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Development and testing of a silicone *in vitro* model of descending aortic dissection

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ABSTRACT

Background: Stanford type B dissection of the descending aorta is a potentially fatal condition that is poorly understood. Limited scientific understanding of the role of current interventional techniques, as well as heterogeneity in the condition, contributes to lack of consensus as to the most effective treatment strategy. This study introduces an anatomically accurate model for investigating aortic dissection in a laboratory setting.

Materials and methods: A silicone model was fabricated and filled with fluid to mimic human blood. Flow was established, and the model was scanned using a four-dimensional flow magnetic resonance imaging protocol. On analysis, luminal flow rates were quantified by multiplying local velocity by included area.

Results: The upstream total flow was compared with the sum of the flow in the true and false lumens. The two values were within the margin of error. Furthermore, flow rates matched with the relative areas of each compartment.

Conclusions: These results validate our model as a novel and unique system that mimics a type B aortic dissection and will allow for more sophisticated analysis of dissection physiology in future studies.

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1. Introduction

1.1. Pathophysiology and management of aortic dissection

Aortic dissection is a tearing of the aortic wall, typically between intimal and medial layers. This tearing may be due to ischemic injury and effacement of the normal lamellar structure of the aortic wall [1,2]. Once a tear has been initiated, blood flows into the space between aortic layers creating two distinct flow lumens, propagating the dissection in various directions along the aorta. There is usually an "entry tear" at the start of the dissection and a variable number of "reentry tears" along the aorta that allow communication between the two lumens.

Patients with type B dissections are generally treated medically unless clinical suspicion prompts endovascular intervention. Such interventions include placement of thoracic stent grafts to occlude tear sites and obliterate false lumen flow, fenestration of intimal flaps to allow perfusion of occluded vessels, and branch vessel stenting [3–5]. These various techniques may be combined, depending on the needs of the given patient.

Medically managed patients have poor long-term outcomes, however, with complications including false lumen aneurysmal dilation, need for aortic intervention, and significant mortality rates in the first 3 y [6–8]. Currently, there is limited understanding of the fluid mechanics underlying these clinical outcomes. Flow patterns, pressure, shear rates, and luminal volumes are difficult to measure. The effects of these variables on dynamic dissection flap movement, occlusion of distal branch vessels, and long-term aneurysmal degeneration are not well described. This scarcity of data may be supplemented by use of a model system in which these parameters can be studied. We present initial data from a novel silicone model that replicate type B aortic dissections and use four-dimensional phase-contrast magnetic resonance imaging (4D PC-MRI) techniques to measure flow parameters.

1.2. Phase contrast MRI

Four dimensional PC-MRI is a technique for determining the velocity of moving fluid in an MR scan. When a proton spin is subjected to a magnetic field gradient, any motion in the direction of the gradient will induce a phase shift proportional to the in-plane velocity. A pair of magnetic field gradients is applied sequentially to the coil to provide a phase-differential image [9]. The differential mode signal eliminates static components of the MR image. Flow rates can then be calculated based on the measured velocity profiles. This technique is currently being used in patients to interrogate aortic flow dynamics without invasive procedures [10,11].

1.3. Flow division model

Because of the flow division present in a dissected aorta, the pathology can be modeled as two flows in parallel initiating from a common node. This can be described in similar terms as an electric circuit with resistive elements, illustrated in Figure 1. Because mass, and hence flow rates, must be conserved, the individual flows in each branch of the conduit must add to the total flow entering the node, and the pressure drops across both branches must be equal. In addition, the branch resistances can be added together as resistances in parallel, yielding the following overall resistance:

$$R_{tot} = \left(\frac{1}{R_T} + \frac{1}{R_F}\right)^{-1} = \left(\frac{R_F}{R_T R_F} + \frac{R_T}{R_T R_F}\right)^{-1} = \left(\frac{R_F + R_T}{R_T R_F}\right)^{-1} = \frac{R_T R_F}{R_F + R_T}$$

where R_{tot} is the total resistance, R_F is the false lumen resistance, and R_T is the true lumen resistance. Because the pressure drop across the branches must equal the product of resistance and flow rate, expressions for the branch flow rates can be determined as follows:

$$\Delta P = Q_{tot} R_{tot} = Q_{tot} \frac{R_T R_F}{R_F + R_T} = Q_F R_F = Q_T R_T$$

$$\frac{Q_F}{Q_{tot}} = \frac{R_F R_T}{(R_F + R_T) R_F} = \frac{R_T}{R_F + R_T}$$

Furthermore, Poiseuille's law states that the resistance of a conduit of circular cross section is inversely proportional to the radius raised to the fourth power, and therefore, its area squared [12,13]. Thus, assuming that the branches have circular cross section, and that the impedance of conduits are purely resistive (i.e., rigid), the flow ratios can be rewritten as follows:

$$\frac{Q_F}{Q_{tot}} = \frac{\frac{1}{A_T^2}}{\frac{1}{A_F^2} + \frac{1}{A_T^2}} = \frac{\frac{1}{A_T^2}}{\frac{A_T^2 + A_F^2}{A_F^2 A_T^2}} = \frac{A_F^2}{A_T^2 + A_F^2}$$

yielding an expression for the flow rate based on the cross-sectional areas of the respective branches.

1.4. Objective and hypothesis

We seek to recapitulate human aortic anatomy and create a silicone model of a type B dissection. As opposed to previous work in the field [14,15], this model possesses a compliant, mobile intimal flap and anatomically accurate entry tears and dimensions. It is predicted that this model will demonstrate basic flow conservation and that the PC-MRI data can be used to successfully interrogate flow dynamics in the dissected aorta.

2. Methods

2.1. Model fabrication

Clinical computed tomography images of human aorta were acquired, segmented, and reconstructed to form three-dimensional models *in silico*. These were subsequently used to rapidly prototype molds for fabrication of silicone models. A two-mold process was used to produce silicone models with intimal flaps that could be distended. First, a 0.5-mm intimal