Proceedings of the 2020 Design of Medical Devices Conference
DMD2020
April 6, 7-9, 2020, Minneapolis, MN, USA

DMD2020-9071

USING COMPUTATIONAL MODELING DERIVED FROM MICRO CT SCANNING FOR THE POST-IMPLANT ANALYSES OF VARIOUS CARDIAC DEVICES

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ABSTRACT

There are few medical devices currently utilized that have not had, at the very least, a second iteration. Medical device companies continually strive to improve their product to make it the best on the market. Medical devices are often optimized by defining the size of the device, making it more efficient and/or improving the device to tissue interface. Using the capabilities of the Visible Heart® Laboratories various cardiac devices can be implanted in reanimated swine and human hearts for the assessment of the various aforementioned parameters. After the implantation of these devices and assessment in functional anatomies, specimens were perfusion-fixed and then a micro-CT scanner was utilized to take high-resolution scans of the resultant device and tissue interfaces. These scans are used to generate high-resolution (~20 microns) 3D models of the numerous implanted devices, measurement analyses, device simulations, and the creation of virtual reality scenes. All can then be used for detailed visual analyses. These abilities to render high-resolution models will allow medical device designers to closely evaluate their designs, in order to optimize their next iterations.

Keywords: *Micro-CT, Modeling, Stenting, Valve replacement, Pacemakers*

NOMENCLATURE

CT	Computed Tomography
µCT	Micro Computed Tomography
DES	Drug-Eluting Stents
DICOM	Digital Imaging and Communications in Medicine
MRI	Magnetic Resonance Imaging
PCI	Percutaneous Coronary Intervention
TAVR	Transcatheter Aortic Valve Replacement

INTRODUCTION

In 2016, the Census Bureau concluded that $173.1 billion dollars were spent on medical devices in the United States alone. This number was projected to grow in the upcoming years due to the development of transcatheter implanted medical devices such as coronary stents, cardiac valves, closure devices and/or pacemaker technologies. Large amounts of research and development funding is directed towards future device iterations of these devices to miniaturize them, improve functionalities and/or device to tissue interactions. Within the Visible Heart® Laboratories, cardiac devices can be implanted in reanimated large mammalian hearts (including human) to assess function. Post-reanimation, these hearts are scanned using micro-CT to study the device/tissue interactions more closely.

Previously, our laboratory has performed post-device implantation imaging in cardiac specimens, using endoscopes, MRI and/or CT scans. Although these images can prove to be very useful, each had their limitations. For example, endoscopes only gathered video footage of superficial anatomy within the heart. MRI and CT scans provided DICOM files which can be evaluated using DICOM analysis software. However, these methods for scanning can have drawbacks. Specifically, isolated cardiac specimens used for MRI scanning, need to be held stationary and immobilized in agar gel (M Eggen et al., 2011). This procedure can potentially cause device movements or dislodgements when applying or removing the gel. Furthermore, an MRI scan has limited resolution and can be subject to artifact when imaging ferrous medical devices. CT imaging in a clinical scanner allows for resolution of about 0.35mm, but often require contrast injections to better identify anatomical structures. Additionally, while performing either MRI and CT scanning, the given specimen is in a fixed position, while the X-ray source and detector are spun 360 degrees around the specimen. In isolated heart models with multiple implanted devices, these scanning methods can cause numerous artifacts.

Our research group has routinely been utilizing the University of Minnesota's Geological Sciences' X5000 micro-CT scanner (North Star Imaging, Minneapolis Minnesota) to obtain images with fewer artifacts and with resolutions as low as 12 microns. With these resolutions, we can accurately isolate the critical features of an implanted device and closely examine how it interacts with the cardiac tissues (coronary, valves, atrial appendages, etc.), without device size limitations.

Methods

Our research group routinely reanimates large mammalian hearts using the Visible Heart® methodologies (Chinchoy et al. 2000). Occasionally, human hearts deemed not viable for transplantation, can also be reanimated using these methodologies. When hearts are reanimated, an array of cardiac devices can be implanted. After device implantations these hearts are preserved using a formalin fixation method (Anderson et al., 2009). Here we describe the study of reanimated and preserved hearts with coronary stents and artificial valves employing a micro-CT scanner.

The micro-CT scanner utilized in this work requires the specimen to be mounted on a fixed platform. The specimen spins 360 degrees at a rate of ~0.01˚/s during the scan for a total of 1500 projections all while the X-ray source and detector remain stationary, as seen in **figure 1**. This allows us to focus on a single device at a time preventing artifact from additional devices. The advantage of using perfusion-fixed specimens is that they maintain their end-diastolic anatomy, are not biological hazards, and the formalin can be rinsed out prior to scanning.

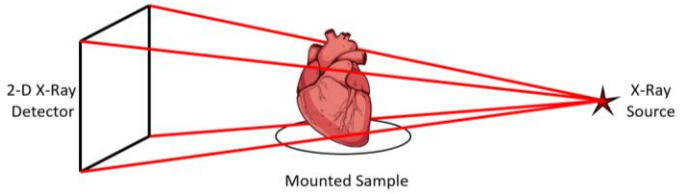

Figure 1. A simplified schematic of the micro CT layout during a scan.

When setting up scanner parameters, there are several main variables that need to be finalized before initiation. These variables are: 1) the scanner voltage (kV), 2) the current (mA) and 3) the focal spot diameter (µm); which all work in unity which as shown in **figure 2**.Voltages and currents are variables that can be changed, while the focal spot diameter is the resultant of the first two set variables. Since medical devices are typically made out of very dense materials, such as cobalt-chromium or nitinol, a high penetration voltage is needed. If there is insufficient power, the X-ray is unable to penetrate through the device to be discovered by the detector. However, if the power is excessive, it will easily penetrate through the tissue and will not be detected. Different focal spot diameters are needed depending on the materials the devices are composed of, while also allowing the cardiac tissues to be detected. For example, to retrieve high-resolution of coronary stent struts a resolution of about 20µm is needed, while a voltage of 170kV and 0.25mA current was found to detect both the stent and vessels while valves require a resolution around 25-30µm.

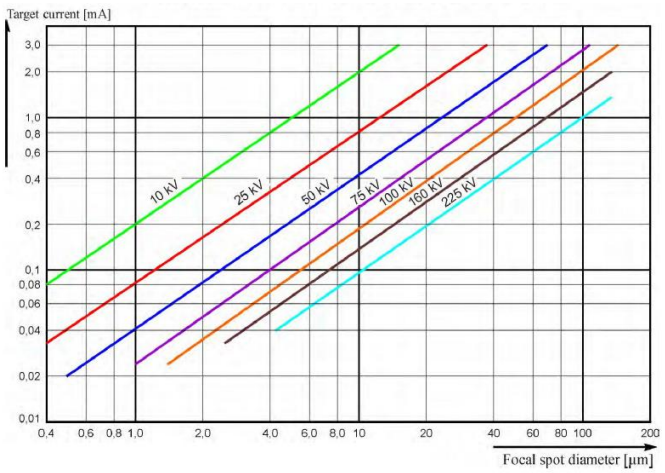

Figure 2. A chart provided in the NSI X5000 instruction manual showing the relationship between scanner voltage, current and focal spot diameter.

After scanning, the obtained images are reconstructed to create DICOM images similar to an MRI or CT scan, which are further analyzed using Mimics (Materialise, Belgium) software. A 3D surface model can be created on Mimics from the individual DICOM slices by stacking the 2D image data. Subsequently, these reconstructions can then be viewed through coronal, sagittal and transverse planes. Once these images are compiled into a surface model, "masks" can be created based on selected grayscale values of the given images. These values are based on the density of the specimen; i.e. tissues and medical devices will have vastly different grayscale values. The Mimics software provides predefined threshold sets, but custom thresholds can be made by filtering desired grayscale values in a bandpass-like approach to create a mask. These masks can be further manipulated; by manually removing or adding to each slice. By manipulating the created masks, we have been able to segment the various implanted medical devices from the tissue with high resolutions. Once all desired portions were segmented, these masks were then used to create 3D objects.

Results

Stenting

To date, over 50 porcine hearts have been reanimated and used to deploy coronary stents for the purpose of better understanding device to tissue interaction of various bifurcation techniques within the coronary arteries. **Figure 3** shows a two stent bifurcation technique (culotte) that was deployed in the left anterior descending coronary of a swine heart. Our group has scanned a subset of these bifurcation stenting cases, where both the devices and tissues were detected utilizing micro-CT. There is still over 70 bifurcation techniques to be scanned using these methodologies. The analyses of the initial scanned subset have begun laying the groundwork for a database of models that can be used for accurate measurements of stent struts, bifurcation

angles, and malapposition. These measurements can in turn be utilized for computational simulation work, designing the next generation of drug eluting stents, or optimizing bifurcation procedures.

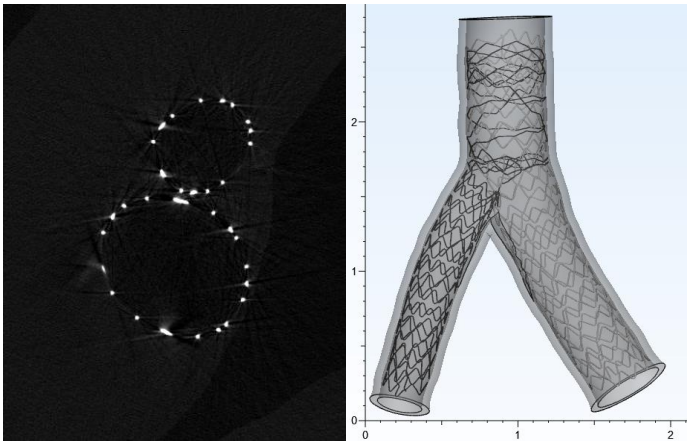

Figure 3. The larger main vessel and smaller side branch visualized distally from the bifurcation (left) and the final 3D model (in cm) showing stent/stent interaction and apposition (right).

Valves

In addition to coronary stenting, transcatheter aortic valve replacement (TAVR) procedures have been routinely performed in the lab. In one particular study, an Evolut R (Medtronic, Minneapolis, Minnesota) valve was implanted in a reanimated human heart (Sanchez et. al.,2019). To summarize, a heart with mild signs of aortic stenosis was deemed not viable for transplantation and was donated to the lab for research. The heart was reanimated using the Visible Heart® methodologies and the valve deployment was documented using multi-modal imaging modalities and subsequently perfusion fixed. This human heart and the implanted Evolut R valve were scanned in order to closely analyze the post-procedural frame deformations, as shown in **figure 4**.

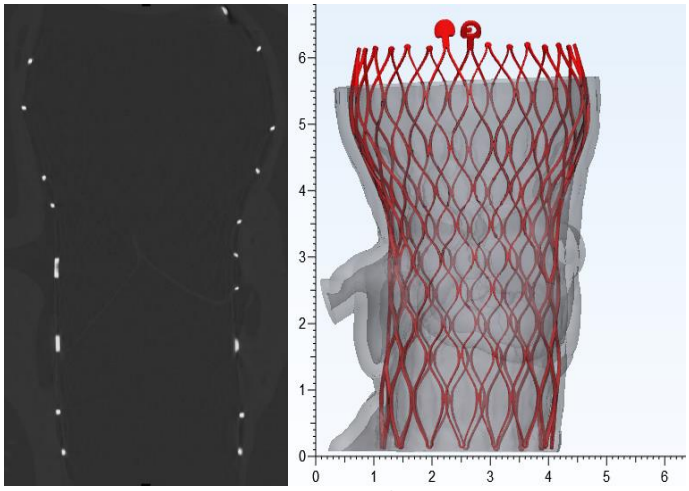

Figure 4. The native aortic valve and artificial valve were isolated during the scan (left) allowing for the creation of a 3D model (in cm) to be further analyzed (right).

Conclusions and Future Work

To date, we have numerous scans of various performed bifurcation techniques in both reanimated swine and human hearts; allowing us to better analyze and visualize the stent interactions within a given coronary vessel. These different techniques could also be examined to see how the strut metal and tissue interactions differ based on how they were deployed. Moving forward, these scanning and reconstruction techniques and the resulting measurements, will provide critical translational data for stenosed human heart coronaries. The previously discussed TAVR case, which was deployed in a stenotic human aortic valve, is an example case of using diseased state models for scanning. Having additional implanted TAVR devices will allow us to critically compare how such artificial valves interact with a variety of complex native valve anatomies with varying levels of aortic stenosis.

Moving forward, we would perform scans on hearts implanted with pacing technologies to closely analyze the varied and alternate site placements of pacemaker leads and/or leadless pacemakers. Additionally, the results of acute and chronic implantations (e.g., encapsulation) can be studied.

Employing the proposed micro-CT imaging methodologies to critically analyze these multiple device deployments should provide novel insights as how to better design the next generation of cardiac devices. Furthermore, cardiologists and medical device designers will gain the needed insights relative to device/tissue interaction in highly varied cardiac anatomies.

ACKNOWLEDGEMENTS

We would like to thank the other members of the Visible Heart® Laboratories for their relative support on this. We would also like to thank the organ donors and their family for gifting hearts for research and LifeSource for their generous efforts in procuring these specimens.

REFERENCES

Anderson, S. E., A. J. Hill & P. A. Iaizzo (2009) Microanatomy of Human Left Ventricular Coronary Veins. *Anatomical Record-Advances in Integrative Anatomy and Evolutionary Biology,* 292**,** 23-28.

Chinchoy, E., C. L. Soule, A. J. Houlton, W. J. Gallagher, M. A. Hjelle, T. G. Laske, J. Morissette & P. A. Iaizzo (2000) Isolated four-chamber working swine heart model. *Annals of Thoracic Surgery,* 70**,** 1607-1614.

Eggen, M., Bateman, M., & Iaizzo, P. A. (2011). Methods to Prepare Perfusion Fixed Cardiac Specimens for Multimodal Imaging: The Use of Formalin and Agar Gels. *Journal of Medical Devices, 5*(2), 27539.

Omdahl, P., M. D. Eggen, M. D. Bonner, P. A. Iaizzo & K. Wika (2016) Right Ventricular Anatomy Can Accommodate Multiple Micra Transcatheter Pacemakers. *Pace-Pacing and Clinical Electrophysiology,* 39**,** 393-397.

Sanchez, J. D. Z., M. G. Bateman & P. A. Iaizzo (2019) Multimodal imaging of a self-expanding transcatheter aortic valve replacement (TAVR) procedure in a reanimated human heart and post-implant analyses. *International Journal of Cardiovascular Imaging,* 35**,** 2135-2137.