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Review

Biomechanics of the Ascending Thoracic Aorta: A Clinical Perspective on Engineering Data

Alexander Emmott, MEng,[a,b] Justine Garcia, MEng,[b,c] Jennifer Chung, MD, MSc,[d]
Kevin Lachapelle, MD, FRCSC,[d] Ismaïl El-Hamamsy, MD, PhD, FRCSC,[b,e]
Rosaire Mongrain, PhD,[b,c] Raymond Cartier, MD, FRCSC,[b,e] and Richard L. Leask, PhD[a,b]

[a] *Department of Chemical Engineering, McGill University, Montreal, Quebec, Canada*
[b] *Research Center, Montreal Heart Institute, Université de Montréal, Montreal, Quebec, Canada*
[c] *Department of Mechanical Engineering, McGill University, Montreal, Quebec, Canada*
[d] *Division of Cardiac Surgery, Royal Victoria Hospital, Montreal, Quebec, Canada*
[e] *Division of Cardiac Surgery, Montreal Heart Institute, Université de Montréal, Montreal, Quebec, Canada*

ABSTRACT

Aneurysms of the ascending thoracic aorta often require prophylactic surgical intervention to resect and replace the aortic wall with a synthetic graft to avoid the risk of dissection or rupture. The main criterion for surgical intervention is the size of the aneurysm, with elective surgery recommended with a maximal aortic diameter of 4.2-5.5 cm depending on valve type and other patient risk factors. Although the risk of dissection and rupture increases with the size of aneurysm, different pathologies, including aortic valve phenotype and connective tissue disorders uniquely influence the mechanical dysfunction of the aortic wall. Dissection and rupture are mechanical modes of failure caused by an inability of the tissue to withstand local tissue stresses. Tensile testing of aortic tissues, therefore, has been used to reveal the mechanical parameters of diseased and healthy tissues to better characterize the mechanical function of aortic tissues in different

RÉSUMÉ

Les anévrismes de l'aorte thoracique ascendante exigent souvent une chirurgie prophylactique pour réséquer et remplacer la paroi de l'aorte par un greffon synthétique afin d'éviter le risque de dissection ou de rupture. La recommandation d'une intervention chirurgicale non urgente repose principalement sur la taille de l'anévrisme dont le diamètre aortique maximal est de 4,2-5,5 cm selon le type de valve et les autres facteurs de risque du patient. Bien que le risque de dissection et de rupture augmente en fonction de la taille de l'anévrisme, les différentes pathologies, y compris le phénotype de la valve aortique et les anomalies du tissu conjonctif, influencent uniquement le dysfonctionnement mécanique de la paroi de l'aorte. La dissection et la rupture sont des modes mécaniques de l'insuffisance causée par une incapacité du tissu à résister aux stress tissulaires locaux. Par conséquent, des essais de traction sur les tissus aortiques ont été

Aneurysms of the thoracic aorta have an incidence of approximately 10.4 per 100,000 person-years.[1] Aneurysms are often asymptomatic until they undergo dissection or rupture resulting in catastrophic hemorrhage, tamponade, and death. For patients lucky enough to make it to a hospital after a dissection or rupture, the in-hospital mortality (41%) is bleak.[2] Such nonelective ascending aorta replacements have a surgical mortality of 15%-24%, whereas elective replacement is much safer with an estimated surgical mortality of 3.4%.[3,4]

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Corresponding author: Dr Richard L. Leask, Department of Chemical Engineering, McGill University, 3610 University St, Montreal, Quebec H3A 2B2, Canada. Tel.: +1-514-398-4270; fax: +1-514-398-6678.
E-mail: richard.leask@mcgill.ca
See page 43 for disclosure information.

It is therefore not surprising that the number of prophylactic ascending thoracic aorta replacements has increased significantly in the past decade. The number of aortic replacements will continue to increase because of our aging population and improved cardiac imaging.[5]

Approximately 60% of thoracic aortic aneurysms (TAAs) involve the aortic root and/or ascending aorta.[6,7] Elective aortic resection and replacement by a synthetic graft is recommended at maximum ascending aortic diameters at a range of 4.2-5.5 cm, depending on etiology and need for concomitant cardiac surgery.[8-11] This metric of aortic size is derived from population studies that showed a hinge point increase in rates of complications at a diameter > 6 cm, where the yearly risk of rupture and dissection is approximately 4%.[12,13] The underlying biomechanical principle inferred is Laplace's Law, which states that the mechanical stresses increase in the vessel wall in proportion to the vessel diameter. This is very

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patient groups. In this review, we highlight the principles and methods of *ex vivo* tensile analysis as well as the composition and structural properties that contribute to the mechanical behaviour of the ascending aorta. We also present a clinically oriented description of mechanical testing along with insight into the characterization of aneurysm. Finally, we highlight recent advances in echocardiography, computer tomographic angiography, and magnetic resonance angiography that have the potential to measure biomechanical properties noninvasively and therefore help select aortas at risk.

utilisés pour révéler les propriétés mécaniques des tissus pathologiques et sains et mieux caractériser le fonctionnement mécanique des tissus aortiques chez les différents groupes de patients. Dans cette revue, nous soulignons les principes et les méthodes de l'analyse *ex vivo* en traction ainsi que la composition et les propriétés structurales qui contribuent au comportement mécanique de l'aorte ascendante. Nous présentons également une description axée sur l'aspect clinique de l'essai mécanique ainsi qu'un aperçu sur la caractérisation de l'anévrisme. Finalement, nous soulignons les récentes avancées en matière d'échocardiographie, d'angiographie par tomodensitométrie et d'angiographie par résonance magnétique qui ont le potentiel de mesurer de manière non invasive les propriétés biomécaniques et par conséquent d'aider à sélectionner les patients exposés au risque de dissection ou de rupture de l'aorte.

simplistic and fundamentally ignores the well documented remodelling of the vessel microstructure that occurs.[14-16] In fact, ascending TAA dissections often occur at less than the surgical threshold diameters, which suggests that size alone is insufficient to describe the mechanical integrity of the tissue.[17-19] Recent reports have suggested that the diameter cutoffs might be an overly aggressive approach and is almost certainly putting some patients unnecessarily at risk of surgical and early morbidity.[20-22] Understanding aortic biomechanics of TAA is key not only to better patient stratification for surgery but also to elucidating the mechanobiology of this deadly pathology.[23]

Ultimately, the cause of dissection or rupture in the ascending TAA is a mechanical failure of the vessel wall where the local stresses in the tissue exceed the mechanical integrity of the vessel. Mechanical testing of human tissue allows one to categorize and understand human tissues using the same engineering parameters that allow us to understand the mechanical behaviours of materials. In this article, we present the structural components and changes within the thoracic aorta, the mechanical principles behind current surgical guidelines, and testing methods that are currently used to characterize aortic tissues. We then review the state of our understanding of the structural and tensile properties of the ascending thoracic aorta (Supplemental Table S1) and currently available *in vivo* estimates of TAA biomechanics. In doing so, we hope to provide insight into the behaviour of normal and abnormal aortic tissue mechanics, which might provide a better framework than size alone, in selecting patients for surgery.

Mechanical Structure of the Ascending Aorta

Normal structure of the ascending aorta

The ascending aorta is the primary conduit for blood flow and the largest artery in the body. The ascending aorta contains 3 tissue layers, the intima lined by a single layer of endothelial cells, the elastic media, and the largely collagenous adventitia. The elastic media dominates the mechanical response of the ascending aorta, accounting for approximately 80% of the vessel thickness in normal ascending aortas. The media is comprised of alternating concentric layers of fenestrated elastic sheets, lamellae, and smooth muscle cells (SMCs) (Fig. 1A).[24] Within these sheets are interspersed collagens (types I, III, IV, and V), mucopolysaccharides, and an abundance of fibrillar matrix proteins.[24,25] The elastic lamellae and collagen fibrils (including adventitial collagens) define the passive elastic behaviour and the tensile strength of the tissue, respectively.[26] A mechanically normal ascending aorta, characterized by its distension and recoil, allows the vessel to store

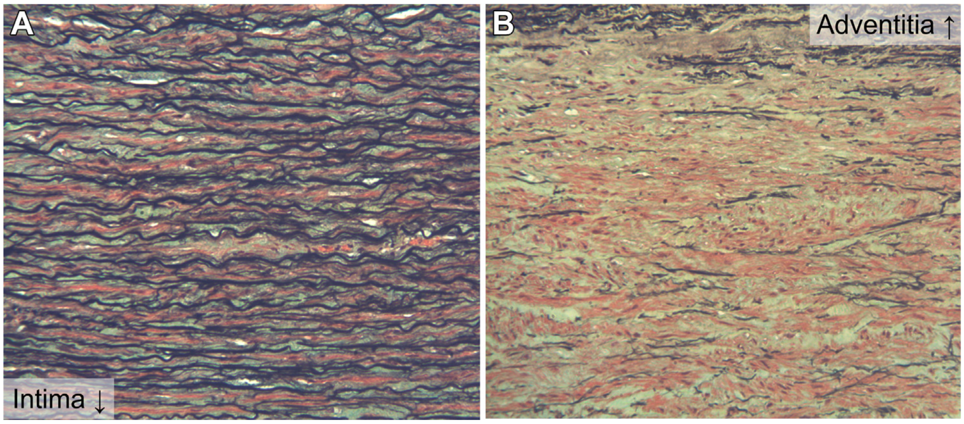

Figure 1. Histopathology of the ascending aorta using Movat pentachrome staining in (**A**), a 52-year-old man with a nondilated ascending aorta, and (**B**), a 51-year-old man with a 5.8-cm dilated ascending thoracic aortic aneurysm. **Black** indicates elastin; **red/purple**, smooth muscle cells; **blue**, mucopolysaccharides; and **yellow**, collagens.