, and performed Fourier smoothing on the segmentation contours (17, 18). The spacing between successive segmentation contours was approximately half of the vessel radius. Then, these contours were lofted to form a lumen surface model for visualization purposes (Fig. 1: a–e). To construct true centerline paths, we computed mathematical centroids from the lumen cross-sectional contours, connected the lumen centroids, and applied Fourier smoothing to remove high frequency perturbations (Fig. 1: a–c, f–h) (14).

Quantification of Vessel Geometry and Deformations

Using the re-constructed centerline paths, we quantified the following metrics along with their changes between inspiration and expiration: curvature, curve angle, branching angle, axial length, ostia location, and left-to-right ostia distance (Fig. 2). Curvature was defined as the inverse of the radius of a circumscribed circle around three points P_a , P_i , and P_b on the centerline path (Fig. 2a). The arclength between P_a to P_i and P_b to P_i was set as the average radius of the renal artery. The detailed algorithm of curvature calculation was introduced in a previous study (14). Special attention was paid to the peak curvature within the proximal 30 mm of the renal artery since that is where intravascular implants are generally located. At the point with the peak curvature, curve angle, Φ , was computed as the angle between two vectors connecting P_a to P_i and P_i to P_b (Fig. 2b). Branching angle, θ , was defined as the angle between two vectors, d_a , along the centerline path of the abdominal aorta, and d_b , along the path of the renal artery (Fig. 2c). The vector d_a was formed by two points on the aortic centerline: the point closest to the renal ostium, and a point superior to that, separated by an arclength of the average renal artery diameter. The vector d_b was formed by two points on the renal centerline: the renal ostium centroid and a point distal to that, separated by an arclength of the average renal artery diameter. A branching angle greater than 90° indicates a downward tilt, and a branching angle less than 90° indicates an upward tilt. Ostium 1 was defined as the branching point of the renal artery from the abdominal aorta and ostium 2 as the first bifurcation point of the renal artery (Fig. 2d). Renal axial length was defined as the arclength of the centerline path from the ostium 1 to ostium 2. Left-to-right ostia distance was defined as the distance between left and right ostia 1, and left and right ostia 2.

We reported average population data as mean $\pm$ standard deviation (SD). We performed two-tailed paired t-tests to compare inspiration vs. expiration, left vs. right renal arteries, and ostia 1 vs. 2. Statistical significance was defined as $P < 0.05$ for single comparisons. For multiple comparisons, significance threshold was adjusted by Bonferroni-Holm correction (19). All calculations were performed with use of the statistical package in Excel (Microsoft, Redmond, WA).

RESULTS

Renal Arterial Curvatures

Curvature plots for inspiration and expiration, and the difference between inspiration and expiration, are illustrated for each of five subjects (Fig. 3). In addition, the curvature corresponding to each point on the renal centerline was averaged for all five subjects within the proximal 5 to 30 mm for each renal artery (Fig. 4). Mean curvatures, first peak curvatures, and maximum curvature changes due to respiration in the left and right renal arteries are shown in Table 1. Mean curvatures were computed by averaging curvature values over the vessel length, first peak curvatures were defined by the most proximal peaks on the curvature plots, and maximum curvature changes correspond to the maximum curvature difference from inspiration to expiration within the proximal 30 mm of the renal artery. From inspiration to expiration, the mean curvatures were significantly increased in the left renal artery ($P < 0.05$). The first peak curvatures were significantly greater in the right renal artery than those in the left renal artery during inspiration ($P < 0.05$), but only trended greater during expiration ($P = 0.05$). From inspiration to expiration, the maximum curvature changes were significantly positive in the left renal artery ($P < 0.01$).

Curve Angles, Branching Angles, and Axial lengths

Curve angles at the first peak on the curvature plots, renal branching angles, and axial lengths are shown for inspiration, expiration, and expiration – inspiration in Table 2. With expiration, curve angles at the first peak increased significantly on the left and right sides ($P < 0.05$). Curve angles at the first peak were greater in the right renal artery than those in the left renal artery at both inspiration ($P < 0.03$) and expiration ($P < 0.02$). From inspiration to expiration, branching angles and axial lengths of the renal arteries did not change significantly. At both inspiration and expiration, the right renal artery was longer than the left renal artery except in the case of subject 3 ($P < 0.05$ when subject 3 was excluded).

Ostia Translations

Translation of ostia 1 and 2 from inspiration to expiration in left-to-right, anterior-to-posterior, and inferior-to-superior directions are shown in Table 3. Ostium 1 translated superiorly non-significantly ($P = 0.26$) and posteriorly significantly ($P < 0.05$) in the left renal artery, and superiorly significantly ($P < 0.05$) and posteriorly non-significantly ($P = 0.07$) in the right renal artery. Ostium 2 translated superiorly and posteriorly in the left and right renal arteries ($P < 0.05$). Superior translation of ostium 2 was significantly greater than that of ostium 1 in the left renal artery ($P < 0.005$). In the right renal artery, superior ($P = 0.03$) and posterior ($P = 0.04$) translation of ostium 2 trended greater than that of ostium 1, but the differences were not statistically significant. Changes in right-to-left ostia distance were 0.1 ± 0.4 mm ($P = 0.68$) and -2.2 ± 1.6 mm ($P < 0.05$) for ostia 1 and 2, respectively. Change in ostia 2 right-to-left distance was significantly greater than that of ostia 1 ($P < 0.05$).

DISCUSSION

During respiration, we observed complex motion of the left and right renal arteries in the form of changes in curvature and position of ostia. Mean and maximum curvature changes

were significant in the left renal artery ($P<0.05$). Ostia 2 translated significantly superiorly and posteriorly, and also translated medially with a significant decrease in right-to-left ostia 2 distance ($P<0.05$). The decrease in ostia 2 left-to-right distance was resulted from the rightward translation of left renal ostia 2 and leftward translation of right renal ostia 2 (Table 3). Draney et al. reported superior, posterior, and lateral-to-medial kidney movement, which is consistent with these findings (11). Translation of ostia 1, on the contrary, was not statistically significant, and its magnitude in superior direction was significantly less than the translation of ostia 2 ($P<0.005$ on the left side). This suggests that the abdominal aorta remained relatively static, and the translation of the kidneys correspond to the deformation of the renal arteries. The superior displacement of the kidneys appears to cause the changes of curvature in the renal arteries with expiration. Moreover, the decrease of ostia 2 right-to-left distance may explain the significant increase of mean curvature ($P<0.05$) and maximum curvature change ($P<0.01$) on the left side (Table 1). This is corroborated by the fact that the renal artery lengths did not significantly change with respiration.

The left and right renal arteries exhibited different deformations due to respiration. As stated above, the left renal artery exhibited significant mean curvature change and maximum curvature changes during respiration, whereas the curvature changes on the right side were not significant. However, the first peak curvatures were greater in the right vs. the left renal artery ($P<0.05$). Moreover, curve angles at the first peak were greater in the right vs. the left renal artery during inspiration ($P<0.03$) and expiration ($P<0.02$). This may be explained by the geometric differences between the left and right renal arteries as well as the location of the inferior vena cava (IVC). The configuration of the right renal artery, branching anteriorly from the abdominal aorta and extending past the IVC posteriorly, leads to greater first peak curvature values on the right side. In addition, the IVC is adjacent to the proximal region of the right renal artery, and hence may provide mechanical support of the artery. The average change in curvature due to expiration was less than 0.001 mm^{-1} within the region 15–25 mm distal from the renal ostium for the right renal artery, where the IVC was in contact with it (Fig. 4). On the left side, the renal arteries generally run parallel to the left renal veins, however, in subjects 2 and 3, the left renal vein exhibited entanglement with the distal portion of the left renal artery (Fig. 5). The entanglement may function as a mechanical fulcrum, and augment left renal artery deformation proximal to the entanglement (2). Morphology of both renal arteries and veins may be an important factor to estimate the degree of renal artery deformation for individuals. Moreover, it is possible that the greater deformation of the left as compared to the right renal artery is indeed causative to the greater incidence of left renal artery stent fracture (2).

Quantification of arterial geometries based on computed centerline paths may help in the analysis of MRA images with blurring artifact. In some patients, we observed blurring of lumen boundaries, possibly due to motion of the renal arteries despite breath-holding. In fact, several studies observed cranial motion of the kidneys and distal renal arteries during sustained breath-holding due to diaphragmatic motion (20, 21). Other motion sources include gross patient motion, bowel motion, and cardiac-induced pulsation (20). To quantify geometric differences of vessels from one image to another, the exact vessel representation is necessary. Centerline paths constructed from centroids based on a 2D segmentation contours may decrease the sensitivity to blurring artifacts, and subsequent Fourier smoothing of the centerline paths removes spurious spatial frequency components which may further reduce sensitivity to blurring (12, 13).

This is a baseline study focused on establishing explicit techniques for quantifying renal artery deformation due to respiration. Although this study quantified metrics of vessel geometry and deformation due to respiration, the results are limited by the quality of MRA images. Sub-mm voxel size may be necessary to detect the subtle deformation of the

proximal renal arteries. In addition, respiration depth of subjects was not quantified in this study. Due to the limited image volume, we were not able to locate any fiducial marker on the diaphragm to measure its position during inspiration and expiration. Moreover, our limited subject population does not enable general conclusions about renal artery motion, especially for patients with vascular disease. It is possible that patients with atherosclerosis, renal artery stenosis, or AAA may exhibit quantitatively and qualitatively different motions. For example, patients with renal artery implants and AAA endografts with renal branch components may exhibit less renal artery displacement due to mechanical support of the implanted device (9). Further studies should follow to investigate renal artery deformations of patients with abdominal aortic aneurysms, with and without implanted devices.

In conclusion, this study enabled the utilization of MRA and geometric modeling to quantify respiratory-induced deformation of renal arteries. We quantified the complex geometries of the renal arteries in 3D, and compared the differences between inspiration versus expiration and left versus right. Superior and posterior translation of the kidneys during expiration appears to induce bending and upward angling of the renal arteries. Curvature changes of the left and right renal arteries were notably different possibly due to the asymmetric arterial geometry as well as the presence of the IVC on the right side. Future studies will apply this robust methodology to examine the deformation of renal arteries, as well as over branch vessels, in patients with vascular disease. These studies may help correlate arterial deformation and implant performance, ultimately improving the design of renal stents and aortic endografts with renal branch components.

Acknowledgments

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Figure 1.

Construction of 3D models (a–b–c–d–e) and centerline paths (a–b–c–f–g–h). **a:** Magnetic resonance angiography (MRA) images were loaded into the custom software SimVascular. **b:** Vessel paths were constructed by connecting the hand-picked lumen centers with interpolated cubic splines. **c:** Along the vessel path, 2D level set segmentations were performed to segment the lumen boundaries of the vessels. **d:** Segmentation contours were lofted to form a 2D lumen surface. **e:** The modeling process (a to d) was conducted for each inspiration and expiration MRA image. The resultant solid models during inspiration (light grey) and expiration (dark grey) were visualized together. **f:** After lumen segmentation was completed, centroids were computed from the segmentation contours. **g:** Centerline paths were constructed by connecting the multiple centroids with cubic splines, and reconstructed by optimized Fourier smoothing. **h:** Curvature, axial length, branching angle, and ostia positions were computed based on the centerline paths.

Figure 2.

Illustrations of the calculation of curvature, branching angle, and ostia position. **a:** Curvature at P_i was defined as the inverse of the radius, R , of a circumscribed circle around three points P_a , P_i , and P_b on the centerline path. The arclength between P_a to P_i and P_b to P_i was defined as the vessel radius, averaged over the length of the vessel. **b:** Curve angle, Φ , was defined as the angle between two vectors, $\vec{P_aP_i}$, connecting P_a to P_i , and $\vec{P_iP_b}$, connecting P_i to P_b along the path of the renal artery. **c:** Branching angle, θ , was defined as the angle between two vectors, d_a , along the centerline path of the abdominal aorta, and d_b , along the path of the renal artery, each the length of the average renal artery diameter. **d:** Ostia 1 and ostia 2 were defined as the renal ostium centroid and the point of the first renal artery bifurcation, respectively.

Figure 3.

Respiratory changes of renal artery morphology of five subjects during inspiration (light grey) and expiration (dark grey) were visualized (left column). Also plotted are the corresponding curvatures during inspiration (light grey solid line) and expiration (dark grey solid line) as well as their difference (black dashed line) for the right (center column) and left (the right column) renal arteries (RAs). The first proximal peak of each curvature plot during expiration was marked as Peak 1.

Figure 4.

Curvatures, averaged across the five study subjects, are plotted during inspiration (light grey solid line) and expiration (dark grey solid line), as well as their difference (black dashed line) shown with standard deviation (light grey area), within the proximal 5 to 30 mm of each renal artery for **a**: the right and **b**: left renal arteries (RAs).

Figure 5.

Renal vein and artery morphology of subjects 2 and 3 are shown. The inferior vena cava, left and right renal veins during expiration were visualized with renal arteries during inspiration (light grey) and expiration (dark grey). Also plotted are the corresponding curvatures during inspiration (light grey solid line) and expiration (dark grey solid line) as well as their difference (black dashed line) for the left renal arteries (RA). The region of contact with the left renal vein was highlighted on the left renal artery (black arrow).

Table 1

Mean curvature, first peak curvature, and maximum curvature changes during respiration

		Mean curvature (mm ¹)	First peak curvature (mm ⁻¹)	Maximum curvature changes (mm ¹)
Left renal artery	Inspiration	0.079 ± 0.012	0.088 ± 0.035 [†]	--
	Expiration	0.089 ± 0.012	0.123 ± 0.044	--
	Delta	0.010 ± 0.007*	0.036 ± 0.029	0.054 ± 0.025*
Right renal artery	Inspiration	0.066 ± 0.008	0.133 ± 0.058 [†]	--
	Expiration	0.068 ± 0.018	0.150 ± 0.049	--
	Delta	0.003 ± 0.013	0.017 ± 0.019	0.009 ± 0.044

Values are mean±SD. Delta indicates Expiration - Inspiration.

* indicates significant changes due to respiration (P<0.05).

[†] indicates significant difference between left and right (P<0.05).

Table 2

The first peak curve angle, branching angle, and axial length during respiration

		Curve angle at the first peak (°)	Branching angle (°)	Axial length (mm)
Left renal artery	Inspiration	$23.2 \pm 7.5^{\dagger}$	112.5 ± 10.7	42.1 ± 8.9
	Expiration	$31.2 \pm 8.9^{\dagger}$	108.5 ± 10.2	43.1 ± 9.0
	Delta	$8.0 \pm 4.5^*$	-3.9 ± 6.9	0.9 ± 1.0
Right renal artery	Inspiration	$37.4 \pm 13.3^{\dagger}$	120.1 ± 15.2	51.0 ± 14.3
	Expiration	$42.0 \pm 11.1^{\dagger}$	120.4 ± 12.5	51.9 ± 14.4
	Delta	4.6 ± 4.8	0.3 ± 6.7	0.9 ± 1.1

Values are mean $\pm$ SD. Delta indicates Expiration - Inspiration.* indicates significant changes due to respiration ($P < 0.05$). † indicates significant difference between left and right ($P < 0.05$). for multiple comparisons between left and right and between ostia 1 and 2.

Table 3

Three-dimensional translation of ostia 1 and 2 from inspiration to expiration

		Translation of ostium 1 (mm)	Translation of ostium 2 (mm)
Left renal artery	LR	0.4 ± 0.7	0.9 ± 1.3
	AP	$0.6 \pm 0.5^*$	$3.5 \pm 2.1^*$
	IS	$1.4 \pm 2.4^\ddagger$	$9.7 \pm 3.6^{*\ddagger}$
Right renal artery	LR	0.4 ± 0.9	-1.1 ± 1.1
	AP	0.3 ± 0.3	$3.6 \pm 2.5^*$
	IS	$1.5 \pm 0.9^*$	$10.8 \pm 6.1^*$

Values are mean $\pm$ SD. LR, AP, IS indicates left-to-right, anterior-to-posterior, and inferior-to-superior translations, respectively.

* indicates significant changes due to respiration ($P < 0.05$).

‡ indicates significant difference between ostia 1 and 2 ($P < 0.05$). No statistical significance was found between left and right. Significance threshold was adjusted by Bonferroni-Holm correction for multiple comparisons between left and right and between ostia 1 and 2.