Dr Gleason serves on Abbott's Medical Advisory Board and is the national principal investigator of an Abbott and Cytosorbents clinical trial unrelated to this work. His institution receives research support from Medtronic and Boston Scientific. None of these sources of commercial support are related to this work.

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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.

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(third row, left to right). The symbols σ and τ are used to distinguish the normal and shear components, respectively. It can be appreciated that the normal stress terms in the stress tensor are defined as those when $i = j$. Emerel and colleagues² are comparing the $\sigma_{\theta\theta}$ (the circumferential normal, aka “hoop,” stress) with σ_{zz} (the axial normal stress), which they newly identified as relating to dissection risk.

Our literature is replete with the phrase “shear stress” with regard to the aorta. Emerel and colleagues² have offered a different, and perhaps more pertinent, perspective on aortic wall stress.

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REPLY FROM THE AUTHOR: WALL STRESS, WALL SHEAR STRESS, TENSILE STRESS, NORMAL STRESS, LONGITUDINAL STRESS, ETC

Reply to the Editor:

Agnosco fateor! (“I admit I was wrong,” as Guillaume Budé wrote to Erasmus.¹) Gleason’s letter is correct—I mistook the designation of “wall stress” (the expression used by Emerel and colleagues² in their original article) to mean “wall shear stress.” As such, in the description of their principal findings in my Commentary,³ readers should replace the expression “wall shear stress” or “WSS” with “wall stress.”

Figure 1 shows all the possible stresses acting on an element of a solid body. There are 9 of them! Mathematically, they form a second-order tensor—a generalization of the force vector in simple mechanics. It is important to keep track of them, preferably with standard nomenclature in a given application.

The distinction among them is important. In the context used by the Emerel and colleagues,² “wall stress” is the stress that tends to distend the aorta when the lumen is pressurized with blood. The pressure, or force per unit area, acts perpendicular to the wall. Think of the Laplace law. Wall shear stress, on the other hand, is the force per unit area exerted on the wall (and parallel to it) by flowing blood. This force is like friction and arises from the viscosity of blood. As Gleason states in his letter, both stresses may play a role in producing aortic pathology. Excess “pressure” stress may act directly on the integrity of the connective tissues comprising the wall. Inappropriate wall shear stress may affect the integrity and signaling of

FIGURE 1. Mechanical stress is not a scalar or a vector. It is a tensor with 9 components.