COMPUTER AIDED ANALYSIS OF MEDICAL, ULTRASOUND-ECHOCARDIOGRAPHIC IMAGES[1]

Balázs ASZTALOS

Department of Process Control
Technical University of Budapest
Műegyetem rkp. 9.
H–1111 Budapest, Hungary
Phone: +36 1 463-4026
Fax: +36 1 463-2204
E-mail: asztalos@fsz.bme.hu

Received: April 7, 1998

Abstract

Ultrasound echocardiography is widely used clinical technique, but images obtained using current technology are still processed manually with semi-automated methods. In contrast to this, the newly developed system works in an automated way, first obtaining a series of long and short axes views of the heart synchronised by the ECG in real time, then processing them off-line. After detection of the internal edges of the left ventricle, the system determines the short/long axes areas, diameters, calculates the volume of the left ventricle frame by frame and, based on this, the ejection fraction for each cardiac cycle.

The developed system is currently being tested and the results correlate well with data determined by other methods.

Keywords: computer analysis, biomedical engineering, ultrasound echocardiography, image processing.

1. Introduction

Left ventricular volume measurements provide much useful information in diagnostic cardiology. These measurements enable determination of volumes throughout the cardiac cycle with applications in quantifying volume changes in valvular lesions, valvular stemosis, ischaemic damage or cardiomyopathic processes as well as evaluation of response to treatment including vasodilator agents and valve replacement and repair.

Techniques used to measure left ventricular volume include biplane angiography (including contrast angiography and radionucleotid angiography), cine computed tomographic images and two-dimensional ultrasound volume imaging. Biplane angiography has been used as a reference standard

[1]The research was carried out under the postgraduate scholarship of the Hungarian Academy of Sciences and also with the support of the Hungarian Scientific Research Fund (OTKA F024112). A phase of the work was accomplished during a visit at the Rotary Centre for Cardiovascular Research, Griffith University, Brisbane, Australia, in 1994.

for further studies, although it assumes the left ventricular chamber to be ellipsoid in shape, ignores the volume of the cavity taken up by the papillary muscles and requires invasive cardiac catheterization.

In this study paired biplane two-dimensional echocardiography has been used which involves the short axis view across the heart at the papillary muscle level and a long axis view taken from apex to base of the heart. An algorithm based on a model of the ventricular shape can then be used to calculate volumes of the left ventricle throughout the cardiac cycle. With the volumes calculated it is possible to determine the ejection fraction and the volume changes in the entire cardiac cycle.

Two-dimensional echocardiography also provides other very important data including ventricular wall motion and wall thickening. By determining the ventricular contour, wall motion of individual points along the ventricular edge can be followed. This can provide clinically useful data in terms of wall function or dis-function.

As previous articles show [1], it is possible to use computer assisted methods to implement data processing. Although a variety of preliminary reports have endorsed the automatic tracking of the endocardial boundary [2], its wide usage has not been introduced in clinical practice yet.

2. System Description

2.1. System Objectives

The objective of the developed system is to provide a way in which images of the left ventricle, obtained from echocardiographic experiments, can be processed automatically with minimum interaction of the users such as doctors or researchers, and useful data such as ejection fraction and wall motion throughout the entire cardiac cycle can be gained.

The objectives of the system are the following:

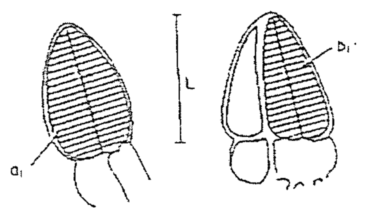
- Enable the collection of at least 10–20 frames by a cardiac cycle to make volume and wall motion curve determination possible.
- Provide a method for pairing the images taken in short axis and long axis views and based on this 3D volume calculation.
- Develop and implement an algorithm which can perform an automatic edge detection of the left ventricular wall on the echocardiographic images.
- Implement various methods for volume calculation based on the captured images in order to provide comparable information for the validation processes.
- Based on the result of the edge detection, calculate wall motion throughout the cardiac cycle.
- The developed system has to be user-friendly.

Following the guidelines given by the objectives, a system called **CarmA** (Automated System for **Car**diac Ultrasound **I**mage **A**nalysis) has been developed. This report contains the technical and physiological background, the system description, the performed validation processes and proposals for further development.

2.2. *Practical Issues on Implementation*

Before and during the development of the system several questions emerged. It was useful to examine and solve them carefully before the final implementation, because it made the realisation easier and clarified the necessary steps and validation processes. Here are the most significant problems which occurred:

- For calculating the volumes of the left ventricle it is necessary to have at least two views of the ventricle, preferably perpendicular. Based on these views it is then possible to calculate the volume of the ventricle frame by frame. The two views, which were used are the short and long axes views, as they are the most standard views in ultrasound echocardiography. A typical calculation method can be seen in *Fig. 1.*



$$V = \frac{\pi}{4}\sum_{i=1}^{n} a_i b_i \frac{L}{n}$$

Fig. 1. Simpson's Rule I for calculating the volume of the left ventricle

- With one echocardiography only one view can be obtained at a time and therefore the requirement set in the previous point cannot be fulfilled. To overcome this problem the heart was assumed to work in a steady state, namely each cardiac cycle is similar to the previous ones, at least over a short time interval. Therefore it is possible to obtain one series of images in one view, then turn the probe and acquire the next series in the next view. Pairing the images is done by synchronising the first image of both series. This can be performed by analysing the ECG signal provided on the video image. As the most characteristic part of the ECG signal is the QRS complex, the R wave was used to trigger the experiment.

- Due to the speed requirement it was advisable to divide the software part of the system into two parts, one is for real-time image capture (**capture**), the other is for image processing and analysis (**CarmA**). The main feature fro the **capture** part is the high speed, while **CarmA** runs off-line.

2.3. System Components

The basic configuration of the **CarmA** system can be seen in *Fig. 2*. A brief functional description of the parts will be given in the following paragraphs.

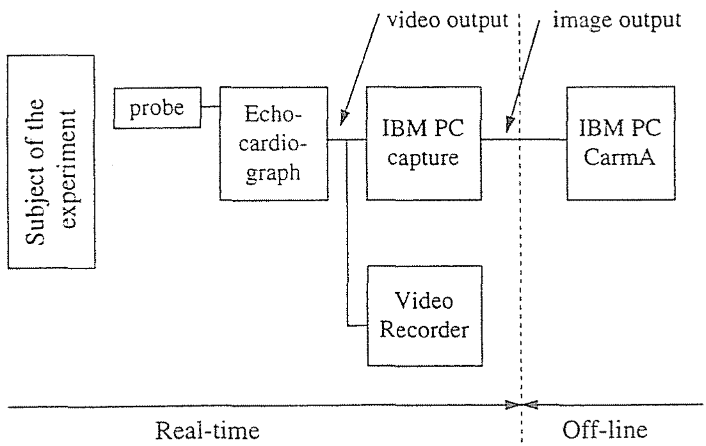


Fig. 2. Basic configuration of the system

Definitions

- **Subject of experiment**: Heart of an animal or person.
- **Probe**: The probe of the echocardiograph which is used to emit and receive the ultrasound signals in order to obtain echocardiographic images.
- **Echocardiograph**: The ultrasound system which is operated in two-dimensional mode to obtain the images. Its video output is compatible with the standard PAL system. Therefore it can be used to transfer the obtained pictures to the videorecorder as well as to the computer's frame grabber board.
- **IBM PC-capture**: Acquisition of the synchronised short and long axes image series is the task of this unit. Image series are synchronised by triggering on the R wave of the ECG.
- **IBM PC-CarmA**: The **CarmA** software performs all off-line image processing and analysis. Because of the number and size of the images

this unit cannot be implemented real-time on an IBM PC compatible computer with current technology. However, in the future with faster computers and hardware, real-time analyses can be possible. The **CarmA** software has been written in Borland C++ 5.0 as a Windows 95 application. The software has been designed to be user-friendly and to fit in with the usual Windows programming techniques.

2.4. Description of the Image Analysis System (Capture, CarmA)

The **capture** program was written to perform real-time image digitisation and all other data collection necessary to carry out the experiments. It was implemented in a machine close assembly language and was optimised toward speed enhancement. Images were taken consecutively by switching between the 4 memory blocks of the frame grabber, while data transfer to the memory of the host computer was also performed in the background. By this method 20–30 images, necessary for a cardiac cycle, were obtained. The flow chart can be seen in *Fig. 3*. First short axis, then long axis images were taken and the image capture was triggered by ECG spike detection.

After real-time image acquisition, the main part of the software package is performed off-line. As with all the Microsoft Windows applications, the **CarmA** software is also an event-driven software package with a menu structure appearing on the screen after initialisation (*Fig. 4*).

The flow-chart of the image analysis process can be seen in *Fig. 5*. As the processing of a single image and the processing of one image from the series is exactly the same (in the present off-line version), the flow-chart applies to both situations. The flow-chart is a simplified picture of the image processing part. There are many other necessary processes defined which are not significant in the image processing but which are essential to the function of any software package. Some of these are error detection units and interface units to indicate the stage of image processing as the computer carries out its analysis.

First step on the raw images is smoothing to reduce the noise caused by the spikes that accompany any ultrasound echocardiographic image. The smoothing is performed by a 3×3 averaging-smoothing filter. In order to determine the area carrying useful data an echo-finder algorithm detects the ultrasound cone. Assuming that the image contains the ventricle, an inner point of the ventricle is detected by minimising the following function:

$$\overline{I}(x,y) = \frac{1}{N} \sum \sum_{i,j \in K(x,y)} a(|(x,y) - (i,j)|) I(i,j)\,, \tag{1}$$

where $I(i,j)$ is intensity of a pixel at the (i,j) co-ordinates and $a(\cdot)$ is a cost function based on the distance from the investigated pixel. As pixel

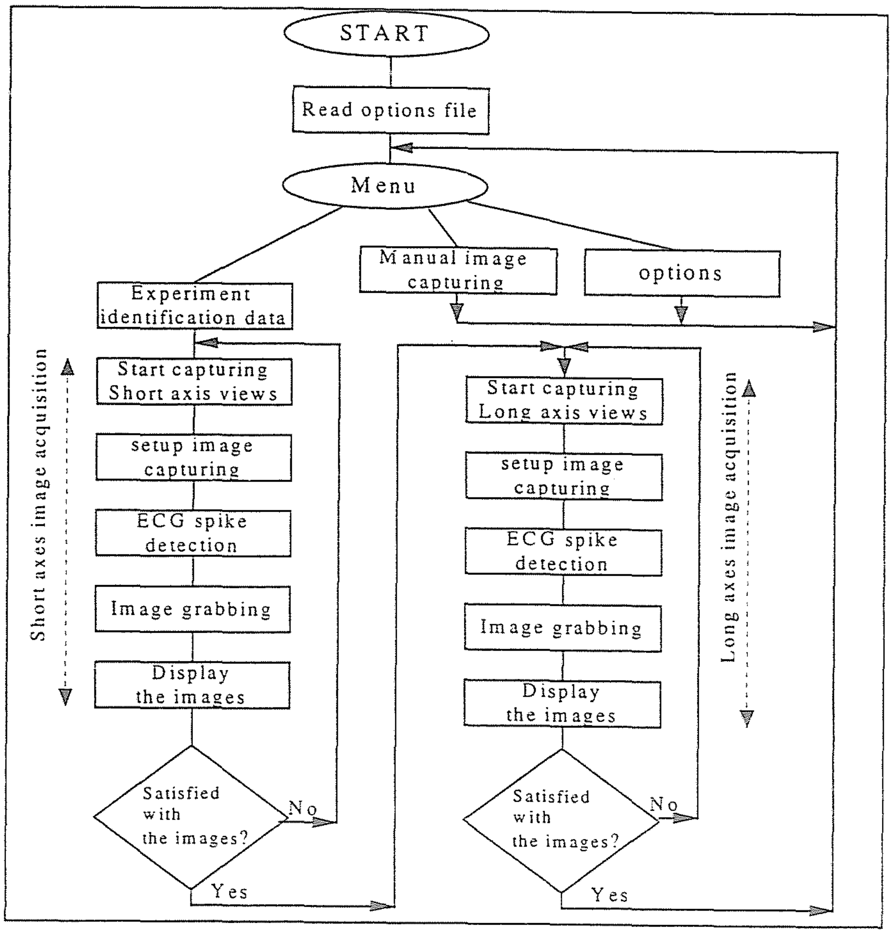


Fig. 3. Flow-chart of the image digitisation process

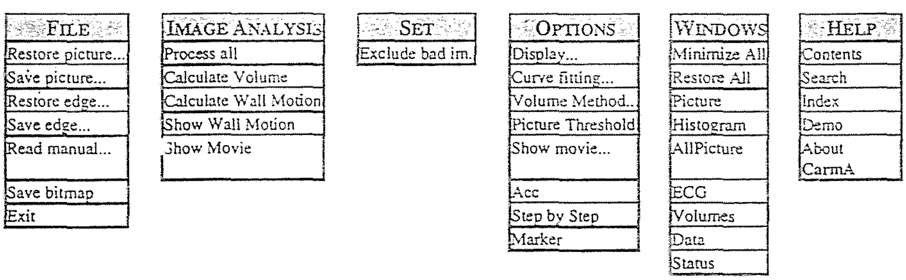


Fig. 4. The menu structure of the **CarmA** system

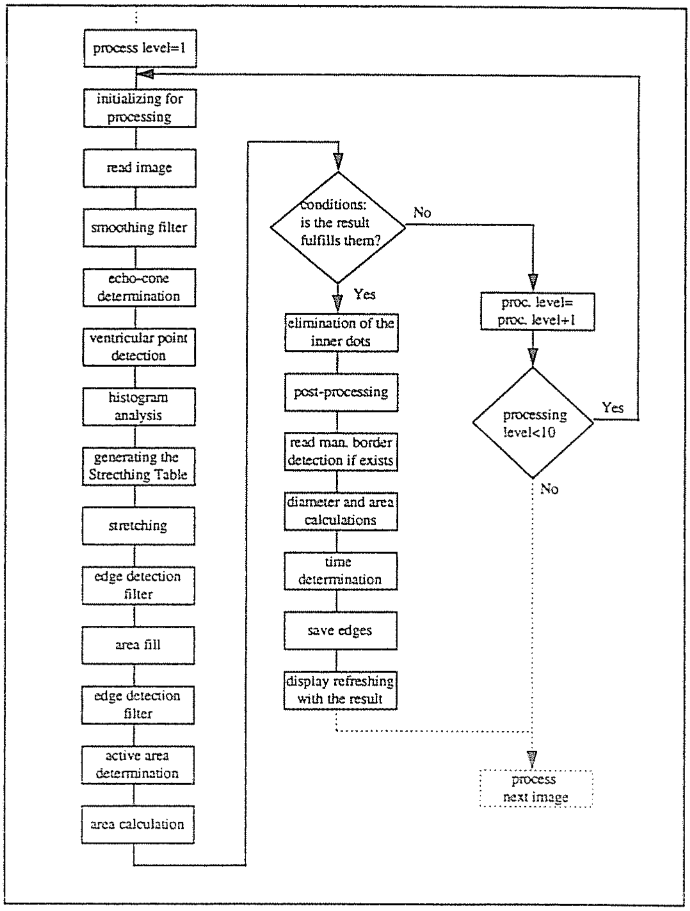


Fig. 5. Simplified flow-chart of one-image analysis

intensity increases in the tissue area, by finding the minimum of this function the darkest region can be found, therefore a point inside the ventricle can be detected. The correctness of this detection is decided in the next step, when a radial edge detection (2) filter is performed. For enhancement, histogram analysis and stretching is done before the edge detection.

$$F(r^i) = \frac{1}{3}\left\{x(r^i+2)+x(r^i+1)+x(r^i)-x(r^i-1)-x(r^i-2)-x(r^i-3)\right\}, \tag{2}$$

where r^i is the distance from the previously determined ventricular point, $x(\cdot)$ is the local brightness. This filter finds the edge point when its $F(\cdot)$ value is larger than a predefined value. By *active area calculation* the validity of the detected edge can also be determined. The detected edge is refined by eliminating inner dots and lines and also by smoothing (*post-processing*).

Obtaining all contour lines, areas and volumes can be calculated, and having all volumes of a cardiac cycle provides the ejection fraction also.

Based on the detected edges, wall motion, its speed and acceleration can easily be calculated. This gives useful information on the functionality of different heart segments.

2.5. *User Interface of the System*

As mentioned earlier, the whole system conception was to make a user-friendly system. The user interface which seemed to best fit this requirement can be seen in *Fig. 6*.

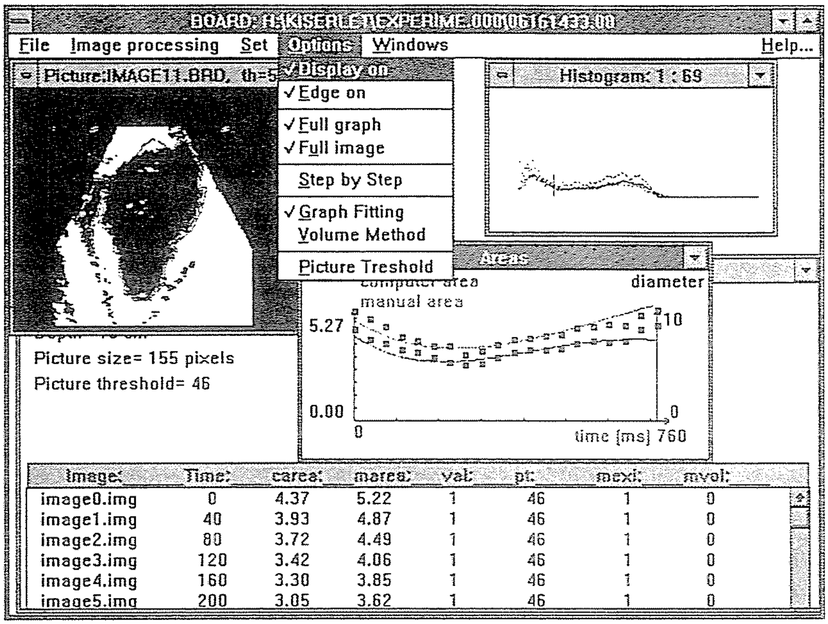


Fig. 6. User interface of the program **CarmA** in Windows environment (sheep heart, short axis view, end-diastole)

A typical screen can show an image, its histogram, and the ECG signal which belongs to the experiment. Furthermore when the experiment is processed, the area/volume curves and text data can also be seen. All windows are resizeable and movable and they can be separately opened, closed and viewed. There is an extra window which can display all resulting images together with their edges.

3. Materials and Methods of the Validation

Validation processes were carried out as a part of a larger study which focused on the role of the endogenous hormone, adenosine, in regulating cardiac efficiency in anaesthetised sheep with elevated cardiac work loads. The methods described below are valid for the whole validation process, the same animal experiments and methodology were used to answer the different validation questions.

Using an Ekoline Echo 5500D echocardiograph with a Hewlett Packard 5 MHz short focus mechanical oscillating transducer, the heart was imaged directly from its surface. Papillary level short axis and long axis views were recorded using PAL format and VHS video tape for subsequent off-line analysis. The apical 2 and 4 chamber views were not possible to be obtained as the transducer could not be placed in an appropriate position for such an analysis using a right sided thorocotomy.

Image analysis was carried out by two methods which differed only slightly from one another, the greatest difference being the amount of operator time required. Both methods were off-line analyses of the pre-recorded images. One method used the fully automated edge detection system (**CarmA**) and the other used a semi-automated system (with the help of a cardiologist expert). The first step in the analytical process of both systems was to frame grab and digitise a sample cardiac cycle for both the long and short axis views of each set of measurements made. In the second step the **CarmA** system performed the automated data processing and parallel with this the cardiologist has prelimited the ventricle on the frame grabbed images. As a final step the results were compared and statistically analysed.

4. Results

We have obtained satisfactory results with automatic boundary detection in 10 sheep with 103 series of images (53 short axis, 50 long axis) consisting of 2060 pictures. In a series the frames followed each other in a 40 ms interval which enabled us to monitor the cardiac cycle precisely. With the detection and tracking of the endocardial-blood interfaces the computer calculated the cavity areas and they were compared to the manually performed boundary detection. *Fig. 7* shows a typical statistical result for one of the cardiac cycles.

5. Discussion

This report has discussed the development of a software system, **CarmA**. Two-dimensional ultrasound measurements of the left ventricle have been

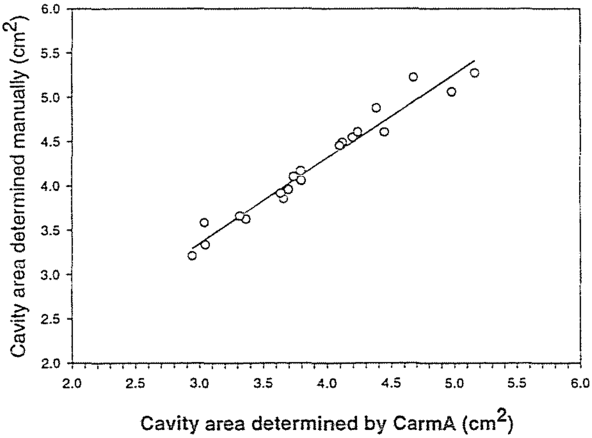


Fig. 7. Comparison of the manual and automatic boundary detection. (Line fit $y = 0.98x + 0.50$, $r = 0.98$)

found to correlate well with angiographic, autopay (involving segmental cavity areas) and reproducibility. This is consistent with recent findings using similar automatic boundary detection systems [3], [4], [5].

The benefits of the discussed system:

- As images are available for the entire cardiac cycle, usually at least for two cardiac cycles, it is possible to calculate not only the end-systolic and end-diastolic areas and volumes of the left ventricle, but areas and volumes can be determined for each frame (usually 12–30 frames per cardiac cycle depending on the heart rate). Therefore not only the ejection fraction but the changes of the volume can also be analysed frame by frame.
- Wall motion of the left ventricular wall can also be determined throughout the cardiac cycle.
- As the system is fully automatic, it gives an objective way of measurement, eliminating the subjective elements of the edge detection which is usually introduced by other methods.

Further refinement is needed in order to analyse various sicknesses, as the system presently works best with healthy, not largely distorted sick hearts. By faster and faster hardware, real-time processing has also become viable, parallel processing and a faster algorithm are also targets of future development.

By using advanced image processing techniques, a computer can more efficiently analyse the blood-tissue interface and hence analyse changes in area, percent fractional area change and rates of area change over time. Comparison of this method of analysis with off-line manual methods have highlighted the areas of the technique which require adjustment, to allow a clinically suitable system. Therefore at present the off-line automatic measurement system which was developed may be the balance point between a technology providing data in real-time and the earlier manual methods.

References

[1] UCHIYAMA, T. – KAJIWARA, N. – KOBAYASHI, Y. – ISHII, H.: Comparison of Manual and Computer-Assisted Automatic Measurement of Wall Thickness of the Left Ventricle in Two-Dimensional Echocardiography. *Japanese Circulation Journal*, 1994 Vol. 58, No. 49–56.

[2] PEREZ, J. E. – WAGGONER, A. D. – BARZILAI, B. – MELTON, H. E. – MILLER, J. G. – SOBEL, B. E.: On-line Assessment of Ventricular Function by Automatic Boundary Detection and Ultrasonic Backscatter Imaging. *J. Am. Coll. Cardiol.*, 1992 Vol. 19, pp. 313–320.

[3] MARCUS, R. H. – BEDNARZ, J. – COULDEN, R. – CHROFF, S. – LIPTON, M. – LANG, R. M.: Ultrasound Backscatter System for Automated On-Line Endocardial Boundary Detection: Evaluation by Ultrafast Computed Tomography. *J. Am. Coll. Cardiol.*, 1993, Vol. 22, No. 3, pp. 839–847.

[4] COLLINS, S. M. – SKORTON, D. J. – GEISER, E. A. – NICHOLS, J. A. – CONETTA, D. A. – PANTIAN, N. G. – KERBER, R. E. Computer-Assisted Edge Detection in Two-Dimensional Echocardiography: Comparison with Anatomic Data. *Am. J. Cardiol.*, 1984, Vol. 53, pp. 1280–1387.

[5] WAGONNER, A. D. – BARZILAI, B – MILLER, J. G. – PÉREZ, J. E.: On-line Assessment of Left Atrial Area and Functional by Echocardiographic Automatic Boundary Detection. *Circulation*, 1993, Vol. 88, pp. 1142–1149.