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MULTI-DISCIPLINARY ANALYSIS OF COOLING PROTOCOLS FOR HUMAN HEART DESTINED FOR TRANSPLANTATION

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ABSTRACT

A new cooling protocol for realistic human heart preservation was designed and investigated numerically with an objective to extend the usable life of an organ between its harvesting and implantation. A high resolution MRI imaging of actual human heart was used to create a 3D geometric model used for simulations based on OpenFOAM software platform. The conjugate cooling protocol uses internal cooling by perfusing a liquid inside the heart and external cooling by submersing the heart inside cooling gelatine. Multi-domains, multi-physics, three-dimensional simulation was performed to obtain unsteady temperature and stress fields inside the heart during the shortest cooling process.

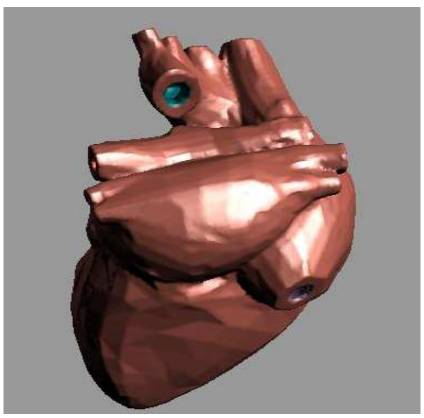
Key Words: *heart simulation, organ preservation, transplantation, heart cooling, stress analysis, blood flow, conjugate heat transfer.*

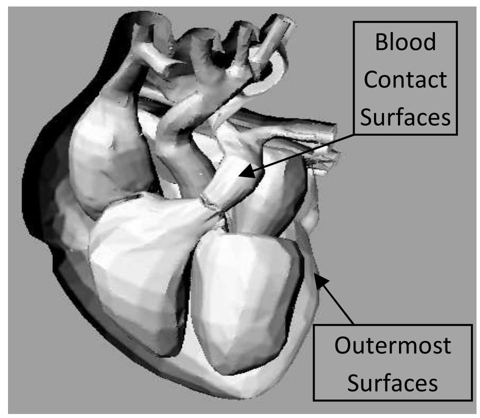
1. INTRODUCTION

The main current problem of organ transplantation is the relatively short time that organs can survive from the moment of their harvesting to the moment of their surgical transplantation into the recipient's body. Currently, human hearts can be used for transplantation only during 4 hours between harvesting to its implantation when kept submerged in a saline solution at temperature close to freezing of water [1]. Cold preservation is using the advantages of decreasing cell temperature, thus causing the cell metabolism to be decreased. As a result, oxygen and glucose consumption and carbon dioxide production will be decreased as well [2]. Thus the cell damage due to lack of oxygen will be decreased [3]. Numerical studies in this field are very challenging due to geometric complexity and lack of certain experimental data. Dulikravich [4] demonstrated, in the case of two dimensions, that it is possible to maintain specified cooling rates at any point of the cooled object by varying container wall temperature distribution. Dennis and Dulikravich [5] used 3-D spectral finite elements to simulate unsteady temperature field and thermal stress field during freezing of an idealized canine kidney submerged in gelatine without perfusion. They also for the first time demonstrated the optimized time-varying thermal boundary conditions use on the surface of a spherical freezing container and suggested use of optimized internal perfusion of the organ during the cooling process.

2. SIMULATIONS AND RESULTS

Complex geometry of human heart is one of the challenges of this work. Zhang and Bajaj [6] applied finite element method for meshing the 3-D human heart from MRI scan data. In this research, human heart geometry presented by Bajaj has been used for simulations. Multi-physics nature of this research requires having three separate domains; inside the heart, heart, and outside the heart. The first step in creating the required domains is to separate innermost (blood contact) surfaces from outermost surfaces which are shown in figure 1.

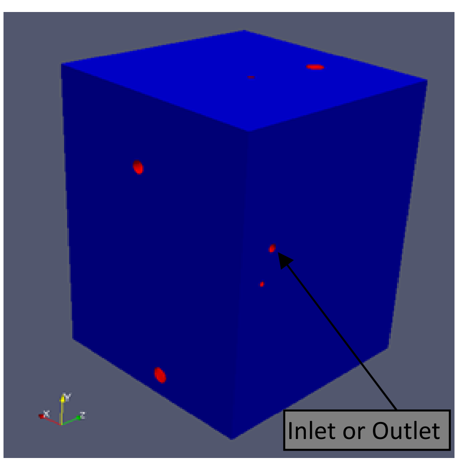


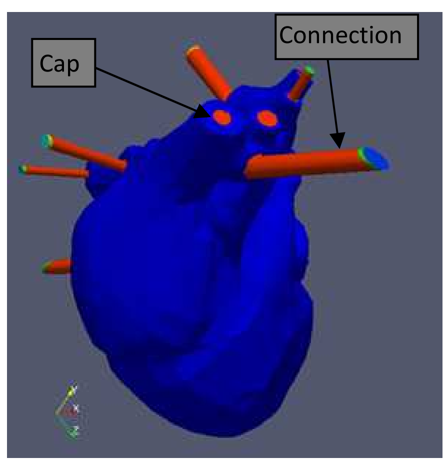


a) b)

Figure 1. Heart model: a) whole heart, and b) blood contact and outermost surfaces.

For each of the two heart circulation systems, two inlets and two outlets were designed to circulate the perfusate inside the heart. Heart was treated as submersed in a cooling gelatin in order to have pure conduction cooling from outside. Heat conduction will give an ability to apply different cooling rates on heart by using different temperatures on the walls of the cooling container.



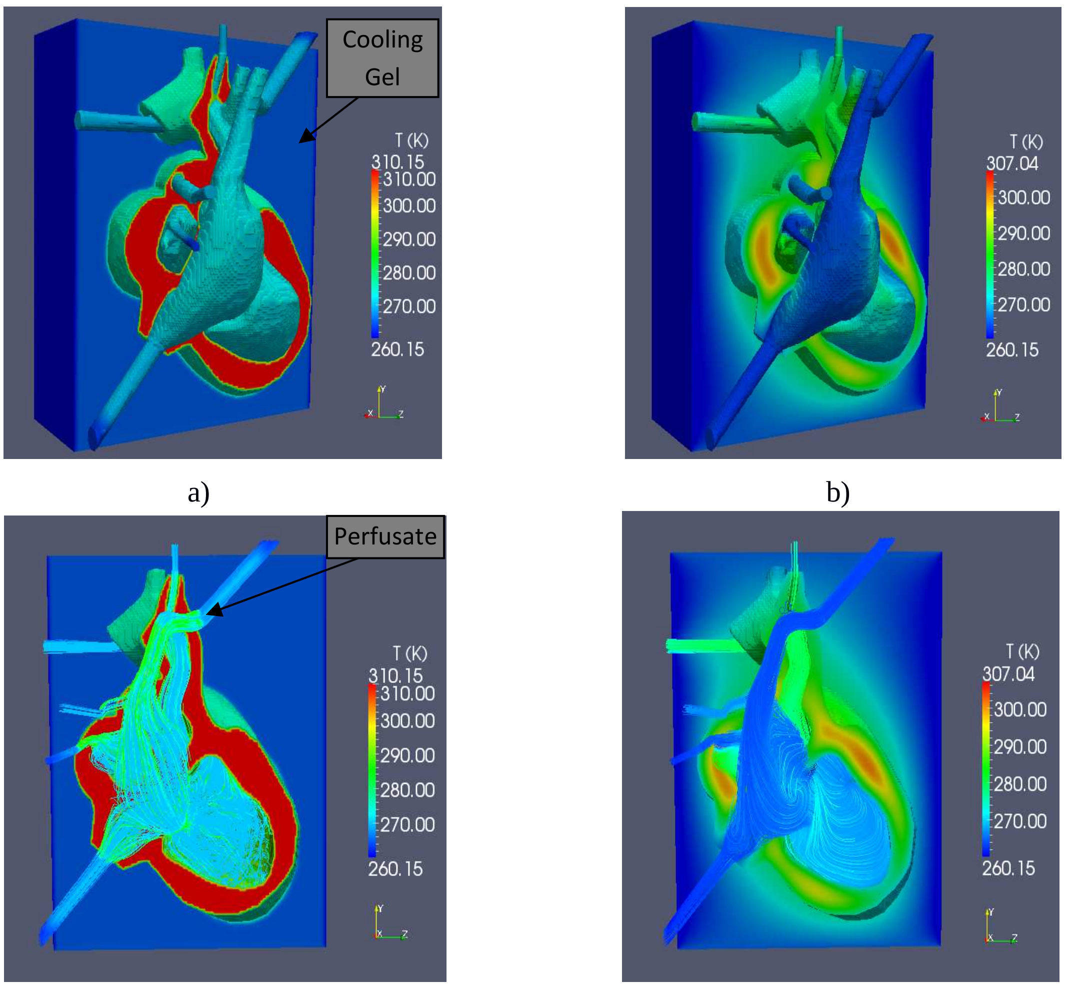


a) b)

Figure 2. Cooling system: a) cooling container, and b) connections and caps.

Figure 2a shows a designed cooling container of 214 mm in length, 212 mm in width and 282 mm in height, with 4 inlets and 4 outlets for cooling the heart. Figure 2b shows the all connections and caps for pumping coolant through the heart right and left circulation systems.

Conjugate heat transfer simulation was performed in OpenFOAM environment [7]. Perfusate flow was considered a laminar flow due to low Reynolds number, and was modeled by using Navier–Stokes equations. In this research, very low inlet and wall temperature were applied in order to better demonstrate variations of the temperature field during cooling process and the capacity of cooling system in removing heat from the heart. The inlet temperature of the perfusate was set to -10^{o}C. Cooling container wall temperature was also set to -10^{o}C. Figures 3a and 3b show that the average heart temperature was reduced 22^{o}C in 300 s. Figure 3c and 3d demonstrate the temperature distributions of perfusate during cooling process.



a) b)

c) d)

Figure 3. Temperature distribution (sagittal view) after: a) 0.5 s, b) 300 s, c) 0.5 s with perfusate view, and d) 300 s with perfusate.

Stress analysis with small deformations was also performed using OpenFOAM to calculate normal and shear stresses applied to the heart tissue during the cooling process. The ultimate allowable stress of the heart tissue is 110 kPa [8]. Magnitude of stress inside the entire heart at 5 s was higher than at 300 s. This was due to larger variation of temperature at the 0.5 s compared to 300 s. The calculated stress was lower than the ultimate allowable stress during the entire cooling process.

3. CONCLUSIONS

A cooling protocol simulation for human heart preservation was designed. In this protocol, external cooling takes place via conduction by using a cooling gelatin between the heart and the walls of the cooling container. Heart internal cooling is by perfusate convection. Different temperature was applied on the cooling container walls in order to have different cooling rates. Gelatin was chosen as the cooling conduction medium and water as perfusate. Three-dimensional, conjugate thermo-fluid-stress analysis was performed using high resolution realistic human heart geometry during 25 minutes of the cooling process. OpenFOAM software was used to perform all numerical time-dependent simulations. The combined conduction/convection cooling is capable of lowering the heart temperature much faster than typically used conduction alone.

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