Computer-generated three-dimensional animation of the mitral valve

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Objective: Three-dimensional motion-capture data offer insight into the mechanical differences of mitral valve function in pathologic states. Although this technique is precise, the resulting time-varying data sets can be both difficult to interpret and visualize. We used a new technique to transform these 3-dimensional ovine numeric analyses into an animated human model of the mitral apparatus that can be deformed into various pathologic states.

Methods: In vivo, high-speed, biplane cinefluoroscopic images of tagged ovine mitral apparatus were previously analyzed under normal and pathologic conditions. These studies produced serial 3-dimensional coordinates. By using commercial animation and custom software, animated 3-dimensional models were constructed of the mitral annulus, leaflets, and subvalvular apparatus. The motion data were overlaid onto a detailed model of the human heart, resulting in a dynamic reconstruction.

Results: Numeric motion-capture data were successfully converted into animated 3-dimensional models of the mitral valve. Structures of interest can be isolated by eliminating adjacent anatomy. The normal and pathophysiologic dynamics of the mitral valve complex can be viewed from any perspective.

Conclusion: This technique provides easy and understandable visualization of the complex and time-varying motion of the mitral apparatus. This technology creates a valuable research and teaching tool for the conceptualization of mitral valve dysfunction and the principles of repair.

Advances in 4-dimensional imaging have inundated the clinician with multiple methods of quantifying the time-varying motion of different cardiac structures. Three-dimensional echocardiography, gated magnetic resonance imaging (MRI), finite element analysis, and motion-tracking techniques are among those technologies that have improved the depth of our understanding of valvular function in normal and pathologic states.¹⁻⁹

Although these methodologies provide detailed anatomic information, it is often difficult to reduce the associated large data streams into a format that can be easily interpreted. The complex cardiac architecture often obscures the views of interest from within the heart. Additionally, the resulting 4-dimensional reconstructions with high voxel* counts are too large to be used as interactive models for virtual reality surgery simulators. We hypothesized that these problems could be solved by

*A voxel is a unit of graphic information that defines a point in 3-dimensional space.

Figure 1. Tracings of the left atrial and left ventricular surface.

Figure 2. Loft of the left atrial and left ventricular surface.

applying the advanced technology used in commercial entertainment animation software to cardiac anatomic modeling. In this article we describe a technique that transforms time-varying coordinate data into animated reconstructions, allowing the user to specify which structures are visible, as well as the perspective of interest.

Materials and Methods

Axial 1-mm sections of a male human cadaver mediastinum (Visible Human data set¹⁰) were used as our anatomic reference model. The digital photographs of these histologic sections were imported into Maya (Alias Wavefront, Toronto, Canada), a commercial 3-dimensional animation software package. These slices were then stacked in virtual space, and the cardiac structures of interest were

traced in contiguous slices, resulting in nonuniform rational B-spline curves (Figure 1). Each individual structure was defined by these curves, resulting in a lofted* surface (Figure 2). These multiple lofted surfaces were then converted into a high-resolution 3-dimensional polygonal model of the heart (Figure 3). Texture maps[†] (derived from intraoperative photographs) were applied to different tissues in the model (Figure 4).

Animation of this model was accomplished with the use of both normal and pathologic high-resolution ovine cardiac motion-tracking data. Radio-opaque fiduciary markers of the left ventricle and

*A loft is a surface that passes through a series of profile curves.

†Texture mapping is a process in which a 2-dimensional image is wrapped around a 3-dimensional object. Texture mapping is the electronic equivalent of applying wallpaper, paint, or veneer to a real object.

Figure 3. Polyglonal wire-frame model of the human heart.

mitral apparatus were recorded by using in vivo, high-speed, biplane cinefluoroscopy, as reported previously.^{3,7,11-14} These time-varying coordinates for both normal and pathologic conditions (ischemic mitral insufficiency induced by means of left circumflex artery occlusion) were used for these initial animations. A separate simple animation model of the ovine ventricle and mitral apparatus was created; this model contained the fiduciaries of the recorded motion data sets.

These resulting dynamic ovine models were then used to animate the static human model. In the normal data set the ovine fiduciaries were overlaid onto the corresponding human fiduciaries by rotating and scaling. This process maintained the relationship of the anatomic structures while allowing orientation of the scale and position of ovine motion into the human coordinate system. The reference starting position for both ovine and human valves was during leaflet coaptation at peak left ventricular pressure. Using a deformation tool in Maya, the human heart model was passively animated on the basis of the motion of the ovine markers. As each ovine marker travels through its motion cycle, it is programmed to exert a zone of influence on the human model. The mathematic drop off of these deformers is based on nonuniform rational B-splines. The zones of influence are automatically averaged in relation to the position of the raw data points to create a smooth interpolation. The result is the animation of the human mitral valve on the basis of the ovine mitral valve data set (Figure 5).

Figure 4. High-resolution rendering of the human heart.

As expected, in the abnormal ischemic data set there was a significant baseline discrepancy in the systolic reference position (peak left ventricular pressure) between the insufficient ovine mitral apparatus and the normal human apparatus. After rotating and scaling the fiduciaries for the anterior and posteromedial annulus, the human model annulus and ventricle were deformed in the anterolateral region to match the pathologic changes caused by the ischemia (Figure 6). The ovine motion data were processed as described above.

Results

Numeric motion-capture data from an ovine model were successfully transformed and animated into a 3-dimensional model of a human mitral apparatus. This methodology yielded a highly realistic human heart model composed of 28 structures (ranging from 194 to 2806 polygons each) and a total of 28,290 polygons. With the exception of the atria and ventricles, all elements in the model were single-layer constructions.

This process was automated with the exception of best fitting the ovine markers to the human fiduciaries. To achieve a best fit, a modest amount of manual alignment of the markers was required. The processing time required for reconstruction of a single frame with a high-speed desktop computer was just under 1 minute; rendering* a complete cardiac cycle required approximately 20 minutes. This model yielded a relatively low polygon count, resulting in reduced microprocessor requirements. This allows for fast real-time manipulation in a virtual

*Rendering is the process of translating mathematic elements, including models, lights, and textures, into a high-resolution visual image from a given perspective.

Figure 5. A, Wire-mesh version of the normal ovine mitral valve. The yellow paths illustrate the fiduciary motion during the cardiac cycle. B, Animation frame of a normal human mitral valve during systole.

reality environment. Models with very large polygon counts might overwhelm the microprocessor, resulting in slow, jerky motion, and might cause the computer to crash, making real-time manipulation impractical.

Anatomy was clarified by reducing the scene to only the desired elements. Adjacent structures that mask the mitral

valve have been eliminated. Additionally, the freedom of perspective in a virtual reality environment allowed us to visualize the anatomy from an ideal point of view. The observer is able to view mitral valve motion from the surgeon's perspective in an operating room, as well as from the perspective of a red blood cell as it flows into the left ventricle.

Figure 6. A, Wire-mesh version of circumflex ischemia in the ovine mitral valve. The yellow paths illustrate the fiduciary motion during the cardiac cycle. B, Animation frame of circumflex ischemia in a human mitral valve during systole.

The previously published quantitative analysis of the change in annular dimensions during acute ischemic mitral regurgitation was consistent with the animations presented in this article.¹³ The pathologic mitral annulus appeared asymmetrically dilated compared with normal and anterior leaflet loitering and was clearly visible during the cardiac cycle.

Videos

The resulting animations are available for review as a supplement in the online version of the *Journal*. These include a fly-through of the heart, normal and ischemic mitral ap-

paratuses, and the P3 Cam, a view of the mitral valve from the perspective of a viewer standing on the P3 leaflet.

Discussion

Three-dimensional animation has previously been used to illustrate surgical techniques. Cutting and colleagues¹⁵ were the first to apply studio-quality 3-dimensional animation for training surgeons in reconstructive operations of the cleft lip and palate. The technique presented here advances this concept by morphing different cardiac species and modeling true anatomic motion. Indeed, any time-varying coordinate data (human or animal) can be converted into clean recon-

structions at high detail. The creation of a predefined mesh of individual cardiac structures creates the ability to specify the anatomy of interest and selectively apply motion data that can then influence the adjoining tissue. In the current example this technique allows understandable visualization of the complex time-varying motion of the mitral apparatus.

One promising application of this technology is in the training of surgical residents. Cleft lip and palate repair animations are currently being used to train plastic surgery residents and surgeons in developing countries.¹⁵ These animations do not contain physiologic motion but rather the techniques of tissue reconstruction. Our current animations provide insight into the normal and pathophysiologic states of the mitral valve. Transparency and perspective can be used to emphasize important aspects of annular geometry and leaflet motion. This model allows the future creation of animations that would demonstrate different technical aspects of reparative mitral valve surgery.

Although animations are instructive, the next advancement in training is the use of interactive surgical simulation. These dynamic models require considerably less computer power to display in real time and are easily incorporated into virtual reality environments, an attractive basis for an interactive surgical simulator. Currently, several first-generation simulators, including laparoscopic surgery, catheterization, and endoscopy, are becoming integrated into physician training.¹⁶⁻¹⁹ Although the relative benefits of these limited first-generation devices remain controversial, the temporal and financial benefits of such training will drive its further development.²⁰⁻²⁶ The demands of society have already integrated this technology into military and commercial aviation training.²⁵ Likewise, the processes of surgical certification and recertification will probably someday incorporate this technology.²⁷

Limitations

It should be emphasized that the human mitral valve animations created are the results of morphing ovine motion onto the human heart. Until more accurate human fiducial data sets are available, this is the most accurate methodology to present the subtleties of mitral mechanics. Additionally, we are assuming that the anatomic relationships of the fiducials are the same in the 2 different species. Although tagged MRI studies are promising, the accuracy is currently limited. However, radiographic fiducials on gated MRI can be tracked and converted into 3-dimensional animations by using the same method presented in this article. Further refinements in this technique might include the addition of an automated least-squares fit solution for best fitting the raw data fiducials to the predefined cardiac mesh. This would minimize human error and reduce processing time.

Conclusion

This technology creates a valuable research and teaching tool for the conceptualization of mitral valve dysfunction and the principles of repair. It might serve as the basis for cardiac surgery simulation training.

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Discussion

Dr Pasala Ravichandran (*Portland, Ore*). This study certainly adheres to the principles stated by the president in his speech on exploring pioneering spirit. It is also a great example of the best minds from the west and the east putting their ideas together in practice. We, especially the surgeons at the teaching institutions, have been looking for a system similar to a flight simulator used to train jet pilots to understand the cardiac morphology and the complex procedures we do and then teach them to the residents. This might be the first step toward finding an answer.

The authors here describe a technique of studying the human mitral valve by using a commercial animation package called Maya. Maya means “magic” or “illusion” in ancient Sanskrit. The magic here is creating a 3-dimensional image of the heart and the mitral valve and using language like morphing. It is almost like language commonly used by skateboarders—let’s go morphing dude—. I will try to explain this process in 2 sentences. The method involves applying radiopaque markers on the mitral valve apparatus ovine model. The data that are collected are animated and morphed into a human model by using Maya’s deformation tools. The article explains in the simplest terms the complex process of animation, even though the whole process is completely new to most of us.

I have a few comments and questions. The human mitral valve is a very complex structure created, fortunately, with a very good margin for error. It has leaflets with very large opposing surfaces. A large number of first and second outer cords are present to compensate. Papillary muscles contribute to both leaflets. In other words, there are very good compensatory mechanisms to let disease states become really severe before you actually see any functional changes. Therefore my first question is, how does the complexity of the human valve affect the quality of animation and the interpretation of the findings?

Dr Grossi. I think the answer to that is first that it is not magic, even though the name of the program is Maya. This is basically an anatomic study. This is based on anatomy with real human models and real pathophysiologic data sets from the animal laboratory. I think what we are limited to now is what our fiduciaries are, and right now we are in a stage at which the best fiduciary markers are those that are placed and can be recorded by means of high-speed biplane cinefluoroscopy. I think that in the future we are going to be having gated MR data sets that are going to give us these fiduciary markers at a greater or at least as good resolution but more importantly on an individual patient. I think we will have a way that we could study a patient, take their anatomic data set and their motion

data set, and through fiduciary analysis display it in an anatomic model, such as the one that we have created.

Dr Ravichandran. The second question you kind of answered. Do the radiopaque markers themselves affect the function of the valve?

Dr Grossi. We have not seen any data that that has occurred.

Dr Ravichandran. The third question is the last one. Will this technology be useful in studying the homograft valve function by tagging them in the future and for analyzing their modes of failure?

Dr Grossi. I think there are a lot of data that can be extracted. I think there were some subtleties in the animation there that people might not have appreciated, but in the ischemic model, when the valve became ischemic, we saw fluttering to the leaflet valves. Late one night last week, as we were going through this data set, everybody was complaining that there was something the matter with the data, that the leaflets were fluttering. I said, no, this has been a very well-recorded observation, so I think for a non-physician to be able to be looking at this and saying there is something wrong, maybe we are a little too jaded, but I think a lot of insight can be taken when looking at these data through a visual form. The data that we can extract now are very complex. This is a way of data reduction, of visualizing and allowing us to use it. At the same time, I think there is a warning out there. I missed a slide, but I think in the future, just as currently in laparoscopic surgery, the trainers are going to be used by surgical trainers for training, certification, and recertification. This is already mandated in commercial aviation and the military. I think, perhaps by the end of another decade, these types of models will be used in our specialty also.

Dr Vaughn Starnes (*Los Angeles, Calif*). Dr Grossi, I enjoyed the article very much and it sort of had a “wow” effect. It is quite amazing work you are doing. A question I have about how you constructed the human fiduciary was a static model, right? A cadaveric model?

Dr Grossi. Right.

Dr Vaughn. And if we tried to validate the model in the future, have you looked at some of the 3-dimensional reconstructions that are already going on with echocardiography. I mean, does this valve look like what a 3-dimensional reconstruction looks like on the echocardiographic models that we have available today and are using clinically?

Dr Grossi. The problem with the 3-dimensional echocardiograph is that it is not fiduciary data. In other words, the heart or the valve leaflet moves through the cardiac cycle and moves in time and space, and you are looking at a given single frame. The only way to do it, to look at it, is not from 3-dimensional echocardiography but from 4-dimensional echocardiography. It would be something like the TomTec post hoc analysis system, in which you average several cardiac cycles and get an in-depth motion to be able to pick out fiduciaries, but you are quite limited in terms of what is available there. I think the only way you can really get fiduciary data is going to be some sort of gated MR study or perhaps as echocardiography gets better and we have a higher resolution 4-dimensional echocardiograph.