Transesophageal echocardiographic strain imaging predicts aortic biomechanics: Beyond diameter

Alexander Emmott, MEng,[a,b] Haitham Alzahrani, MD,[c] Mohammed Alreishidan, MD,[c] Judith Therrien, MD, FRCPC,[d] Richard L. Leask, PhD,[a,b] and Kevin Lachapelle, MD, FACS, FRCSC[c]

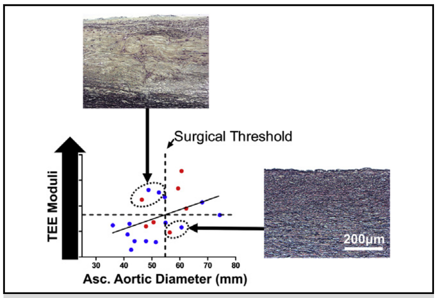
ABSTRACT

Background: Clinical guidelines recommend resection of ascending aortic aneurysms at diameters 5.5 cm or greater to prevent rupture or dissection. However, approximately 40% of all ascending aortic dissections occur below this threshold. We propose new transesophageal echocardiography strain-imaging moduli coupled with blood pressure measurements to predict aortic dysfunction below the surgical threshold.

Methods: A total of 21 patients undergoing aortic resection were recruited to participate in this study. Transesophageal echocardiography imaging of the aortic short-axis and invasive radial blood pressure traces were taken for 3 cardiac cycles. By using EchoPAC (GE Healthcare, Madison, Wis) and postprocessing in MATLAB (MathWorks, Natick, Mass), circumferential stretch profiles were generated and combined with the blood pressure traces. From these data, 2 in vivo stiffness moduli were calculated: the Cardiac Cycle Pressure Modulus and Cardiac Cycle Stress Modulus. From the resected aortic ring, testing squares were isolated for ex vivo mechanical analysis and histopathology. Each square underwent equibiaxial tensile testing to generate stress-stretch profiles for each patient. Two ex vivo indices were calculated from these profiles (energy loss and incremental stiffness) for comparison with the Cardiac Cycle Pressure Modulus and Cardiac Cycle Stress Modulus.

Results: The echo-derived stiffness moduli demonstrate positive significant covariance with ex vivo tensile biomechanical indices: energy loss (vs Cardiac Cycle Pressure Modulus: $R^2 = 0.5873$, $P < .0001$; vs Cardiac Cycle Stress Modulus: $R^2 = 0.6401$, $P < .0001$) and apparent stiffness (vs Cardiac Cycle Pressure Modulus: $R^2 = 0.2079$, $P = .0378$; vs Cardiac Cycle Stress Modulus: $R^2 = 0.3575$, $P = .0042$). Likewise, these transesophageal echocardiography–derived moduli are highly predictive of the histopathologic composition of collagen and elastin (collagen/elastin ratio vs Cardiac Cycle Pressure Modulus: $R^2 = 0.6165$, $P < .0001$; vs Cardiac Cycle Stress Modulus: $R^2 = 0.6037$, $P < .0001$).

Conclusions: Transesophageal echocardiography–derived stiffness moduli correlate strongly with aortic wall biomechanics and histopathology, which demonstrates the added benefit of using simple echocardiography-derived biomechanics to stratify patient populations. (J Thorac Cardiovasc Surg 2018;■:1-10)



TEE moduli can predict aortic pathology that aortic size cannot.

Central Message

TEE-derived stiffness moduli can identify abnormal aortic mechanical properties that diameter-based guidelines cannot.

Perspective

Current clinical guidelines assume that there is a critical aortic diameter at which the risk of catastrophic tissue failure increases dramatically. Aortic dilation is a hallmark of the disease but does not represent an intrinsic tissue material property. We have shown that TEE stiffness moduli correlate with ex vivo mechanical indices and can identify patients with pathological wall remodeling.

See Editorial Commentary page XXX.

ET

From the [a]Department of Chemical Engineering, and [c]Department of Surgery and [d]Division of Cardiology, Royal Victoria Hospital, McGill University, Montreal, Quebec, Canada; and [b]Research Centre, Montreal Heart Institute, Montreal, Quebec, Canada.

This work is supported by a Natural Sciences and Engineering Research Council of Canada grant. A.E. is supported by a McGill Engineering Doctoral Award.

Received for publication Nov 8, 2017; revisions received Jan 9, 2018; accepted for publication Jan 16, 2018.

Address for reprints: Kevin Lachapelle, MD, FACS, FRCSC, Cardiac Surgery Department, McGill University Health Centre–Glen Site, 101 Boul. Decarie, C07-1284, H3A 3J1 Montreal, Quebec, Canada (E-mail: kevin.lachapelle@mcgill.ca).

0022-5223/$36.00

https://doi.org/10.1016/j.jtcvs.2018.01.107

Abbreviations and Acronyms

AA = ascending aortic
CCPM = Cardiac Cycle Pressure Modulus
CCSM = Cardiac Cycle Stress Modulus
TEE = transesophageal echocardiography

Scanning this QR code will take you to the supplemental figures and video for this article.

Acute dissection and rupture are usually fatal complications of aortic aneurysms, and prevention is only possible with surgical intervention before these acute complications. Presently, all guidelines use the maximum aortic diameter as the decisional criterion for surgical intervention.[1,2] Unfortunately, approximately 40% of patients who present with dissection have aortic diameters below surgical criteria.[3] Accordingly, novel criteria are needed to identify those who are at risk of dissection or rupture.

Ascending aortic (AA) aneurysms result from pathological remodeling of the vessel wall.[4] Thinning and fragmentation of elastic lamellae, deposition of collagens, and accumulation of extracellular glycosaminoglycans are the most common characteristics of nonsyndromic and nontraumatic aneurysm formation.[5-7] This extensive tissue remodeling alters the biomechanical properties of the aorta.[8,9] Aortic rupture and dissection occur as the result of a loss of mechanical integrity of the vessel wall. Notably, ex vivo mechanical measures of AA tissue, such as stiffness, energy loss, and ultimate strength, have been shown to vary with tissue remodeling. Stiffness[10,11] and energy loss[12,13] both increase with pathological remodeling, whereas strength of the aorta decreases.[11] These changes in biomechanics were demonstrated using the ex vivo stress-strain relationship based on testing of resected tissue. Reliably estimating these metrics in vivo would provide more information for surgical decision-making.

Dynamic echocardiography is routinely used to assess cardiovascular function because of its high temporal resolution without the need to expose patients to contrast agents or ionizing radiation. Dynamic speckle-track strain-imaging of the aorta is an attractive approach to translate the measurement of tissue mechanics from a postoperative ex vivo analysis to a preoperative in vivo assessment.

Previous studies have suggested that aortic stiffness can be deduced from echo strain-imaging.[14-18] Indeed, transesophageal echocardiography (TEE) studies have revealed that the aortic wall of a subset of patients with bicuspid aortic valve[14] and patients aged less than 50 years[16] is less stiff than those with tricuspid aortic valve or aged more than 50 years. However, no direct comparison between intrinsic risk factors, including ex vivo mechanics and underlying wall pathology, has been made.

In this study, we demonstrate that speckle-tracking echocardiography can reliably estimate the biomechanics of aortic tissue obtained ex vivo. Specifically, we used preoperative TEE strain imaging of the aorta with concurrent blood pressure tracing to calculate 2 new stiffness moduli of the aortic wall, which were then compared with ex vivo mechanical analysis and tissue histopathology in patients undergoing aortic resection.

MATERIALS AND METHODS

Study Cohort

In compliance with the Canadian tri-council policy statement on ethical conduct for research involving humans, informed consent was obtained from 21 patients undergoing elective aortic valve or aortic resection surgery. AA diameters ranged from 3.6 to 6.1 cm, that is, from mild to severe dilation.

Ex Vivo Tensile Analysis

A specimen of the aortic ring was obtained for each patient immediately after resection, clipped for anatomic orientation, and stored in physiologic saline at 4°C until further processing and testing. The maximum aortic diameter was measured for each ring before sectioning four $1.5 \times 1.5\ cm^2$ testing squares, equally distributed around the circumference of the aorta representing the 1-anterolateral wall, 2-posterolateral wall, and the 3-inner and 4-outer curvature. Five unique thickness measurements were taken for each testing square using a Mitutoyo Litematic VL-50A constant force digital micrometer (Mitutoyo Corp, Kanagawa, Japan). The testing squares were then connected to an EnduraTEC ELF 3200 planar biaxial tensile tester (Bose, Eden Prairie, Minn) using hooked 4-0 silk sutures in a 37°C bath of Ringer's lactate solution. The testing squares were oriented for equibiaxial stretching along their circumferential and longitudinal axes. Each sample was preconditioned for 7 cycles (ie, stretch and relaxation) followed by 3 cycles of data acquisition at a constant displacement rate of 0.1 mm/s in the range of 0% to 60% strain. The resultant stress-strain relations were analyzed using MATLAB (vR2014a; MathWorks, Natick, Mass). More detailed tensile methodology using this setup has been described previously.[10,13,19,20]

Circumferential ex vivo energy loss and stiffness were calculated from the circumferential engineering stress-strain relation. Energy loss is the percentage of elastic energy needed to stretch the testing square that is dissipated when the tissue is relaxed. The physiologic interpretation of energy loss is the percent loss of elastic recoil energy in the tissue that is not returned to blood flow (ie, maintaining normal Windkessel function). Its physical definition is the ratio of the area between the loading and unloading curve over the area under the loading curve (Figure 1, *A*). Because aortic tissue has a nonlinear stress-strain curve (Figure 1, *A*), stiffness is defined as the slope of a line tangent to the stress-strain loading curve; formally, this parameter is the apparent elastic modulus (defined at 50% strain) and has been reported previously to describe aortic stiffness in humans.[12,13]

Transesophageal Echocardiographic Strain Imaging

All TEE imaging was performed at the time of surgery, after administered anesthetic but before the sternotomy, using a GE Vivid 7

ET