Teaching heart function—One application of medical computer animation

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INTRODUCTION

Medicine has developed current methods of teaching heart function over several centuries. There have been few fundamental changes in these teaching techniques over the last several decades. The method of text study followed by laboratory activity is essentially the same for both undergraduate and medical school students. For the latter, a more comprehensive study of experimental animals is involved, and surgical procedures are observed on patients. Once in medical school, almost all teaching is by demonstration, with a very small number of students per instructor.

This technique of demonstration and individual instruction limits the number of detailed phenomena which may be taught simultaneously, and the rate at which they may be presented. However, the complete description of heart function includes information of several types. The volume, configuration, and movement of chambers, valve operation, pressure and flow, electrical waveforms, and heart sounds all yield meaningful information. Specialized instruments provide the cardiophysiologist with massive amounts of raw data relating to each characteristic. Such data are often subjective, and when many different types are brought together, are usually unintelligible to medical students, and in fact to practicing physicians without special training. Thus, a major task of heart researchers and medical educators is to devise methods to efficiently integrate and disseminate heart function information.

As the volume of heart physiology and research data increases, there is a mounting need to present these complex interrelationships clearly and simply. This paper is concerned with the application of computer techniques to teaching heart function.

The short history of digital computing has seen many pertinent developments. The 10 year history of computer driven plotting equipment and software is of direct interest in teaching the interrelationship of the several attributes of heart function. The initial application of computer driven plotters was directed towards static images, whether cathode ray tube or electromechanical plotter. Later, the effectiveness of programs and plotting equipment improved and production of multiple frames became economically feasible. Initial dynamic presentation applications were directed almost entirely to the hard sciences. Lately, a small percentage of applications have been developed for the soft and social sciences.

The very recent history of programmed or computer aided instruction (CAI) also lends some insight as to how one can assist the teaching cardiologist. Current CAI practice labels a computer as anything from a simple sequencer to a large scale time shared system. Most visual teaching material has been prepared for conventional teaching methods. However, when based on properly organized material, learning results have consistently validated the concept of programmed instruction based on visual input by qualified teachers (teaching cardiophysicists).

The initiation of cooperative heart study activities
between The Aerospace Corporation, and the Cardiovascular Research Laboratory, Loma Linda University School of Medicine, in the Spring of 1967 placed these disciplines in direct view of each other, and under circumstances which provided a continuing exposure to the latest developments in CAI. This study activity represents a cooperative effort by both organizations to determine whether the capabilities of the respective disciplines can be combined to provide both improved methods for teaching heart function, and to alleviate demands placed on the time of the over-burdened teaching cardiophysiologist.

**Initial static image production**

**Concept**

The Aerospace Corporation has supported perspective computer graphics investigations from company funds since 1964. On initiation of this cooperative heart study, it immediately became apparent that these capabilities should support some research applications in visual portrayal of cardiac phenomena. A pictorial representation of the exterior surface of the human heart and great vessels was selected, both as a first experiment, and as an application suitable for developing basic techniques and providing broad experience. Following the terminology of Fetter, there was no formal aims definition other than to achieve a reasonably satisfactory static image with hidden lines removed, and there was no overall communications design.

**Specimen preparation and film data recording**

Successful data transcription required an innovative approach based on the unusual application of standard techniques. The primary anatomic data was obtained from a post mortem heart; a series of 6 post mortem hearts was used to develop overall data transcription techniques. The particular heart serving as the final model was free from congenital or acquired heart disease.

Each blood vessel leading to or from the heart was cut perpendicular to its long axis at approximately 2 cm. from its junction with the heart chambers. The specimen was washed completely free of clots and inspected for evidence of structural abnormality. All heart chambers were filled with small pieces of plastic foam nearly transparent with respect to diagnostic x-ray wavelengths. This foam distended the chambers so that the heart resembled its relaxed (diastolic) configuration. The specimen was next positioned in a specially fabricated square plexiglass moun-

![Figure 1-Post mortem heart specimen](http://www.computerhistory.org)
of one heart chamber to another, and registration pin images for picture orientation.

Data transcription

The polytome pictures or x-ray negatives are exceptionally "noisy" because of poor edge definition and emulsion noise due to x-ray scatter, which cause all but limited details to be out of focus. Thus, the next step was for the noise due to the above sources to be "filtered" by subjective exercise of the physicians' past experience during examination of each negative in the labeled sequence. This was accomplished by applying his knowledge of heart structure during the process of "edge tracing" to convert very noisy section data to "filtered" clean sections clearly depicting the outlines of heart chamber surfaces, heart valves, and chamber wall thickness.

Each individual x-ray negative was positioned on a light table, and a transparent sheet of mylar was appropriately registered. Mylar registration was of particular importance, in order that level to level relative alignment could be maintained when the outlines were transcribed to polar coordinate form. The heart chamber boundaries, external heart wall, and registration marks were traced by the physician onto the mylar overlay with an india ink pen. A representative tracing is shown in Figure 3—Mylar Section Outline. Each mylar overlay was coded relative to its associated x-ray negative, so that the sequence was maintained in proper order. The anatomic data (surfaces of the heart) was thus transformed to outline form, and transferred to a media which would facilitate its specification in polar coordinate form during the next step in the data transcription process. Using the registration marks for alignment, the set of mylar tracing edge outlines could be seen to provide a three-dimensional reconstruction of the heart. That is to say, they formed a Serial Heart Atlas. A reconstruction from selected Atlas sections is pictorially represented in Figure 4—Mylar Heart Surface Reconstruction.

It is of substantial importance to note that this data transcription process was achieved without damaging the original heart specimen. Medical ethics were maintained, new research data were developed, and the specimen was returned to the Pathology Labora-
tory where the remainder of the routine autopsy was carried out. Also, the tissue specimens obtained during further medical analysis substantiated the fact that the post mortem heart utilized was free from structural disease not only on the gross, but also on the microscopic level.

The Atlas of mylar tracings was then leaved through rapidly several times to obtain a qualitative impression as to which vertical line would best serve as an axis for aligning the sequence of polar coordinate plots. A line connecting the center of the pulmonary artery and the apex or bottom tip of the heart was selected for this purpose. Each coded piece of mylar was then taken in turn from the sequence and mounted on a light table. A sheet of polar coordinate paper was then registered in an appropriate position relative to pulmonary artery/apex line and the mylar registration marks. Thus, each "non-destructive slice" from the specimen, as represented by a unique mylar edge outline sheet, was oriented in orthogonal 3-space by its z value (on the axis formed by the origin of the several polar coordinate systems) and by maintaining within each mylar plane a constant relationship between \( \theta = 0^\circ \) and the specimen box registration pins.

The first level selected was at the bottom tip or apex of the heart, and sequential levels were at 0.5 cm. increments until the top of the pulmonary artery was reached. Outlines for the main body of the heart were transferred to polar coordinate paper oriented about the pulmonary artery/apex axis. When the great vessels began to appear at the top of the heart, the multiple surface capability of the perspective plot package was utilized. The pulmonary artery edge outlines were transferred as a separate surface, but with a base level equal to the z value of the top surface of the heart and zero offset relative to the pulmonary artery/apex axis. The aorta, superior vena cava, and pulmonary veins were each treated in a similar fashion, except that appropriate x, y offset coordinates were specified relative to the pulmonary artery. At this point, data transcription was essentially complete. It remained to arrange the data in that format most convenient for processing by the perspective package driver.

**Perspective plot program**

The operating program used for initial efforts implemented the algorithms described in "The Perspective Representation of Functions of Two Variables" by Kubert, Szabo, and Guiuliani. Basically, the function to be plotted, \( f(x, y) \), is given in terms of a set of rectangular coordinates \((x, y, z)\) where \( z = f(x, y) \). As in the present case, non-rectangular inputs may be utilized; they are processed internally into rectangular values. Visibility of a rectangular surface formed by evaluating the function of \( x, y, z \), is developed by forming a grid connecting all equal values of \( x \) and all equal values of \( y \). For non-rectangular point arrays, a grid is formed, and points connected for all equal values of \( z \) and all equal values of \( \theta \). Standard trigonometric methods are followed for selecting a viewing point and projecting the grid structure thus formed to a desired projection plane. The initial version of the program applied visibility test criteria between each point and any other points in the array near the line of sight. If more than one array (surface) is present, the tests were applied along the line of sight in each additional array. After completing visibility testing, the grid structure identified earlier was formed by connecting all visible points. This entire process is as illustrated in Figure 5—Heart Grid Projection, which depicts the specimen, grid overlay viewing point, and project on plane and image.

Limited core availability of the IBM 7094-II constrained array size. Thus, "square" arrays of function evaluation points were utilized wherever possible. These factors were taken into account when selecting the location line for parting radii for a numerical dissection by animation experiment, and also when selecting the number and orientation of radii to be used in specifying each divided specimen thus obtained. Thus, each polar coordinate level was represented by a z value, \( \theta_{\text{origin}} \), \( \Delta \theta \), number of radii, and \( \rho \) value list for the first section, and a similar set of parameters.
for the second section. The external surfaces of the heart, and the external surfaces of each of the great vessels were then each divided into that number of subsections which would best satisfy the square array condition. These measures reduced the exterior surfaces of the heart and great vessels to a collection of ordered polar coordinate points \((p, \theta, z)\) which were listed in an appropriate format and converted to a data deck. This method of representation resulted in 14 subsurfaces and 780 mesh points.

**Initial results**

The first heart images were obtained during July-August '67 and required 45 minutes of IBM 7094-II time, later reduced to 20 minutes. Examples of these experiments were plotted on an IBM 1627 (CalComp) and are illustrated in Figure 6—Closed Heart, and Figure 7—Numerically Dissected Heart. In general, the plot routine performed as expected, and provided useful imagery even though minor anomalies resulted from the visibility algorithm and the data transcription process. At times, a normally invisible line would be seen at the tip and would result in spurious lines being drawn until it crossed the next boundary. The data transcription process did not provide complete closure between the bases of the several great vessels at the top of the heart, and the resulting gaps allowed portions of the inside of the heart to become visible. However, the results were sufficiently representative of heart structure to establish the future usefulness of computer animation, provided some improvements could be made in overall perspective plot program computing time. A continuing liaison effort was initiated between the Cooperative Heart Study and the Aerospace computer graphics research activities to both observe current progress and be well aware of any impending developments which might result in more efficient image computation. Also, additional activity was initiated to eliminate data transcription noise and obtain a numerical description of a smooth surface heart. Finally, planning was undertaken for production plotting on the Waveform Display/Analyzer, a high speed, interactive, precision film scanner/recorder having a pin-registered 35 mm film transport.

**Improved image computation time**

During the latter part of 1967, the visibility test algorithm was substantially revised in that the projection plane was divided into a rectangular grid, and object mesh points were projected into these projection plane sub-elements. This enabled visibility testing to be limited only to the immediate area of the projection plane sub-element, i.e., was the projection plane sub-element occupied by another object mesh point and if so, which of the two competing mesh points was closest to the observer? This new algorithm resulted in roughly a geometric decrease in perspective program running time, since it was no longer necessary to compare each object mesh point to all points where the line of sight crosses the grid in the object or objects under consideration. It yielded IBM 360/65 frame times of approximately 20 sec.

As before, occasional image anomalies became apparent as illustrated in Figure 8—Closed Heart—
New Method. Base gaps at the top of the heart still allow projection of small portions of the interior. However, line drawing anomalies now resulted primarily from line segment closure errors between adjacent projection plane sub-elements. Limitations on the number of line segments allowed to occupy a projection plane sub-element, and on the amount of closure testing, would occasionally result in short erroneous connections or "hanging stubs." Certain algorithm improvements were able to decrease this type of visual noise. At this time, it was postulated (and later substantiated) that dynamic motion would tend to effectively mask all but a small number of such anomalies, and that those remaining would be sufficiently obscured to not visibly detract from the overall image quality.

Heart beat algorithm

Basic movement data

Perspective plot package probable compute times and plot quality were now such as to justify development of a heart beat algorithm. Perturbation of the static heart surface image so that a dynamic (cine) image sequence would realistically depict the beating human heart from any viewing angle represented a significant challenge. A solution to this problem was achieved by a combination of data transcription techniques, computer graphics, innovative utilization of cardiac research instrumentation, and most importantly, something that can be described no more explicitly than the creative interplay between experience in cardiology and experience in data reduction.

The starting point was the selection of an electrocardiogram (EKG) from a healthy heart beating at a rate of 60 beats per minute. A bar plot depicting the cycle times of the right and left atria and right and left ventricles in the overall cardiac sequence was then constructed to the same time scale as the EKG. Chamber movement within these cycle times was derived from two primary sources: cineangiography and ultrasound. Cineangiography data is provided by high speed motion pictures obtained from x-ray/image amplifier pictures of the heart pumping blood containing blood-soluble radio-opaque contrast media. Such high speed x-ray motion pictures are then analyzed by a cardiologist for qualitative aspects and, by measuring distances on projected images for qualitative information. The measured dimensional changes are plotted against time. Ultrasonic techniques provide independent determination of the same spatial data, i.e., variation of chamber dimensions with time. Sound in the 2.5 mho range is generated at a prf of approximately 1 kh. The transducer is placed on the chest over the heart, and the returns are displayed in a spatially calibrated A-scope format, which allows direct observation and determination of dimensional changes. Spatial displacement determined according to these methods was then folded with the chamber cycle times in the overall cardiac sequence to produce the plot of volume vs. time for atria and ventricles shown in Figure 9—Heart Chamber Volume Sequences.

Chamber static and dynamic mapping

Conversion of this two-dimensional summary expression to a perspective portrayal of three-dimensional distributed movement required mapping of the atrial and ventricular areas into the grid representing the external surface of the heart, and establishing appropriate vectors for each point so mapped. Chamber area mapping was accomplished by hand sketching outlines on two static perspective plots. After validation, the data were then mapped onto 80 column free form coding sheets. Map resolution was increased by assuming a variation in acceleration and magnitude of distance moved between the center and edge of a chamber area, with the central region having the highest acceleration and the edge the least. Thus, each external heart surface grid point was assigned a chamber and type designation, and a multiplier was assigned to each type and applied as appropriate. Specification of direction, acceleration, and magnitude for grid
Figure 9—Heart chamber volume sequences

heart technique of displaced polar coordinate sections provides satisfactory results. Function evaluation at specified intervals also provides usable data. Isometric drawing data can be transcribed so as to provide the basis for logically correct object surface descriptions. In each of these representative data transcription methods, as well as other similar ones, almost any data transcription or data generation method will work, as long as it may be represented by some valid algorithm.

The input data are then processed by a driver to create a properly organized grid structure \((P_x, v, z)\) data set.

**Basic motion description method**

Computer animation depends upon systematic perturbation of a basic logical entity resulting from data transcription/driver output. The systematic perturbation may result from either analytical function evaluation or from empirically derived data. Heart motion was empirically determined by measuring spatial displacement through ultrasonic pulse displacement with time, and direct measurement from cineangiography. Another logically similar method originated by Fetter is based on transcription of landmark (e.g., shoulder, elbow, wrist) movement from the photographs of Muybridge. Identical methodology may be applied to other dynamic inanimate phenomena not conveniently expressed by analytical notation. In each of these cases, similarity to surface description methods exist, in that a driver is used to assemble the basic landmark movement in orthogonal 3-space, and also interpolate as required for mapping into the object surface description and for perturbation at the selected framing rate.

**Motion animation**

Availability of an object surface description in the form \((P_x, v, z)\), and motion specification in the form of properly interpolated empirical description of landmark position variation with time, allows computer animation to proceed. If the object surface description and landmark motion drivers are written in generalized form, they may be coupled to the animation driver, and animation may be accomplished at any desired rate. If not, all motion perturbation must be related to silent or sound projection rates on an a priori basis.

It should be noted that all of the preceding GENERALIZED MOTION ALGORITHM discussion is concerned solely with perturbation aspects of computer animation. Perspective, hidden line removal, list processing organization for “save” procedures, etc., are separate subjects.
Feasibility test film

Validation of the algorithm was undertaken by selecting a non-rotating, beating view at a heart rate of 60 beats per minute. This parametric combination allowed a full heart beat cycle to be completed in one second. Thus, the number of plots was determined by the standard sound projection rate of 24 frames per second. The perspective plot package drivers, which now consisted of the heart surface formatter and perturbation algorithm, were set up for 24 plots.

After computation, the plots were produced by an IBM 1627 (CalComp) using india ink on white paper. The plotting time of several minutes per image (frame) was acceptable for only the shortest animation sequences. For validation purposes, however, the availability of a large, high contrast, hard copy image supported easy visual error checking. The cyclical characteristic movement of a beating heart allowed efficient use of a single sequence, in that it minimized the amount of raw plotting required. Repeated (film) printing provided unlimited viewing time to check all aspects of perturbation algorithm fidelity. The automatic scaling and centering algorithms within the perspective plot package were also evaluated for contributions to overall image quality.

Inspection of the actual plots which were to serve as the basic animation cells immediately disclosed excessive image centering movement. This required alteration of the centering algorithm for subsequent animation efforts and, in the validation case, frame-to-frame registration on the two vessels having maximum displacement between each other, i.e., the pulmonary artery and superior vena cava, as the individual plots were cut and punched to standard animation cell format. Static and "flip" evaluation of the cell booklet indicated that an approximately correct portrayal of a heart beat had been achieved. Finally, labeled overlays and titling were prepared on clear acetate.

Cine footage was obtained by standard animation photography procedures. Double printing (2 sequential exposures) of each frame supplied half-rate motion to allow longer times for dynamic error check observation. Multiple sequences of standard single printing supplied footage for standard motion validation.

Overall evaluation of the feasibility test film disclosed that the basic perturbation algorithm was logically sound. The only motion anomalies resulted from two individual grid point mapping errors (out of 780), and a data transcription error in specifying right atrial movement. As expected, minor grid line direction plotting errors produced by the new visibility check algorithms were largely masked by the dynamic movement. The simple 3 minute film was a happily unexpected success of major significance. An algorithm had been developed for accurately expressing natural physiological motion in numerical form, thus opening the door to high speed computing synthesis of natural motion by computer animation.

Experimental teaching film

Communication design

During the 6 to 8 weeks that were required to develop and validate the perturbation algorithm, communication design had been occurring. A script outline had been developed for a film to disclose technique capabilities and education possibilities to cardiologists and physicians. Animation requirements involved illustrating dynamic portrayal of heart surface smoothing, 360° rotation, tipping about the vertical axis at classical viewing positions, and computer synthesized dissection to allow viewing of interior heart structure. As in all manual or computer animation activities, each scene outline was reviewed to reduce to a minimum the number of raw stock animation frames. At this point, a highly detailed animation script was prepared, which completely specified all data necessary to compute each individual frame of raw stock animation. This information was also required to enable correct sequencing of raw stock animation in assembling the complete scenes.

Production computer animation

Computer run output was produced on tape suitable for driving an IBM 1627 (CalComp) incremental plotter. This resulted from the fact that the Aerospace (San Bernardino Operations) Mathematics and Computation Center has an extensive investment in plotting systems and applications programs, and production experience historically traceable to the incremental plotting systems programs developed at STL by K. G. Tomikawa and J. R. Blackmer. This type of output, while not of optimum efficiency, was indeed satisfactory, and had the substantial advantage of providing a useful run validation mechanism through selected hard copy plots.

The script outline required several thousand frames of computer animation. The IBM 1627 (CalComp) incremental plotter tapes were converted to a format suitable for driving the Waveform Display/Analyzer (WD/A), a high speed, computer driven (IBM 1800), interactive, precision, film scanner/recorder. Of particular importance, this system possessed both a highly accurate pin-registered 35mm camera, and
a real-time interactive console for monitoring plot production. The translation program provides: (a) simultaneous film recording, and a tape of WD/A instructions, or (b) a tape of WD/A instructions only. The first capability is normally used for film image validation of raw animation stock frames. The second is used for high speed plotting at essentially tape read speed, when raw stock frames are assembled into scene sequences.

It is interesting to note that the second capability was immediately developed after the first raw stock frames were produced. Selected frames had been validated on the IBM 1627 (CalComp) plotter, the tapes translated and a 35mm film master exposed on the WD/A. Two days of desk effort plus two days of printer time were required to produce a script usable by an optical printer operator and for production of 16mm master footage. This immediately indicated the preferability of using standard tape-to-tape copy, i.e., tape to film copy methods.

Approximately 2 weeks of elapsed junior programmer time developed an IBM 1816 (typewriter) conversational tape-to-film animation sequence assembler. A simple tape search program and capabilities for an elemental dialogue concerning titling and plot frame identity allowed the two days for script production and two days of effort for producing a 16mm master animation scene sequence to be reduced to approximately 2 1/4 hours WD/A plot time plus a straight 35mm to 16mm reduction run. Thus, it was now possible to eliminate optical print script preparation time, and to provide the optical printing operator with a reduce and copy job, eliminating time consuming optical printer sequencing.

Film tutorial

During production of the animation footage, live action footage had been shot for the remainder of the script. Communication design had been based on an aims definition to provide an experimental film outlining teaching capabilities which could be implemented with this new technique. The first version of the film was entitled “Heart Motion by Computer Graphics”.9 It was a medically oriented tutorial which outlined the capabilities of digital computers, incremental and CRT plotters, computer graphics perspective plot programs, anatomic data acquisition techniques, basic animation, and examples of computer animation and teaching situations. A full 24 frame sequence depicting one complete beat is illustrated in Figure 10—Complete Heart Cycle. The film was directed toward medical students, post-graduate physicians and patients.

Initial teaching experience was obtained in a variety of situations: (a) laymen were shown the short feasibility film at an Aerospace open house, (b) the physician co-author used both the short feasibility film and the “Heart Motion by Computer Graphics” tutorial during his teaching activities at the Loma Linda University School of Medicine, and (c) both senior authors have made a variety of presentations to selected physician and engineering groups.

Two significant reactions were obtained from this early teaching experience: (a) medical exposure established teaching potential, particularly when combined with simultaneous presentation of associated cardiac parameters, and (b) the medically oriented scenes and narration were not suitable for engineering or programming evaluation. Therefore, additional live action scenes were developed to emphasize data conversion and computer programming aspects of the problem.
A second, engineering oriented film, "Teaching Heart Function by Computer Animation" was prepared. These two films have served to adequately present salient technical and teaching factors to both types of audiences.

Advantages and disadvantages

The unique nature of this type of material has stimulated forward looking teaching physicians. Particularly, those with sufficient exposure to advanced instrumentation and computational methods to produce an appreciation of the substantial teaching advantages which could be provided by audio visual material based on computer animation technology. Such technology enables the cardiac educator to readily develop any desired static or dynamic normal or diseased heart condition. A portrayal may be developed without waiting for the right type of cardiac condition to become available for photography through open heart surgery. Similarly, there is no need to place impossibly large animation requirements upon the already overloaded medical illustrator who normally is much more of an anatomically trained and highly skilled detail technician, rather than a proficient animator. High speed computation allows the production of animation from any desired viewing point with equal ease of illustration, once the basic data transcription has been accomplished. Of particular interest, is the fact that "numerical dissection" techniques allow internal dynamic viewing of any "heart preparation" desired; this type of presentation cannot be accomplished by any means other than manual or computer animation. Computer animation techniques also greatly facilitate the presentation of any desired combination of cardiac structure and associated functional attributes. Thus, the teaching physician can, with a minimum of effort, direct the production of an incremental visual presentation of increasing complexity, and where required, increasing functional rate, all with appropriate audio on the sound track.

Audio visual material does not have the personal contact of the live classroom and does not allow for the comprehensive stimulation of fast moving question-and-answer dialogue. However, well developed instructional material of the type outlined in this paper can summarize and greatly condense the presentation of significant material from many hours of classroom and laboratory work into two half-hour films or tapes. It should be strongly emphasized that the techniques of computer animation are particularly adaptable to utilizing experience gained over the last few years from programmed and computer aided instruction. And, that such films could be used for audiences ranging in size from a single student or physician to a hundred or more at any time during the day or night.

Current activity

Current activity of this aspect of the Cooperative Heart Study is devoted to planning teaching system development requirements. Immediate effort concerns accomplishing the additional data transcription necessary to specify the atria, ventricles, and valves. Subsequent data transcription will provide that data in numerical form necessary for introducing electrocardiograph plots, ultrasonic cardiograph plots, pressure, and flow. The last data transcription activities will be directed toward introducing visual presentation of heart sound data.

Parallel activities concern additional computer graphics research for achieving perspective presentation without the grid structure, but retaining sufficient surface and edge detail to provide adequate visual cues. Similarly, the present perspective plot package driver is being evaluated to determine what changes would make it more usable for high volume production of animation. That is to say, what data and control information formats will allow minimum time requirements for input deck preparation.

Other medical investigations are being devoted to outlining a catalog of required normal and diseased presentation and, in particular, the explicit content and sequence of these presentations. These medical teaching studies are also considering whether or not computer animation can best be applied to teaching heart function through group orientation or by individual consoles. Finally, if individual consoles are to be used, should they be film or video tape oriented and, should they provide only an ordered presentation, or should they allow random sequences based on student response?

Other possible applications

Finally, some limited consideration is being given to the identification of needs, and the analysis of the probability of success for extending computer animation techniques to other medical fields such as pulmonary studies or teaching obstetrics. The generality of the algorithm for accurately expressing natural physiological motion in numerical form (as earlier independently conceived by Fetter and as outlined in this paper) provides for high speed computing synthesis of natural motion by computer animation, and thus allows realistic identification of solutions to such teaching problems.
SUMMARY AND CONCLUSIONS

The historical development of a computer animation technique for teaching heart function has been reviewed. Of particular importance, early planning activities were organized to be ready to take advantage of future solutions to clearly identified problems.

The initial feasibility test film validated the perturbation (heart beat) algorithm. Most importantly, it established a basic algorithm for expressing natural physiological motion, thus allowing high speed computing synthesis of unlimited amounts of additional natural motion by computer animation. At this point, the aims definition, communication design, and additional data transcription and computer programming were undertaken for production volume automatic drawing (computer film recording) of heart animation. Live action footage was photographed to round out communication design requirements. The animation and live action footage were combined to produce an experimental heart function teaching film tutorial and an engineering oriented film explaining programming details. Medical and engineering acceptance accorded these films well appears to justify additional development.

The generality of basic data transcription and animation techniques allows direct application to other medical teaching activities outside the area of cardiology such as pulmonary studies, obstetrics, and other similar problems.

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