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Evolution of Cardiac Biomodels from Computational to Therapeutics

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ABSTRACT

Biomodeling the human anatomy in exact structure and size is an exciting field of medical science. Utilizing medical data from various medical imaging topography, the data of an anatomical structure can be extracted and converted into a three-dimensional virtual biomodel; thereafter a physical biomodel can be generated utilizing rapid prototyping machines. Here, we have reviewed the utilization of this technology and have provided some guidelines to develop biomodels of cardiac structures. Cardiac biomodels provide insights for cardiothoracic surgeons, cardiologists, and patients alike. Additionally, the technology may have future usability for tissue engineering, robotic surgery, or routine hospital usage as a diagnostic and therapeutic tool for cardiovascular diseases (CVD). Given the broad areas of application of cardiac biomodels, attention should be given to further research and development of their potential.

INTRODUCTION

Creating a replica of a particular organ is one method to understand the intrinsic behavior and functionality of human organs. Such recreations have acquired the term biomodeling. Emerging as a new area of medical science, researchers have used various ambiguous terms to describe the same process: phantoms, anatomy models, stereolithography models, or, plainly, models.

This recreation can either be in-silico (virtual) or as a physical object [Fantini 2008]. The virtual biomodel can be further divided based on the source of the initial data used to derive it; either sourced from mathematical algorithms or from medical imaging data. To generate a biomodel to be patient-specific, medical imaging of the particular organ is required. This can be done via multiple modalities, with computed tomography (CT) and magnetic resonance imaging (MRI) scans being the more common modalities [Starly 2005]. These 2D planar images, taken of multiple sections of the organ, would then be subjected to software processing and converted into a three-dimensional (3D) in-silico model. The in-silico model can be further processed and printed using various prototyping production technology including casting, milling, or 3D printing/rapid prototyping. The end result is a 3D physical biomodel [Starly 2005]. Figure 1 illustrates the 3 variations of the cardiac biomodel.

By far, boney anatomical structures such as the skull, mandibles, and femurs have been popular in biomodel research and medical applications [Karbaschi 2014; Sannomiya 2008; Uma Maheshwaraa 2008]. Boney structures are generally easier to model due to readily available software algorithms. Additionally, biomodels of boney structures are in higher demand due to patient-specific areas of usage such as plastic surgery [Gerstle 2014], customized implants [Silva 2004], and cranio-maxillofacial reconstruction [D'Urso 1999].

While biomodeling of the heart has been well researched over the past 15-20 years [Binder 2000], the difficulty in software processing of soft tissue anatomical structures has posed challenges and hindrances. The objective remains to overcome these challenges to derive a constant therapeutic mode of use of biomodels in clinical settings.

This article presents an outline of the interest, processes, limitations, and future directions of biomodeling of cardiac anatomy structures. We discuss the developmental background; outline the major utilization and the methodology to produce a cardiac biomodel; discuss possible challenges for production of cardiac biomodels in a hospital setting; and present the future directions in which this technology can be driven.

Cardiovascular Diseases—Medical Imaging Technology

Cardiovascular diseases (CVD) are usually accompanied with structural alterations of the heart such as congenital anomalies, dilation of aorta, thickening, thinning and scarring of myocardium, and changes in valvular and subvalvular structures. Mortality from CVD has been projected to rise to an alarming 23.3 million in 2030 [Bhatnagar 2015], thus stressing the need for alternative technology to treat CVD. Commonly used 2D medical imaging such as CT remains an effective modality for diagnosis [Miller 2008],

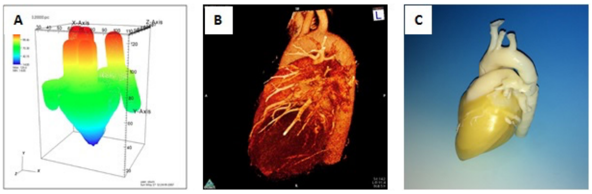

Figure 1. Forms of Cardiac Biomodels. Numerous forms of biomodels can be developed: in silico biomodel from mathematical data (A), in silico biomodel from CT scan data (B), or physical biomodel from CT scan data (C).

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but 3D structures of a biomodel could complement and enhance presentation.

The first widespread and practical usage of CT angiogram (CTA) began between 1996-1997, with the introduction of single slice helical CT, offering considerable improvement of spatial and temporal resolution visualization of the heart. The slice thickness between scans was 3 to 5 mm, but they managed to show some cardiac structural alterations such as thrombus with biphasic motion artifact. Further development of CT led to the breakthrough multislice CT with 4-detector rows (1998), 16-detector rows (2001), and 64-detector rows (2004). The slice thickness then gradually improved from 1-1.25 mm of 4-detector rows to 0.5 mm of 64- detector rows [Hurlock 2009]. The gradual improvement in resolution of CT has allowed for the development of much finer cardiac biomodels with better anatomical details.

Physical Cardiac Biomodels

Cardiac biomodels have been developed either in complete or partial form. Most of the complete forms [Samuel 2015; Costello 2014; Schmauss 2013; Dankowski 2014; Biglino 2015; Costello 2015; Verday 2015; Olivieri 2015; Valverde 2015a; Valverde 2015b; Shiraishi 2006] focus on specific objectives of usage and do not incorporate certain anatomical structures such as the coronary vessels. Some of the partial cardiac biomodels comprise of certain anatomical structures such as the aortic valve [Maragiannis 2014], tricuspid valve [O'Neill 2015], mitral valve [Mahmood 2015], atrial and ventricular chamber [Chapron 2013]. A full list of literature of physical cardiac biomodels has been made available as supplementary files online [Cardiac Biomodels].

INTEREST IN CARDIAC BIOMODELS

We have attempted to compile the interest in the biomodels by application for cardiothoracic surgeons, cardiologists, and medical researchers as summarized in Figure 2.

Utilization of Cardiac Biomodels for Surgical Use

Planning and design of the surgical procedure beforehand plays an important role in determining the outcome of an operation [Poldermans 2009]. The planning frequently follows the CT or MRI scans of the heart. Juniors or trainees may experience difficulty in translating the information of the 2D medical imaging into coordinates on the actual 3D organ. The spatial realism of cardiac biomodels allows a visualization of the surgical site and has been proven effective in numerous attempts of procedures such as valve implantation [Armillotta 2007] and structural heart disease planning [Kim 2008].

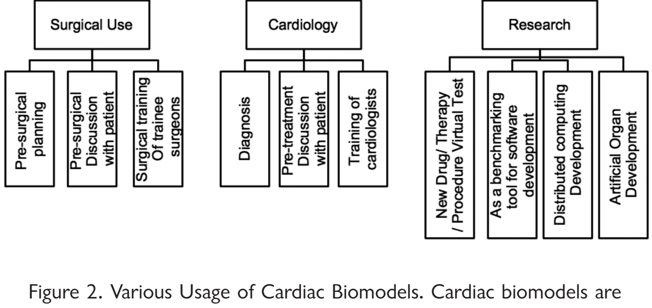

Figure 2. Various Usage of Cardiac Biomodels. Cardiac biomodels are applicable and useful for surgeons, cardiologists, and researchers in numerous ways.

The complexity of surgical processes and lack of knowledge normally instills fear in patients. Inability of patients to understand the surgery has frequently led to anxiety and nervousness [Vivian 2014]. Visual aids such as posters and standard bench models are frequently used. However, the lack of realism in these tools is at times insufficient in representing the actual specific pathological condition. Imaging may be too difficult to understand. In such cases, 3D cardiac biomodels may be more comprehensible [Sailer 1998]. With custom biomodels of the patient's own heart as a visual aid, surgeons may be able to better explain the procedure and the necessity of the surgery.

3D biomodels may serve as a good training tool. When printed with materials that mimic soft tissues, surgeons become more prepared with mock surgeries on the biomodels [Costello 2014] and possibly better surgical outcome. This advantage can also be expanded to medical schools in universities, where cardiac biomodels could become suitable substitutes for cadavers in teaching cardiac anatomy.

Using 3D biomodeling technology, numerous disease biomodels have been attempted, including aneurysm [Sulaiman 2008], hypoplasia [Riesenkampff 2008], failed staged palliation [Sodian 2008], stenosis [Maragiannis 2014], congenital heart disease [Shiraishi 2014] and even tumors [Schmauss 2013]. The use as a tool to understand disease has been generally favorable for diagnosis of CVD with structural alterations.

In addition to usage in operation planning, most researchers have proposed that cardiac biomodels are fit to be used as training tools for cardiothoracic surgical practice. 2D or 3D virtual biomodels are frequently insufficient in providing intuitive understanding of the anatomy localizations [Shiraishi 2014]. The usage of these cardiac biomodels, however, can enhance 3D learning, in addition to allowing simple surgical practice on the model [Kalejs 2009; Bruyere 2008]. Additionally, 3D biomodeling allows the creation of certain specific complex and rare cardiothoracic procedures, thereby allowing insight into rare cardiac diseases, ultimately improving surgeons' knowledge [Knox 2005].

Practices in cardiothoracic surgery such as thoracic endovascular aortic repair (TEVAR) suggest the even closer utilization of medical imaging as an essential technological tool during the course of the operation [Beaver 2015]. We foresee this as a possibility of future incorporation of biomodels as a routine part of diagnosis and preoperative planning for surgeons.

Utilization of Biomodels by Cardiologists

In cardiology, diagnosis and treatment depend on medical imaging. Since cardiac biomodels are constructed from medical imaging data, the models become an improvement and advancement of the imaging techniques, portraying the

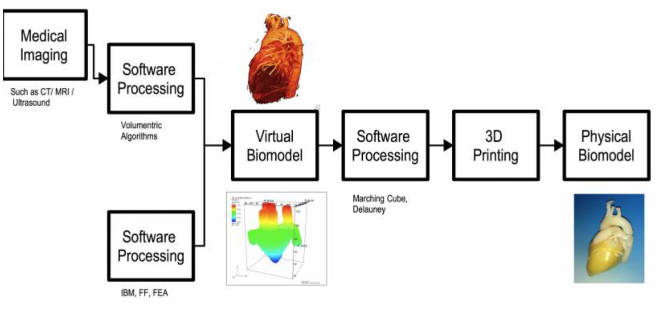

Figure 3. Procedure to Generate Cardiac Biomodels. Medical images are first subjected to software processing to create a virtual biomodel, which consecutively can be further processed and printed using 3D printers to create physical biomodels.

structural conformation of the heart in a 3D form. When compared to 2D portrayal of multislice CT/MRI scans, 3D biomodels allow a clearer overview of the heart structure, making it easier to analyze and determine the state of pathology [Kelley 2007]. This would be especially beneficial for trainees in cardiology, as the models will be able to assist them in understanding the nature of their diagnosis. Relating the 3rd dimension, biomodels were shown to allow a better grasp of the structural abnormalities, hence providing a clearer perspective for the patients [Dankowski 2014; Valverde 2015; Shiraishi 2006; Esses 2007; Schmauss 2014]. Although most cardiac biomodel usage seems to be from a surgical angle from the development of physical models, cardiologists have also attempted to incorporate physical biomodels as a preprocedure planning tool, such as for direct percutaneous mitral annuloplasty [Siminiak 2013].

Cardiologists are also able to utilize the virtual biomodel without the need for it to be printed in 3D form. Examples of models include the virtual biomodel of the ventricle to investigate scar tissues to aid cardiologists in interventional treatment planning [Trayanova 2014]. This becomes advantageous, as there is no need for procurement and maintenance of 3D printers.

Usage of Cardiac Biomodels by Researchers

We have broadly categorized research use of the cardiac biomodel into 4 main areas: virtual testing, software development, distributed computing development, and artificial organ development.

As a replica of the actual heart, the cardiac biomodel has the potential to be used for virtual experimentation. By varying physiological properties such as hemodynamics in the aorta [Canstein 2008], flow rates within the chambers and vessels can be analyzed, which could help in planning therapy for CVD. Such experimentation allows vast permutations that may translate into resource and cost savings.

Certain software researchers are interested in the processing of humongous data from cardiac simulations in order to develop software algorithms [Slagt 2010] and new software languages to enhance the interconnectivity between nodes in a large-scale computing cluster [Aiken 1998]. These simulation data also allow for testing of storage, processing, and communication capabilities of large-scale server farms. Each beat of the virtual biomodel simulation may generate up to 5GB of data.

Big data refers to large sets of data, and cardiac big data researchers collect patient's imaging, demographics, ECG, and treatment data from a multitude of patients to be analyzed conjointly in supercomputers [Scruggs 2015]. Such efforts in virtual heart biomodeling may lead to potential early diagnosis systems for future patients.

The physical cardiac model can also be used for artificial organ development by harnessing the ability of 3D printers to create precise scaffolds in 3D, which would serve as the foundation for in vitro growing of cells and tissue for organ development. This is further elucidated in the section Customized Treatments. Researchers have also utilized the virtual cardiac biomodel to assist in development of devices such as artificial heart valves [Griffith 2009].

BIOMODELING THE CARDIAC ANATOMY

Biomodeling would be a term to describe the whole process of developing and generating a customized and patient-specific cardiac biomodel as summarized in Figure 3. The process begins with acquisition of the medical imaging of the patient using MRI, CT scan, or other modalities. The acquisition method follows standard parameters with some slight tweaking to accommodate the computing algorithms. The data is then processed via a series of algorithms to make a virtual biomodel. The virtual model is usually sufficient for certain medical analysis, but can be processed further and fed into a 3D printer to make a physical biomodel more appropriate for physical usage.

Medical Imaging

Certain steps have remained the same throughout the years when creating a biomodel and are outlined here to give new researchers a brief overview of the methodology. The best and popular initial data for the 3D algorithms are electrocardiogram (ECG) gated CT scans, as opposed to physical biomodels derived from MRI or other modalities. The gantry tilt must be set to zero in order to allow best software processing capability. The finer the slice thickness, the better the resolution of the final model, though this requires much more structure identification processing. It would be best to request slices up to slightly above the aortic arch in order to develop a complete biomodel. Using these slices, each slice is then analyzed, one by one to identify the various chambers and vessels. This step is greatly assisted by the contrast agents injected into the bloodstream during the process of capturing the CT scan. The timing of the scans can either be in systolic or diastolic depending on the anatomical structure highlighted, such as either the left or right ventricle. As soft tissues are harder to differentiate in CT scans, the contrast highlights the chambers and vessels to a clearer extent. The data file output from the medical scans will be in DICOM format and cannot be used in the 3D printer directly, as the data needs to be further processed by software algorithms.

$$p(u,v) = \sum_{i=0}^{m} \sum_{j=0}^{n} N_{i,p}(u) \cdot N_{j,q}(v) \cdot p_{i,j}$$

Figure 4. B-spline algorithm. A b-spline algorithm used with two knot vectors u and v for a 3D reconstruction to generate a closer to reality model. This function also smoothes out any unwanted spikes present in the CT/MRI images that are not present in the actual model.

Software Algorithms

The next crucial step would be to segment and separate the anatomical structures of interest such as the ventricles, auricles, arteries, and veins; each into separate files. Because of the higher border variation between bones and soft tissues, software algorithms can extract boney structures with automated ease; whereas for soft tissues, automatic segmentation software algorithms have not fully matured to handle all the variations of different patients such as variations of tissue density and contrast permeability. Certain algorithms such as the snake algorithm have been attempted [van Assen 2004] but are unable to differentiate very closely located structures such as the coronary arteries and the chambers. To overcome this, researchers prefer to manually outline each anatomical section of the heart, slice by slice, using a pointing device such a mouse or drawing tablet. Albeit tedious, it seems more practical and faster for surgeons. In our attempt there were 400 slices, and the programmer sat together with the cardiothoracic surgeons to identify each anatomy in each slice. We have found the Bamboo (Wacom, Vancouver) drawing tablet to be useful for this task because of its fine resolution, and the detection of the mouse pointer is from the tip of the pen so the user's palm does not disrupt the outlining activity. We discuss the future directions of these algorithms further in the section Challenges of Modeling.

Subsequently, each anatomical structure in each slice is then adjusted for its window width (WW) and window level (WL) values so that each matches the value of air on the outside of the outlined area and the value of metal on the inside. This step may be skipped if the resulting outcome is of sufficient quality. The process also aids in the next step of using the marching cube algorithm to reconstruct in 3D. The reconstruction algorithm creates a surface by joining three adjacent points in 3D. At this stage if the anatomy is 3D printed, it would result in a blob filled with printed material, as the printer has only read the outer surface of the model. In the next stage of reconstruction, a second mock surface is created. The thickness may be varied for vessels and chambers. This surface is created using an extrusion algorithm that takes the normal of each surface and recreates a new surface for a given value in the direction of the normal. This method preserves the contour of the original vessel/ chamber. This also ensures a hollow region within the vessel and chambers, which the 3D printer will be able to decipher as two surfaces and fill only the regions in between the two surfaces with solid printed material. The final output from the algorithm processing would be a dataset in the format that the 3D printer is able to decipher and generate into an intricate, stable (physically intact without crumbling) and closest to original anatomy biomodel. The result of crumbling due to the wrong choice of algorithms has been investigated [Rathinam 2013]. Two good choices of software applications which incorporate all the above algorithms are either Osirix [Rosset 2004] which only runs on the Macintosh platform, or the 3D Slicer [BWH 2015], available on multiple platform but recommended to be run on Linux to take advantage of its processing speed.

Supercomputing

Computing power can be expanded by clustering multiple subunits together. This is known as supercomputing and can be achieved either by positioning all the subunits (in computing referred to as nodes) on the same circuit board (single unit supercomputing), the subunit servers stored in layers within racks with large quantities of server racks strung together in a single large room (cluster computing), or the nodes positioned in different geographical locations (grid computing). Nevertheless, in order to create cardiac biomodels to investigate the anatomical structure only (such as the biomodel in Figure 1, C), a single desktop or laptop with computing power of 3GHz processor clock or above would suffice.

Virtual Biomodels

3D biomodels generated using datasets from medical imaging analysis, which can be viewed in 3D on computer screens, are termed as virtual biomodels. This form of biomodel can be utilized for research or therapeutic purposes [Trayanova 2014] without being further developed into a physical form. A full list of virtual cardiac biomodels and the algorithms utilized has been made available online [Cardiac Biomodels].

Most of these virtual biomodels have been used to evaluate computationally the flow rate of blood and characteristics of myocardium. Such computational methods supersede in terms of being able to process and analyze large numbers of patient data rapidly. The visualization and animation displayed on the computer screen also provide cardiologists with immense information such as areas of pathological structures and the outcome of treatment, as demonstrated by a study involving 36 myocardial infarction patients [Ukwatta 2015]. Virtual biomodels also allow colorful animations to highlight certain pathology.

3D Fabrication and Construction

The next step would be to convert this virtual biomodel to a physical cardiac biomodel with the utilization of a rapid prototyping apparatus to generate the biomodel layer by layer. Stereolithography (STL) is a commonly used apparatus utilizing a high-powered laser to generate plastic biomodels. A variety of 3D printers using different methods to generate 3D objects have been devised [Horvath 2014] and cardiac biomodels have been developed utilizing various machines [Armillotta 2007]. The latest technology in 3D printers also allows the creation of objects with multiple materials simultaneously with dual printheads that can result in both plastic and rubber materials. Such 3D printers can be used to generate an interesting cardiac biomodel as exemplified in Figure 1, C. Simple tubular structures such as the aortic arch can be generated using cost effective low-end desktop 3D printers.

In order to be printed, the virtual data of the cardiac structures would need to be further processed using certain algorithms such as surface creation, hole filling, warping, support structure incorporation and support material filling algorithms. Some 3D printers are quite meticulous on the data fed into them and will halt halfway if encountering an error in the data, and multiple attempts may be required. Commonly, all 3D printers accept data in the format of STL. The 3D printer will read the data file and print out the model, layer by layer, with each layer almost 16-micron thick.

Various plastic and rubber-like materials have been utilized to make biomodels. Among the most common is plastic resin, followed by curing (hardening) using UV. Successful usage of UV-cured resins in printing has been widely reported [Chang 2004a; Chang 2004b]. Other material such as powder [Hurlock 2009], rubberized material such as silicone [Schmauss 2013], or a combination of materials (Figure 1, C) has had a more life-like appeal to surgeons. Surfaces which support cell growth are also available for tissue regeneration purposes [Díaz-Lantada 2010].

After the printout is complete, the model would require post-processing to remove any support material or overhang support that does not construe as part of the original biomodel. Support materials are needed because the molten material that forms the biomodel may require a slightly longer time to harden. This is dependent on the make of the 3D printer and may be a tedious process. Certain support material can be dissolved with liquefaction solvents, removed with waterjets, or blown away with compressed air nozzles. Care must be taken not to damage other anatomical structures.

CHALLENGES OF MODELLING

Considerations for Algorithm Development

The generation of a 3D biomodel from 2D slice medical imaging has had numerous hidden software challenges that are not typically discussed in the literature.

Soft tissue structural variations, constant wringing motion of the heart, and an inability for clear separation of distinctive borders of vessels and chambers from medical imaging has added a layer of difficulty. This is in stark contrast with biomodeling of boney structures, where the distinctive borders between bones and unwanted soft tissues can be easily separated by application of existing bone processing software algorithms, albeit with certain minor difficulties [Díaz-Lantada 2010].

A choice of modality between CT, MRI, or ultrasound also makes a difference in the quality of the biomodel produced and whether the biomodel has all the desired cardiac anatomical structures. The difference of the thickness between slices of scans can be very minute, up to 0.5 mm in CT scans and usually around 5 mm in MRI scans. The larger gap between slices in MRI data requires linear interpolation to fill the gap and results in a loss of anatomical features that may be present in between the slices such as the branches of the coronary vessels.

Some algorithms readily available in software such as Osirix [Rosset 2004] allow the 3D visualization of CT or MRI data in a single click. It is noted that this form of data consists of point cloud data and cannot be 3D printed immediately. Further algorithms of interpolation and smoothing would be required, commonly known as the surface algorithms. The marching cube algorithm presumably solves this step and the delaunay algorithm further refines the final output, but work on algorithm development continues to be carried out because of its inability to handle variations of patient data adequately.

The next section of smoothing algorithms consists of 3D splines. We have attempted the B- spline (Figure 4) to enhance our biomodel and found it to be an excellent choice [Rathinam 2013]. Without the use of the smoothing algorithms, there would be visible striated lines on the final 3D-printed biomodel [Schmauss 2013].

The proponents of open source medical imaging software [Rosset 2004; BWH 2015] allow for the inclusion of various algorithms as plugins from medical research whilst also sharing out the detailed mathematics behind it. On the other hand, the use of pricey commercial software applications deters future algorithm research.

In order to standardize biomodel development, a realism index is proposed to benchmark based on the sum of anatomical features and the variant of each feature as compared with the corresponding real anatomy. Such an index would allow surgeons and cardiologist better insight when choosing the right model for their utilization.

Challenges of 3D Printers

3D printers have a selected choice of materials because the materials must cure (harden) after deposition from the print nozzle. In certain methods of RP, the material will cure under laser or UV light. Other methods deposit a molten material using a heated print head. The material then cures upon cooling back to room temperature. Injection molding also utilizes almost similar principles but allows a wider choice of materials and economy of scale manufacturing. In order to make interconnected parts using molds, multiple molds are utilized and individual parts are joined using liquefying agents. In the case of multiple materials, newer models of 3D printers are able to generate interconnected parts at one time, which may require slightly tedious effort using molds. We have attempted to use 3D printers to generate molds and to cast latex rubber to produce biomodels, though the task tedious.

In order to create a process flow to generate biomodels for hospital consumption, some of the essential technical knowhow to operate and maintain the 3D printer are: the need to service regularly the print heads to prevent material clogging or mechanisms jamming; the choice of proper materials to be utilized; and the knowledge of removing support material as part of post-processing. Certain biomodels require extensive modification of the raw data to prevent overhung structures. As 3D biomodeling is a relatively new technology, several challenges are present and continue to be improved. Technological progress in 3D printing has produced smaller, compact, and non-technical end-user accessibility in contrast to sophisticated large machines.

Another major drawback of producing physical biomodels is the initial cost of procuring 3D printers, as well as the high overall cost for each biomodel [Roque 2013]. Some printers fetch a high cost up to almost a million US dollars, which is a barrier of entry for researchers with low budgets. Currently, the high costs have rendered the technology unfeasible for routine usage in hospital settings [Ikegami 2013], as each model would also then be costly. Additionally, the long processing time for creation of a biomodel further hinders practicability. Due to the extensive amount of time needed for printing, 3D biomodels may not be suitable for emergency usage [Cavanaugh 2015], but this could be solved with more research interest directed to the development of better software algorithms in conjunction with compact manageable desktop 3D printers.

FUTURE DIRECTION OF CARDIAC BIOMODELS

Several future directions are foreseeable for cardiac biomodels given the persistent effort of researchers worldwide.

Stereoscopy

As part of daily routine work, cardiologists utilize medical imaging data in planar 2D view on computer monitors. Hence, we presume that cardiologists are more accustomed to virtual biomodels. On the other hand, being a hands-on activity, cardiothoracic surgeons are presumably in favor of 3D physical biomodels to gain more insight for their procedure. This would, therefore, produce a discrepancy in which form of the biomodel—virtual or physical—would be more suitable for routine clinical diagnostics and therapeutic usage. Additionally, the relatively high cost of production of physical biomodels may hinder the routine use of physical biomodels. This leads to the research of the usage of stereoscopical biomodels.

Stereoscopy is the technique of creating visual depths utilizing stereo eyewear, resulting in a 3D display of the particular object with a finer sense of realism. Usage of stereoscopy in the medical field has been proven to be feasible, as the technology conveys more information than two-dimensional, monoscopic observation alone [Stewart 2014]. Apart from surgeons and cardiologists benefitting from the visualization, stereoscopy would allow patients to have a clearer understanding of the condition of their hearts, in contrast to 2D multislice imaging.

Customized Treatments

We advocate a direction toward therapeutics similar to creating customized patient specific implants for bone reconstructive surgery [Schubert 2013]. Earlier, biomodeling was limited to virtual preoperative planning and design of best fit implants. Development of technology allowed the final implant to be placed onto the patient, directly printed out from the 3D printer, thus greatly assimilating it into the therapeutics phase [Fedorovich 2013; Engstrand 2014]. With the continued successful developments of cardiac biomodels, the implementation for therapeutic cardiovascular use such as customized implants and stents seems achievable.

Organ Printing

3D organ printing, as the name implies, is the printing of organs by growing cells on a scaffold, in which the grown tissues are fused together to produce a single organ. The general trends and methodology have been reviewed [Mironov 2003] and seem to be progressing positively with attempts to print cardiac tissues to form tubular structures [Gaetani 2012], and possibly to treat myocardial infarction with favorable outcome in animal tests [Gaebel 2011].

Robotic Surgery and Artificial Heart

Current robotic surgical practice involves the manual control of robotic arms' motion by the surgeon [Jones 2005], and the incorporation of biomodeling algorithms may improve precision and accuracy. The use of robotic arm movement control using supervised machine learning algorithms has been evaluated in non-medical fields [Argall 2009] and we foresee a near and pragmatic future incorporating both technologies.

In order to assist in the pump function of the heart, the use of the left ventricular assist device (LVAD) has been well established. Recently, total artificial heart (TAH) has been re-explored with positive results in animal studies [Pelletier 2014], indicating a potential inclusion of biomodeling technology for the creation of patient-specific versions.

Conclusion

We have reviewed the latest cardiac biomodels by addressing the benefits, usage, and challenges. Combined with the usage of proper software algorithms, 3D printing of cardiac biomodels is highly feasible in producing replica of a patient's organ. With relatively simple, clear, and accurate biomodels, we foresee and strongly believe in this technology's potential as part of routine use in the hospital setting for assistive diagnosis, preoperative planning, and enhanced doctor-patient communication. With further development and research, every stage in the production of 3D cardiac biomodels could be improved to incorporate a simple, automated process—from imaging to virtual biomodels to printed biomodels to therapeutics.

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