WALL SHEAR STRESS VERSUS WALL TENSILE STRESS: TWO IMPORTANT BIOMECHANICAL METRICS

To the Editor:

My coauthors and I appreciate DeCampi's insightful commentary,¹ entitled "Avoiding the Fate of King George II: Are We Making Progress?" and published with our own article,² "Predissection-Derived Geometric and Distensibility Indices Reveal Increased Peak Longitudinal Stress and Stiffness in Patients Sustaining Acute Type A Aortic Dissection: Implications for Predicting Dissection," in the August 2019 issue of the *Journal*. We found DeCampi's thorough review of wall shear stress (WSS) to be valuable in highlighting this biomechanical parameter as a potentially important factor in helping to improve understanding of aortic dissection, a clearly multifactorial disease. Indeed, previous work from our team applied computational models to estimate WSS in the setting of bicuspid aortic valve (BAV)-associated aortopathy.³ Our 2-way fluid-structure interaction analyses generated estimates of WSS that along with blood pressures, were found to differ in patients with different aortic valve morphologies. Other expert groups have made important contributions with 4-dimensional magnetic resonance imaging to evaluate WSS in ascending aortic aneurysms and type A aortic dissection. Regional elevations in WSS differed on the basis of BAV morphotype with higher WSS in the right anterior region and right posterior region of the aortic wall for patients with right-left BAV and right-noncoronary BAV, respectively.⁴ Severity of aortic stenosis was found to correlate with WSS magnitude and variability, regardless of valve phenotype.⁵ Evidence of extracellular matrix dysregulation localized to areas of heightened WSS has also been demonstrated.^{6,7} We agree with DeCampi's assertion that WSS in aneurysm may be helpful for assembling the complex mechanistic puzzle of aortic dissection. We contend that there are likely to be other important pieces, notwithstanding additional biomechanical forces at play within the aortic wall that govern dissection potential.

FIGURE 1. Ascending aortic longitudinal stress maps of predissection CTAs with the discerned location of dissection as determined by preoperative CTA overlaid in black. (Color scale correlates with degree of longitudinal stress and stiffness, see reference 2.)

To this point, we need to clarify that we did not "calculate and map WSS," as stated in DeCampi's commentary¹ on our study.² Rather, we derived estimates of wall *tensile* stress to acquire new knowledge pertaining to in vivo aortic biomechanics in the human ascending aorta. Wall tensile stress pertains to stress within the aortic wall and is mediated by the distention of the aorta as a result of blood pressure. This stress acts within the aortic wall and stretches the wall tissue to accommodate aortic shape change during the cardiac cycle.^{3,8} Wall tensile stress is therefore distinct from WSS, which arises as a result of the friction of flowing blood against the luminal surface of the aortic wall. Transthoracic echocardiography and computed tomographic angiography are therefore facile, noninvasive methods to derive and make useful new information on in vivo aortic wall biomechanics in patients before a dissection event occurs, thus opening up potentially impactful strategies for aortic risk mitigation.

We assert that noninvasive imaging-derived in vivo biomechanical metrics such as WSS^{2,6} and longitudinal wall tensile stress² when considered alongside other important parameters in the aortic wall reported by our group and others, including but not limited to matrix microarchitectural features and extracellular matrix remodeling,⁹⁻¹² cellular function,^{13,14} and tensile and delamination strength,¹⁵⁻¹⁸ could be used in concert for making more accurate determinations of dissection risk (eg, Figure 1).

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REPLY: THE STRESSES OF CARDIOVASCULAR MECHANICS

Reply to the Editor:

We had the opportunity to read DeCampi's commentary¹ on a recently published study in the *Journal* by Emerel and colleagues from the University of Pittsburgh.² We had also written an accompanying commentary³ to this study. Although we expressed some critiques in our commentary, we agree with Gleason's response to DeCampi's commentary. The original study examined and compared "axial normal" and "circumferential normal" aortic stresses with respect to risk prediction for thoracic aortic dissection, as we indicated in our commentary,³ in contrast to shear stresses.

In continuum mechanics, there are 2 types of forces that require contact between materials: *normal* and *shear* forces. Normal forces act *through* surfaces (ie, *perpendicular* to the surface), whereas shear forces act *along* surfaces (ie, *parallel* to the surface). A *stress* is defined as a force *per unit area*; and *pressure* is the mean normal stress. In 3 dimensions, the totality of stresses on an object is expressed in the Cauchy stress tensor,⁴ τ_{ij} , a 3×3 matrix in which each of the 9 terms is a type of stress, with *i* and *j* denoting row and column, respectively (Figure 1). In cylindrical coordinates, these are σ_{rr} , $\tau_{r\theta}$, τ_{rz} (first row, left to right); $\tau_{\theta r}$, $\sigma_{\theta\theta}$, $\sigma_{\theta z}$ (second row, left to right); and τ_{zr} , $\tau_{z\theta}$, τ_{zz}

FIGURE 1. A depiction of the components of the Cauchy stress tensor on a cylindrical object, in cylindrical coordinates. A segment of aortic wall is depicted. The normal stresses are denoted as σ , with *solid lines*. σ_{rr} is the radial normal stress acting *through* the aortic wall from the inner to outer surface of the aorta and thus *along* a radius from the centerline. It is always orthogonal to both (1) the circumferential tangent line (for a circular cross section, this line will be tangential to the curvature of the wall) and (2) the axial tangent line (for a rectangular cross section, this line will be axially oriented). The other 2 normal stresses act along these lines. $\sigma_{\theta\theta}$ is the circumferential "hoop" normal stress acting through the circumferential wall thickness and along the line instantaneously tangential to the curvature of the wall. σ_{zz} is the axial normal stress acting through the axial wall thickness and along the length of the aorta. The shear stresses are denoted as τ , with *dashed lines*. These act *along* (parallel to) rather than *through* (perpendicular to) the aortic surfaces.