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Residual Shear Deformations in the Coronary Artery

Quantifying arterial residual deformations is critical for understanding the stresses and strains within the arterial wall during physiological and pathophysiological conditions. This study presents novel findings on residual shear deformations in the left anterior descending coronary artery. Residual shear deformations are most evident when thin, long axial strips are cut from the artery. These strips deform into helical configurations when placed in isotonic solution. A residual shear angle is introduced as a parameter to quantify the residual shear deformations. Furthermore, a stress analysis is performed to study the effects of residual shear deformations on the intramural shear stress distribution of an artery subjected to pressure, axial stretch, and torsion using numerical simulation. The results from the stress analyses suggest that residual shear deformations can significantly modulate the intramural shear stress across the arterial wall. [DOI: 10.1115/1.4027331]

Keywords: residual stress and strain, constitutive modeling, finite deformations, nonlinear elasticity, shear strain

Introduction

It is well known that, following the removal of traction forces (e.g., pressure and axial loads), arteries contain circumferential residual strains throughout the vessel wall. Incorporation of these residual strains into the stress analysis leads to a reduction of the predicted transmural circumferential stress gradient. Thus, quantifying residual strains is a crucial step in accurately predicting the transmural stress distribution. Residual strains can be relieved through destructive cuts, allowing the arterial wall to deform into a stress-free configuration. The circumferential opening angle approach, which results from a single radial cut across a thin arterial ring, is generally believed to be sufficient in achieving a nearly stress-free configuration. This approach, therefore, has become the standard in quantifying arterial residual deformations. However, evidences of longitudinal or axial residual deformations suggest that the single opening angle method may not fully characterize the stress-free configuration [1–3].

In this study, we report the existence of residual shear deformations (RSD), which are present along with circumferential and longitudinal residual deformations, in the coronary arteries. RSD are relieved when thin, long axial strips are cut from the artery resulting in the strips deforming into helical spring-like shapes. The coronary arteries are extensively embedded in cardiac muscles and these arteries are therefore subjected to dynamic and multi-axial deformations due to the cyclic cardiac contractions and distensions. These deformations include a significant amount of axial twists, as much as 30 deg of rotation at certain locations [4–7]. Segments of abnormally high twists have been associated with higher incidences of atherosclerotic lesions, suggesting a potential pathological role of large torsional deformations [8]. Given that cells can sense and adapt to their local mechanical environment, RSD may be a compensatory development in response to the torsional loads induced by the heart, analogous to the concept that circumferential residual strains normalize circumferential stresses across the arterial wall at physiologic loads. Moreover, RSD have previously been observed in transverse equatorial ring slices of the rat myocardium [9,10]. When a single radial cut was made in the myocardial rings, the rings opened into a circular sector but the ends of the cut deformed out of the

equatorial plane. Since it is known that the ventricle undergoes twisting and untwisting throughout the cardiac cycle [11,12], myocardial RSD may be a consequence of the twisting deformations. This study is a proof-of-concept presenting the first observational and mechanical modeling of RSD in blood vessels.

We demonstrate that RSD exist in coronary arteries and that the magnitude and direction of the RSD can vary significantly along the axial length of the artery. Furthermore, we propose a kinematics framework for quantifying the deformation field of the RSD. We combine the kinematics of the RSD with that of circumferential and longitudinal residual deformations (LRD) into a single framework. Different combinations of RSD and axial twists were analyzed using computational numerical modeling to demonstrate the theoretical effect of RSD on the intramural shear stress of an artery subjected to physiologic loading conditions of pressure, axial stretch, and axial twist. Our findings suggest that when subjected to certain conditions, the intramural shear stress could be reduced to nearly zero. However, it can also be greatly increased, resulting in a high shear stress gradient across the wall. Quantifying RSD may help to better understand the local mechanical environment of the arterial wall, which in turn may help to better understand and predict mechanically mediated biological responses of arteries under healthy and diseased conditions.

Materials and Methods

Tissue Preparation and Cutting Protocol. Hearts of similar sizes from female American Yorkshire farm pigs (average age of 2 yrs) were harvested immediately following exsanguination at a local abattoir (Holifield Farms, Covington, GA, USA). The left-anterior descending coronary artery (LADCA) from each heart was continuously dissected beginning from its bifurcation from the left main coronary artery. Arteries that exhibited high tortuosity from gross examinations following dissection were discarded. A total of ten coronary arteries suitable for testing were harvested. The arteries were then flushed with isotonic Ca^{2+} and Mg^{2+} -free Dulbecco's phosphate buffered saline (DPBS, Mediatech, Herndon, VA, USA) and placed in ice-chilled DPBS for transport to the laboratory. The harvested LADCAs averaged 7.1 ± 0.8 cm (mean $\pm$ standard deviation) in length.

A destructive cutting protocol was developed to reveal the RSD in each artery; this protocol is illustrated in Fig. 1. In brief, a single continuous straight cut was first made down the length of the

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Fig. 1 Destructive cutting protocol developed to reveal residual shear deformations in the coronary artery. (a) A single straight cut down the length of the artery is made. (b) The artery is laid flat and a parallel strip is stamped down the center. (c) The arterial strip is placed in isotonic saline where it immediately deforms into a tortuous shape. (d) The final configuration is reached following further sectioning into approximate thirds.

Fig. 2 Two helical configurations exhibiting negative (a) and positive (b) shearing directions. The asterisk denotes the ink-labeled adventitial surface of the proximal end, which is used as a reference marker for determining the shearing direction.

artery (Fig. 1(a)). The artery was then opened and laid flat. A parallel strip of the arterial wall was then stamped out using a pair of microtome blades spaced 2 mm apart (Fig. 1(b)). The excised strip was then suspended in DPBS forming a complex tortuous shape (Fig. 1(c)). The long strip was further sectioned into approximate thirds; these sections were designated as S1, S2, and S3, with S1 being the most proximal (Fig. 1(d)). The sections were further incubated in DPBS for 2–3 h at 37 °C to achieve a state of thermodynamic and geometric equilibrium prior to imaging.

To ensure that the helical configuration was not an artifact of the cutting protocol, we performed the same procedure on five similarly sized porcine carotid arteries. We found that the carotid strips deformed into flat, watch spring-like shapes, suggesting only the presence of LRD and not RSD.

Imaging. Each helical configuration was inspected prior to imaging to ensure that the edges were in free suspension. A small drop of black Indigo ink (Higgins Ink, Leeds, MA, USA) was applied to the adventitial surface on the proximal end of each section to distinguish the direction of shear (Fig. 2). Images of the sections were captured using a tripod mounted CCD camera (model PowerShot SD850 IS, Canon, Melville, NY, USA) while submerged in DPBS. The axis of the helical sections was aligned parallel to the plane of the camera lens.

Fig. 3 Template for measuring the residual shear angle. A representative helical section is superimposed with an angle measurement template. Angles β_{1-4} were used to calculate the mean residual shear angle (ω_i). Note that these angles are measured at the intimal surface.

Measurements of Residual Shear Deformations. Following the determination of the shearing direction, the four corner angles (β_{1-4}) of the parallelogram-like shape (Fig. 3) was measured using an open-source image processing software (ImageJ, National Institute of Health, Bethesda, MD, USA). The mean residual shear angle (RSA) ω_i (in rads), measured at the intimal surface, was then calculated using following equation:

$$\omega_i = \frac{K}{4} \sum_{j=1}^4 \left| \frac{\pi}{2} - \beta_j \right| \quad (1)$$

where $K = -1$ or $+1$ for either negative or positive shear direction, respectively.

Kinematics Framework. Our kinematics framework incorporates residual shear deformations with circumferential and longitudinal residual deformations. We first consider a straight, cylindrical section of an artery in the loaded configuration, β_l , and the traction-free configuration, β_u ; let κ_l and κ_u denote a local neighborhood about a point p , with positions $\mathbf{x}_l(r, \theta, z)$ and $\mathbf{x}_u(\rho, \vartheta, \zeta)$ within the body in the loaded and traction-free configurations, respectively. Let this neighborhood be denoted κ_n with position $\mathbf{X}_n(R, \Theta, Z)$ in a locally stress-free configuration β_n . Let the gradient of the map $\mathbf{X}_n(R, \Theta, Z) \mapsto \mathbf{x}_l(r, \theta, z)$ be denoted by $\mathbf{F}$, which may be decomposed into a map from $\mathbf{X}_n(R, \Theta, Z) \mapsto \mathbf{x}_u(\rho, \vartheta, \zeta)$ with gradient $\mathbf{F}_1$ and a map from $\mathbf{x}_u(\rho, \vartheta, \zeta) \mapsto \mathbf{x}_l(r, \theta, z)$, with gradient $\mathbf{F}_2$; thus, $\mathbf{F} = \mathbf{F}_2 \cdot \mathbf{F}_1$.

For the inflation, axial extension, and torsion of a long, straight, axisymmetric tube, neglecting variations along the axial direction, $\mathbf{x}_u(\rho, \vartheta, \zeta) \mapsto \mathbf{x}_l(r, \theta, z)$ is defined as: $r = r(\rho)$, $\theta = \vartheta + \gamma\zeta$, and $z = \lambda_z\zeta$, where $\gamma = \phi/L_u$ is the twist (in rads) per unit traction-free vessel length (L_u) and $\lambda_z = \ell/L_u$ is the axial stretch ratio with ℓ being the loaded vessel length [13]. The deformation gradient for this map is given by

$$[\mathbf{F}_2] = \begin{bmatrix} \frac{\partial r}{\partial \rho} & 0 & 0 \\ 0 & \frac{r}{\rho} & r\gamma \\ 0 & 0 & \lambda_z \end{bmatrix} \quad (2)$$

Imagine dissecting this artery into infinitesimally thin cylindrical shells, allowing each shell to unload to an individual traction-free state, β_n ; assuming an axisymmetric deformation, each shell may take on a different radius, length, and twist from its configuration in β_u (Fig. 4). Note that, in β_n the traction forces as a function of stress components t are:

$$2\pi t_{\Theta\Theta} dR_n = 0, \quad 2\pi t_{ZZ} dR_n = 0, \quad \text{and} \quad [(t_{\Theta\Theta} - t_{RR})/R_n] dR_n = 0 \quad (3)$$

Fig. 4 Theoretical representation of residual strains in an artery. The stress-free configuration consists of a series of infinitesimally thin cylindrical shells that vary in axial lengths and radii (a) and (b). Circumferential and longitudinal residual strains are induced when the shells are axially and circumferentially stretched and assembled into a continuous, but residually stressed, tube (c). Residual shear strains are induced when each shell undergoes a shearing axial twist prior to the assembly (d).

thus, $t_{\Theta Z} = t_{ZZ} = 0$ and, since $P = t_{RR}(r = r_i) = 0$, then $t_{\Theta\Theta} = 0$ as well, where P is the transmural pressure. Also, since $t_{\Theta Z} = 0$, the shearing force along any $\Theta - Z$ plane also equals zero (i.e., $t_{\Theta Z} dR_n dZ_n = 0$). Thus, this configuration is indeed stress-free.

The map from $\mathbf{X}_n(R, \Theta, Z) \mapsto \mathbf{x}_n(\rho, \vartheta, \zeta)$ serves to “assemble” the discontinuous stress-free cylinders into a continuous, traction-free, albeit residually stressed tube and is defined as: $\rho = \rho(R_n)$, $\vartheta = (\pi/\Theta_o)\Theta + \Upsilon(\rho)Z$, and $\zeta = \Lambda_z(\rho)Z$, where Θ_o is the circumferential arc angle, $\Upsilon = \Upsilon(\rho) = \Gamma(\rho)/L_n(\rho)$ is the stress-free twist (in rads) per unit stress-free vessel length $L_n(\rho)$, and $\Lambda_z = \Lambda_z(\rho) = L_u/L_n(\rho)$ is the longitudinal residual stretch ratio [1]. Although Γ may exhibit radial variations (i.e., $\Gamma = \Gamma(\rho)$), the ability to measure only a single RSA at the intimal surface forces us to approximate a single stress-free axial twist (Γ^*) across the arterial wall using the geometric relationship given as

$$\Gamma(\rho) \approx \Gamma^* = \frac{\tan(\omega_i)L_{n,i}}{R_i} \quad (4)$$

where $L_{n,i}$ and R_i are the axial length and circumferential radius in the stress-free configuration at the inner wall, respectively. This approach therefore assumes a homogeneous distribution of residual shear stretches across the arterial wall. Despite Γ^* being a constant, the twist per unit stress-free length (Υ) is radially varying since the stress-free length L_n is radially varying. The gradient of this map is defined as:

$$[\mathbf{F}_1] = \begin{bmatrix} \frac{\partial \rho}{\partial R_n} & 0 & 0 \\ 0 & \frac{\pi \rho}{\Theta_o R_n} & \rho \Upsilon \\ 0 & 0 & \Lambda_z \end{bmatrix} \quad (5)$$

The complete mapping from the stress-free to current configuration is therefore:

$$[\mathbf{F}] = [\mathbf{F}_2] \cdot [\mathbf{F}_1] = \begin{bmatrix} \frac{\partial r}{\partial R_n} & 0 & 0 \\ 0 & \frac{\pi r}{\Theta_o R_n} & r(\Upsilon + \gamma \Lambda_z) \\ 0 & 0 & \lambda_z \Lambda_z \end{bmatrix} \quad (6)$$

Note that the term $(\Upsilon + \gamma \Lambda_z)$ is the twist of a cylindrical shell, as it is deforms from the stress-free configuration to the current configuration.

Stress Analysis. A stress analysis was performed to illustrate the effect of RSD on the intramural stresses in a coronary artery subjected to inflation, axial stretch, and torsion. The general Cauchy stress relationship, assuming incompressible, homogeneous, and isothermal conditions, is given by

$$\mathbf{t} = -p\mathbf{I} + \mathbf{F} \cdot \frac{\partial W}{\partial \mathbf{E}} \cdot \mathbf{F}^T \quad (7)$$

Where p is the Lagrange multiplier, $\mathbf{I}$ is the identity tensor, W is the strain energy density function, and $\mathbf{E}$ is the Green strain tensor. An exponential Fung-type strain energy density function extended for shear was selected for the analysis on the basis of literature available parameters specific for the LADCA. This strain energy function is of the following form:

$$W = \frac{c_0}{2} (\exp^Q - 1) \quad (8)$$

where $Q = c_1 E_{rr}^2 + c_2 E_{\theta\theta}^2 + c_3 E_{zz}^2 + 2c_4 E_{\theta\theta} E_{rr} + 2c_5 E_{\theta\theta} E_{zz} + 2c_6 E_{zz} E_{rr} + 2c_7 E_{\theta z}^2$

Materials parameters c_0 through c_6 were previously determined by Wang et al. [14] and the shear parameter c_7 was solved in-silico by Epps and Vorp [15] using data from the former study. The values for these parameters are $c_0 = 8.92$ kPa, $c_1 = 0.55$, $c_2 = 1.25$, $c_3 = 2.46$, $c_4 = 0.08$, $c_5 = 0.36$, $c_6 = 0.06$, and $c_7 = 0.0759$. Using these material parameters, we solved for the loaded geometry by satisfying boundary conditions in the traction-free configuration, these include:

$$P = \int_{\rho_i}^{\rho_o} \left[\frac{t_{\vartheta\vartheta} - t_{\rho\rho}}{\rho} \right] d\rho = 0; \quad \mathcal{L} = 2\pi \int_{\rho_i}^{\rho_o} t_{\zeta\zeta} \rho d\rho = 0; \quad (9)$$

$$T = 2\pi \int_{\rho_i}^{\rho_o} t_{\vartheta\zeta} \rho^2 d\rho = 0$$

where $\mathcal{L}$ is the axial force, T is the torque, t_{ij} is the i, j -component of the Cauchy stress, where i and $j = \rho, \vartheta$, or ζ . Note, however, that the normal (N) and shearing (S) forces along any $\vartheta - \zeta$ plane within the vessel wall as well as the normal (M) force along the $\rho - \vartheta$ plane, given as

$$N = L_u \int_{\rho_i}^{\rho_o} t_{\vartheta\vartheta} d\rho; \quad S = L_u \int_{\rho_i}^{\rho_o} t_{\vartheta\zeta} d\rho; \quad M = 2\pi \int_{\rho_i}^{\rho_o} \rho t_{\zeta\zeta} d\rho \quad (10)$$

are not necessarily equal to zero. Thus, if a dissecting cut was made along a $\vartheta - \zeta$ plane, the vessel may further deform to relieve these normal and shearing forces; namely, the ring springs open to relieve N and shears and bends to relieve S and M, respectively. The deformation to relieve N results in the circumferential sector and indicates that $t_{\vartheta\vartheta}(\rho) \neq 0$ for all $\rho \in [\rho_i, \rho_o]$. Likewise, the deformation to relieve S and M results in the helical sections and indicates $t_{\vartheta\zeta}(\rho) \neq 0$ and $t_{\zeta\zeta}(\rho) \neq 0$ for all $\rho \in [\rho_i, \rho_o]$.

The loaded geometric configuration was solved through the minimization of the error between the theoretical model pressure (see Eq. (11)) and a desired luminal pressure of 80 mmHg. The axial stretch ratio was $\lambda_z = 1.40$ [13].

$$P_{\text{mod}} = \int_{r_i}^{r_o} (t_{\theta\theta} - t_{rr}) \frac{1}{r} dr \quad (11)$$

Simulation. Five cases, representing various combinations of RSA and axial twists, are shown in Table 1. Case 1 represents an axial twist of an artery without RSD. Case 2 represents zero axial twist but with the presence of a large RSD. Cases 3 and 4 represent similar magnitudes but opposing directions of RSA and axial

Table 1 Combinations of residual shear angles and loaded twist angles utilized in the stress analysis

	Case 1	Case 2	Case 3	Case 4	Case 5
Residual shear angle (ω_i)	0 deg	20 deg	20 deg	20 deg	20 deg
Loaded twist angle (ϕ)	-30 deg	0 deg	-20 deg	-30 deg	20 deg

Fig. 5 Experimental measurements of the residual shear angles. The residual shear angles are given relative to the section numbers. Each artery was divided into three segments denoted by S1, S2, and S3, with S1 being the most proximal section. All sections exhibited residual shear deformations. Both magnitude and direction of the RSD varied greatly along the length of the artery. Each symbol represents measurements from a single artery.

twists. Finally, case 5 represents equal magnitudes and directions of RSA and axial twists.

Statistical Analysis. ANOVA was used to test for differences between multiple means. Statistical analysis was performed using the commercial statistical software XLSTAT (Addinsoft SARL, New York, NY, USA). Results are presented as mean $\pm$ standard deviation (mean $\pm$ SD).

Results

Experimental Measurements. RSDs were observed along all sections of the arteries (Fig. 5). Interestingly, several arteries had adjacent sections with opposing shear directions, suggesting a complex transition zone between these sections. Overall, we found a greater number of positive shear directions (22 positive and 8 negative). Seven out of the ten arteries exhibited both positive and negative shear directions, while the remaining three exhibited only a positive shear direction. The average RSA was positive and similar in magnitude between the sections, with large variability within each section (Table 2). We found no statistical differences in the RSA between these sections (ANOVA). When averaged across all the sections, the RSA was found to be 15.6 ± 5.9 deg.

Stress Analysis. The geometric parameters used for the stress analysis are shown in Table 3. These geometric parameters consist of previously reported values (traction-free parameters, see Ref. [11,12]) along with the measurements made in the present study (stress-free parameters).

We found that the residual shear stress (RSS) gradient increased with increasing RSA (Fig. 6(a)). The in-plane residual stresses (radial, circumferential, and longitudinal) are shown in Fig. 6(b). The circumferential and longitudinal residual stresses are similar to results we have previously reported. However, the radial stress

Table 2 Experimental measurements of the residual shear angles (in deg) from each section

	S1	S2	S3
Mean $\pm$ SD	11.2 ± 14.0	5.1 ± 15.8	11.6 ± 12.7
Max	23.6	20.2	25.3
Min	-13.8	-19.8	-13.7

Table 3 Geometric parameters utilized in the stress analysis

TF outer radius (ρ_i)	1.219 mm
TF inner radius (ρ_a)	0.963 mm
Circumferential opening angle (Θ_o)	169.9 deg
Longitudinal opening angle (ψ_o)	73.9 deg
SF circumferential inner radius (R_i)	20.4 mm
SF longitudinal inner radius (S_i)	5.5 mm
TF axial length	20 mm
Axial stretch ratio (λ_z)	1.40

Note: TF: Traction-free, SF: Stress-free

Fig. 6 Predicted intramural residual stresses. (a) Intramural residual shear stress gradients increase with increasing magnitudes of residual shear angles (ω_i). **(b)** Radial (solid line), circumferential (square markers), and longitudinal (dashed line) residual stresses for residual shear angle $\omega_i = 20$ deg. Note that the radial boundary condition was not completely satisfied using parameters from the literature (the radial stress at outer wall should be zero).

at the outer wall failed to fully satisfy the boundary conditions imposed by Eq. (9). Since there were no traction-forces along the outer wall, the radial stress at that point should be zero. This discrepancy may be attributed to the use of material parameters that were not solved for the current conditions. Table 4 lists the predicted boundary values. Given that Eqs. (9) and (10) specified that the torque T , luminal pressure P , and axial force $\mathcal{L}$ should be zero, it is apparent that the calculated boundary values are nonzero, although these differences do not appear to be significant.

We found that the intramural shear stress distribution of an artery subjected to pressure, axial stretch, and torsion were highly dependent on different combinations of RSA and twist angles (Fig. 7). Case 3, which represented a condition in which the axial twist and RSA were equal in magnitude but opposite in direction, exhibited the lowest stress gradient and mean stress magnitude. Case 5, where the magnitude and direction of the RSA and torsion angle were equal, exhibited the highest gradient and mean stress magnitude. Case 1, which was absent of the RSA, showed that the intramural shear stress was highest along the outer wall and lowest

Table 4 Calculated boundary values in the traction-free state for various values of residual shear angles

	$\omega_i = 0$ deg	$\omega_i = 5$ deg	$\omega_i = 10$ deg	$\omega_i = 20$ deg
T(μ Nm)	0	0.0032	0.0064	0.0131
S(μ N)	0	6.75	13.64	28.5
P(mmHg)	-4.9	-3.9	-3.1	-2.4
L(N)	-0.0018	-0.0012	-0.0008	-0.0004

Note: T: Torque, S: Shearing force along the $\vartheta - \zeta$ plane, P: luminal pressure, L: axial force

Fig. 7 Intramural shear stresses predicted using different combinations of residual shear angles and loaded axial twists. The magnitudes of the angles are within the bounds of experimental and physiological measurements. The intramural shear stress distribution can be greatly affected by different combinations of both the magnitude and direction of the residual shear and axial twist angles.

along the inner. Finally, case 2, representing the presence of only RSA, showed that a small RSS gradient of ~ 35 Pa can be amplified to ~ 4000 Pa, if an axial twist was not applied, in the loaded configuration due to the nonlinearity and large deformation of the arterial wall [16].

Discussion

We have presented experimental evidences of RSD in the coronary arteries in this study. We found that the RSD assessed by measurements of the RSA can vary greatly along the length of the coronary artery. Opposing residual shear directions between adjacent sections served as a noteworthy finding. A previous study that tracked the in-vivo twisting of the coronary arteries, including the LADCA, on beating hearts found adjacent sections of the arteries twisted in opposing directions, forming complex transition zones [5]. The opposing in-vivo twists may serve to explain the opposing residual shear directions found in this study, furthering our speculation that RSD is a compensatory development that serves to normalize or reduce the intramural shear stresses induced by torsional loads on the artery. However, correlating the direction of residual shear and local twists at the same spatial location poses a greater challenge. To do so would require in-vivo measurements of the axial twists, using techniques such as biplanar angiography [6–8], at designated axial locations, then excising the artery and measuring the RSA at those same locations.

Kinematics. We proposed that the stress-free configuration of the coronary artery consists of a series of concentric, infinitesimally thin cylindrical shells, each with a unique axial length and radius. These cylinders undergo axial and circumferential

stretches as well as axial twists as they are assembled into a continuous traction-free tube, and the incompatibility of the layers during assembly results in residual stresses. It is apparent that the infinitesimal cylinder configuration is experimentally intractable. As a result, we must approximate the stress-free configuration by making independent stress-relieving cuts. The deformations from each independent cut would then be mapped into a single traction-free configuration.

The central assumption of this study is that the residual twist (Γ^*) does not exhibit transmural variations. This may be true if the artery is subjected to a constant twist angle throughout its growth and development (i.e., as each infinitesimal cylindrical shell is laid down during growth and development, the angle of twist for each shell is preserved). Since the axial twists are primarily induced by the cardiac motions, this assumption may be valid if there is consistent growth and deformation of the heart during maturation as well [17].

The presence of RSD could suggest nonaxisymmetric alignments of the coronary arterial ECM, particularly of the collagen fibers. It is known that arterial collagen undergoes constant and rapid turnovers, on the order of weeks [13]. The cyclic twisting of the coronaries may allow for nonaxisymmetric depositions of new collagen fibers. This hypothesis can be tested by imaging the collagen fibers across the length of coronary arteries using techniques such as two-photon excitation microscopy [18–20]. RSD also suggest that the artery should exhibit a nonaxisymmetric deformation when subjected to unconfined loading conditions. Indeed, Carboni et al. observed this when they measured the twisting of the circumflex coronary artery under axially unconfined conditions. They found that the arteries can rotate both clockwise and counterclockwise with pressurization [21], although the shear stretch due to the rotation was significantly less than the in-plane stretches due to circumferential and axial elongations.

Limitations. There are several limitations of this study. First, we utilized material parameters found in the literature for the stress analysis. Although these material parameters were determined for the LADCA, they were solved with the consideration of only a single circumferential opening angle (Θ_o), while the present study considered both LRD and RSD in addition. Future works will need to refit the material parameters using the proposed kinematic framework and new experimental measurements. Nonetheless, we believe that the literature parameters serve as a suitable starting point for this preliminary analysis, given that the required boundary conditions are reasonably satisfied.

Second, the RSA measurement techniques can be improved. In this study, the axial strips were taken from one continuous circumferential location. Circumferential variations should be investigated by cutting strips around the circumference of the artery. In addition, by cutting long axial strips and measuring only one RSA per section may have reduced the ability to observe any significant axial trends. The difficulty in sampling more axial locations lies in the need to properly orientate the helical configuration to the camera plane. Therefore, future experiments should include a method to stabilize the helical shapes during imaging.

Third, in this study, the artery was assumed to be in a passive state, absent of smooth muscle cell (SMC) tone. It has been shown that SMC tone can affect the circumferential residual strains and further reduce the circumferential stress gradient in an artery's loaded configuration [22]. Thus, future studies should explore the relationship between SMC tone and RSS.

With these limitations in mind, this study presents the first evidences of residual shear deformations in blood vessels. Thus far, we have observed RSD in the coronary arteries, a vasculature that is subjected to consistent, large cyclic twisting motions. We have proposed a kinematic framework that can incorporate multi-axial residual deformations in order to better predict the in-vivo

mechanical environment of the artery. The findings of this study further the basic understanding of arterial mechanics.

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