ABSTRACT

Brain aneurysms, aortic aneurysms, and cardiac valve replacement are amongst the top three vascular diseases currently treated by the minimally invasive, transcatheter deployment of medical devices (called endovascular or interventional radiology treatment). Several devices such as stents and coils for brain aneurysms, stent-grafts for aortic aneurysms, and stent valves for cardiac valves, are available on the market. The primary limitation of all these devices is non-optimal or 'incomplete' treatment causing recanalization in brain aneurysms, endoleaks in aortic aneurysms, and paravalvular leaks in cardiac valves. These problems are primarily due to improper 'fit' of the device structure to the patient anatomy causing poor apposition or sealing, thereby providing a poor scaffold for vascular remodeling (re-endothelialization) around the implanted device. Overall, therefore, the primary limitation of current endovascular treatment is non-optimal device structure compared to patient vascular anatomy.

The long-term goal of our project is to use advanced computational tools to shift the paradigm from mass-production of medical devices to personalized, patient-matched devices (PMDs) that are optimized to treat each specific individual's pathology. The computational tools to be developed are based on Topology Optimization (TO) of deployable structures. TO is a computational methodology which recasts design problems as material distribution problems such that the algorithm finds an efficient structure that fulfills functional requirements quantified by objective and constraint functions in the optimization scheme. TO thus 'builds' from the bottom-up by adding or removing material at each point in space according to the defined functions and the resulting structures are organic/natural as opposed to structures that are designed top-down by traditional engineering approaches. As endovascular treatment always involves delivery of devices via catheters, the devices must be deployable structures that 'open-up' to conform to the diseased vascular segment as they exit the catheter. Computational conformal mapping involves mathematical techniques that allow for the transformation of complex geometries into simpler ones without altering their essential features. Such mapping could be integrated with topology optimization to enable the design of deployable medical devices as they transition from a collapsed state within the catheter to an expanded state within the vascular segment. Such simulations of topology-optimized deployable structures using conformal mapping have not yet been conducted. The project also facilitates translational research because the regulatory framework for PMDs is currently incipient. By generating topology optimized PMDs for different vascular anatomies, we can define a design envelope for the devices, which will be needed to develop the regulatory approval process.

The goal of this OVPR seed grant is to develop a simulation methodology for topology optimization of deployable structures for the design of patient-matched devices to treat brain aneurysms. We will achieve this goal via two Aims:

Aim 1: Topology optimization to generate device designs in patient-specific aneurysm geometries.

Aim 2: Topology optimization of deployable structures using conformal mapping to enable transcatheter device delivery.

Thus, by the end of this seed grant, we expect to have developed a computational framework that not only optimizes the design of deployable medical devices but also accounts for the unique anatomical features of individual patients. This framework will serve as a strong justification for the submission of external funding applications.