THE MECHANICAL ENGINEERING APPROACH FOR THREE DIMENSIONAL MODELING PROCEDURE AND MEASUREMENTS OF THE HEART ANATOMY

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Committee Members:

Hamid Hefazi, Ph.D. (Chair)
Barclay Gilpin, Ph.D.
Ortwin Ohtmer, Ph.D.

College Designee:

Hamid Hefazi, Ph.D

By Gaurav C. Satam

B.E., 2007, University of Mumbai

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ABSTRACT

THE MECHANICAL ENGINEERING APPROACH FOR THREE DIMENSIONAL MODELING PROCEDURE AND MEASUREMENTS OF THE HEART ANATOMY

By

Gaurav C. Satam

January 2010

The anatomical measurements are usually required for aortic stenosis patient for surgical procedures. The literature study shows that accurate and consistent procedure is not available to obtain the measurements of the heart anatomy. Data obtained from the literature varies across many parameters such as the state of the patient, the measurement definition and the procedure of obtaining the actual measurement. Most of the data studied was measured and analyzed in 2D planes but in reality human heart is a 3D structure and is oriented in 3D space differently in different individuals. In this work a procedure is developed to obtain 3D model of the heart anatomy with a required accuracy. Using the 3D model created, the measurement analysis was carried out to obtain parameters such as the diameter of annulus, aorta, area at the required cross section, 3D angle of the cross section and the volume of left ventricular outflow track (LVOT) and other. The DICOM image files from the computed tomography (CT) scan were used as an input. The software such

as 3D DOCTOR, NX-IMAGEWARE and NX-5 were used to create the 3D model and the measurement analysis.

The analysis of all the data obtained indicates this procedure and anatomical measurements of the heart by the 3D approach is more reliable than the conventional 2D approach. The measurements also show better consistency for a given set of input data. With the growing importance of the minimally invasive surgery (MIS), the developed procedure and data can give reliable assumptions to get stent diameter, forces on the aorta. It can also be used for the development of the customized pre surgery models for MIS.

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TABLE OF CONTENTS

Page

ACKNOWLEDGEMENT..... iii

LIST OF TABLES..... v

LIST OF FIGURES..... vi

CHAPTER

1. INTRODUCTION..... 1

2. PROCEDURE..... 5

3. RESULTS..... 15

LVOT Anatomical Measurement Analysis..... 19
Area..... 20
Angle of Tilt..... 21
Maximum and Minimum Distance..... 22
Aortic Valve Measurement..... 24
Aortic Arch Measurement..... 26

4. DISCUSSION..... 28

Cross Sectional Area..... 28
Angle of Tilt..... 29
Maximum and Maximum Distance at The Cross Section..... 30
Aortic Valve Measurement..... 32
Radius of Curvature of the Aortic Arch..... 33

5. CONCLUSION..... 34

REFERENCES..... 36

LIST OF TABLES

TABLE		Page
1.	Area at the Cross Section	20
2.	Angle of Tilt (degree)	21
3.	Maximum Distance on the Cross Section Plane	22
4.	Minimum Distance on the Cross Section Plane	23
5.	Diameter in Diastole Phase	24
6.	Diameter in Systole Phase	25
7.	Radius of Curvature	27

LIST OF FIGURES

FIGURE		Page
1.	Procedure step 1	6
2.	Procedure step 2	6
3.	Procedure steps 3 and 4	7
4.	Procedure step 5	8
5.	Procedure step 6	9
6.	Procedure steps 7 and 8	10
7.	Procedure step 9	12
8.	Procedure steps 11 and 12	13
9.	Procedure step 14	14
10.	Procedure step 15	15
11.	Three-D DOCTOR model	16
12.	Three-D Curve model in Imageware	16
13.	Three-D Surface model in Imageware	17
14.	Cross section of the required location	17
15.	Measurement at each section	18

FIGURE Page

16. Area at the desired cross section..... 18

17. Angle of tilt..... 18

18. Area of cross section at different distance..... 20

19. Angle of tilt of the cross section at the different distance..... 21

20. Maximum distance on cross section plane..... 22

21. Minimum distance on cross section plane..... 23

22. Definition of the aortic valve diameter..... 24

23. Diameter in diastole phase..... 25

24. Diameter in systole phase..... 26

25. Definition of the radius of the aortic arch..... 26

26. Radius of curvature at diastole and systole..... 27

27. Histogram of area of cross section (Normal distribution)..... 29

28. Histogram of angle of tilt (Normal distribution)..... 30

29. Histogram of minimum distance on cross section (Normal distribution)..... 31

30. Histogram of maximum distance on cross section (Normal distribution)..... 31

31. Histogram of annulus and aortic diameter (Normal distribution).... 32

32. Histogram of radius of curvature of the aortic arch (Normal distribution)..... 33

CHAPTER 1

INTRODUCTION

The literature study shows that the anatomical measurement data is not consistent and varies vastly. The data differs in the definition of the measurement and method followed to obtain it. Most of the data observed in the literature was measured and analyzed in two dimensional (2D) planes [1- 4]. It was observed that any 2D measurements instead of the three dimensional (3D) can give erroneous results. The human heart is the 3D structure and the orientation of it is not same in all individuals [5, 6]. In the present research, an attempt is made to develop a procedure to obtain the anatomical measurements of the heart (of a certain population) and make a customized 3D model. The measurements for left ventricular outflow track (LVOT), aortic valve and radius of curvature of aortic arch were obtained by analyzing number of image sets created. The statistical analysis was carried out on obtained data to get the better idea anatomical measurement of the population.

It is observed that the geometry of the aortic valve and the region around it is very crucial because inaccurate judgment of the geometry could largely affect the risk of thrombotic complications. The geometry of the aortic root is also important for the appropriate flow field. The different methods were tried out in the past to obtain these dimensions and one of them was using the film monitor. The films were

projected on to the monitor and geometrical data was measured using the scaled templates. All the measurements such as aortic diameter, length of the sinus, length between the two diameters etcetera were measured in 2D plane. The results obtained had certain shortcomings. Even though all the aspect of the phase change and views were taken into account it did not provide the accurate results compared to 3D measurements. The idealization of the geometry and 2D measurements provided inaccurate results which in turns affected the future assumptions and calculations based on it [1].

The noninvasive evaluation of the aortic root is usually carried by computed tomography method to find out implications of the transcatheter aortic valve replacements [2]. The transcatherter aortic valve replacement is the next generation method for the heart valve repairs. A considerable knowledge of anatomical measurements of heart is required to perform such procedures. The usual method is to use multi sliced computed tomography (MSCT) scan for the evaluation of performance. The reconstructed and sagittal views are usually used for the measurement assessment. The usual procedure is to measure all these distances and diameters at the end of a diastole cycle. The results obtained from such studies are used for analyzing paravalvular leakage, coronary occlusion and to facilitate the valve replacement procedure. The results obtained in two different views showed significant difference. The calculated difference was between 4.7 mm to 1.1 mm [2] which can be minimized significantly by developing a 3D model and carrying out the

measurement analysis by that model. These measurements will be more reliable and accurate if taken by the 3D model procedure [2].

The assessment of anatomy of the aortic root was carried out on three reconstructed views. The first reconstructed view is the coronal view which is similar to the anterior-posterior view on aortic root angiography. The parasternal long-axis view on transthoracic echocardiogram and the mid-esophageal long-axis view on transesophageal echocardiogram have the same orientation as the single sagittal view. The plane of the reconstructed double oblique transverse view and the plane of the aortic root are parallel [2].

The distance on the 2D planes changes as the object is rotated or tilted in three dimensions which imply that the distances measured would not give reliable and accurate results [2]. This is because with the phase change from diastole to systole there is change in the orientation of aortic arch and other parts around it. The distance between the ostia of the coronary arteries and the coronary leaflets needs to be assessed for percutaneous aortic valve replacement, because this may determine the risk of coronary occlusion. The distance between the ostium of the left coronary artery and the tip of the left coronary leaflet was determined in diastole and systole phase [2].

The aortic valve steniosis is becoming very regular procedure for the aortic valve replacement. The studies are underway to evaluate the performance of the replaced valve. All the analysis which deals with the distensibility and migration requires in depth measurement analysis of the LVOT and aortic valve. The systolic

and diastolic diameters were recorded from the parasternal view. The results were used to find the diameter change during phase change and to evaluate the aortic steniosis severity. Although the results obtained were reasonable, the accuracy was compromised to some extent [3].

So the literature review provided substantial evidence that 2D measurement analysis can be improved for better accuracy. This can be achieved by developing 3D modeling procedure and measurement analysis (using 3D model) which would overcome these shortcomings.

CHAPTER 2

PROCEDURE

Initially, the CT scan images were used as an input for generating the primary 3D model of the heart. All the images obtained from the CT scans are .IMA files which can be imported to the 3D-DOCTOR software by performing following steps.

1. Click on 'create stack' option on file menu of the 3D-Doctor software. Select the option of 'add folder' to add the folder which has the CT scan images of .IMA format. Once the folder is added, all the files will be converted to DICOM images (which are compatible with software) and 'Sort DICOM file' option will be active. Then select the appropriate option given on the right hand side of the screen to arrange the image files according to their sequence of acquisition (by time). Then click 'open' to start the boundary identification of the desired region.

2. It is difficult to take the CT scan images of the heart only. Usually the CT scan images of the body region around the heart are taken, therefore considerable approximations have to be assumed about the location and orientation of the heart. The images after initial stacking are shown below in figure. Once all the images are arranged the 3D wizard option will appear. Then use the 'contrast' option located on toolbar accordingly to visualize desired region clearly.

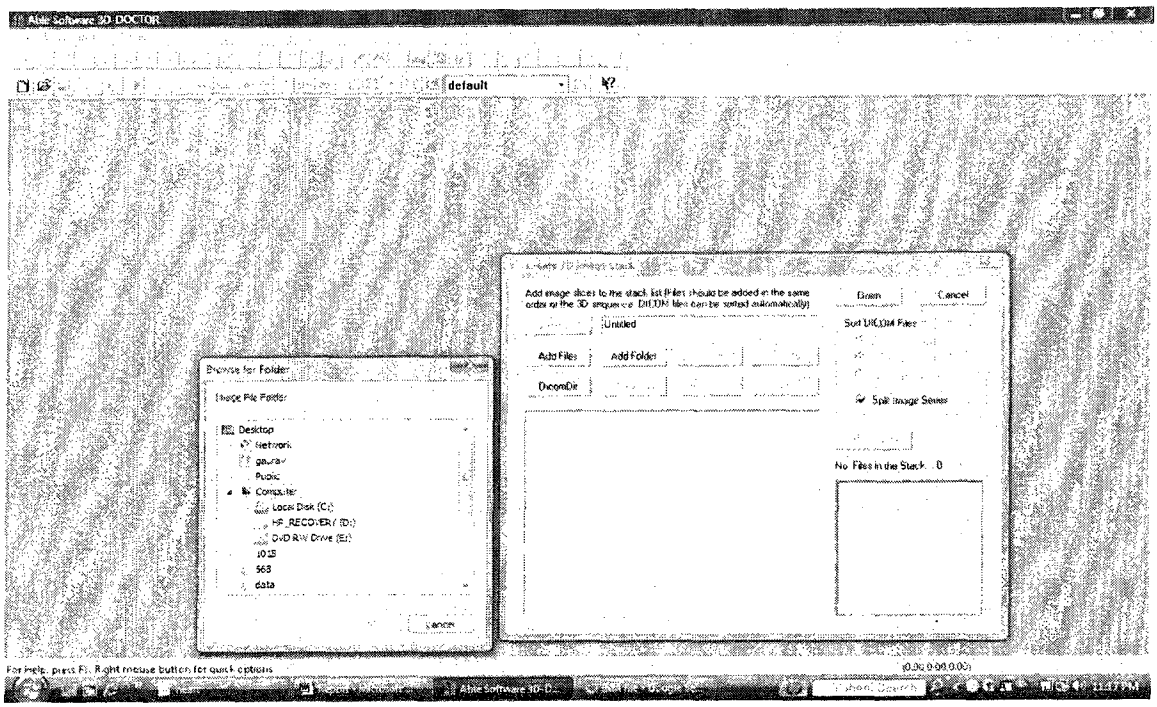

FIGURE 1. Procedure step 1.

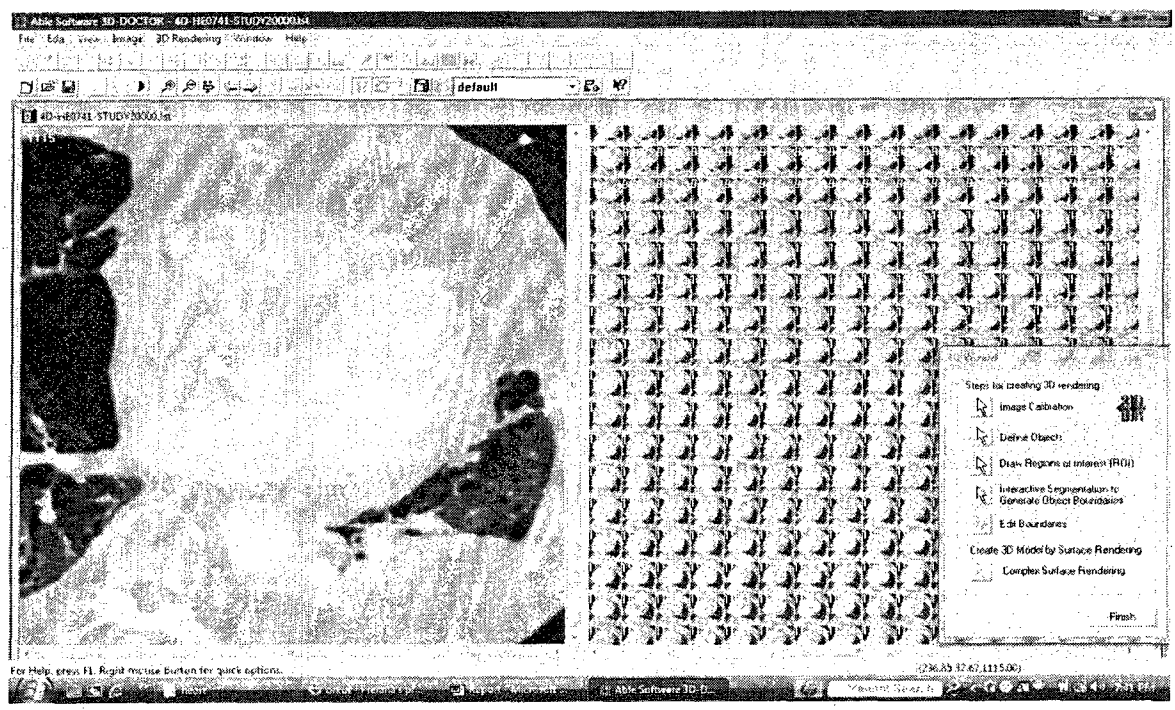

FIGURE 2. Procedure step 2.

3. The slice thickness of each image can be entered by using the image calibration button on 3D wizard.

4. Click on the define object to select the desired region from the complete image as shown below. Once the region is defined the 'interactive segmentation' option can be used to highlight the particular area inside the desired region depending on the pixels and the contrast. The interactive segmentation window has several options, each of which can be used for a different purpose the 'segment plane' option was selected with 'smooth edges' box checked. This would give the approximate boundary around the highlighted region.

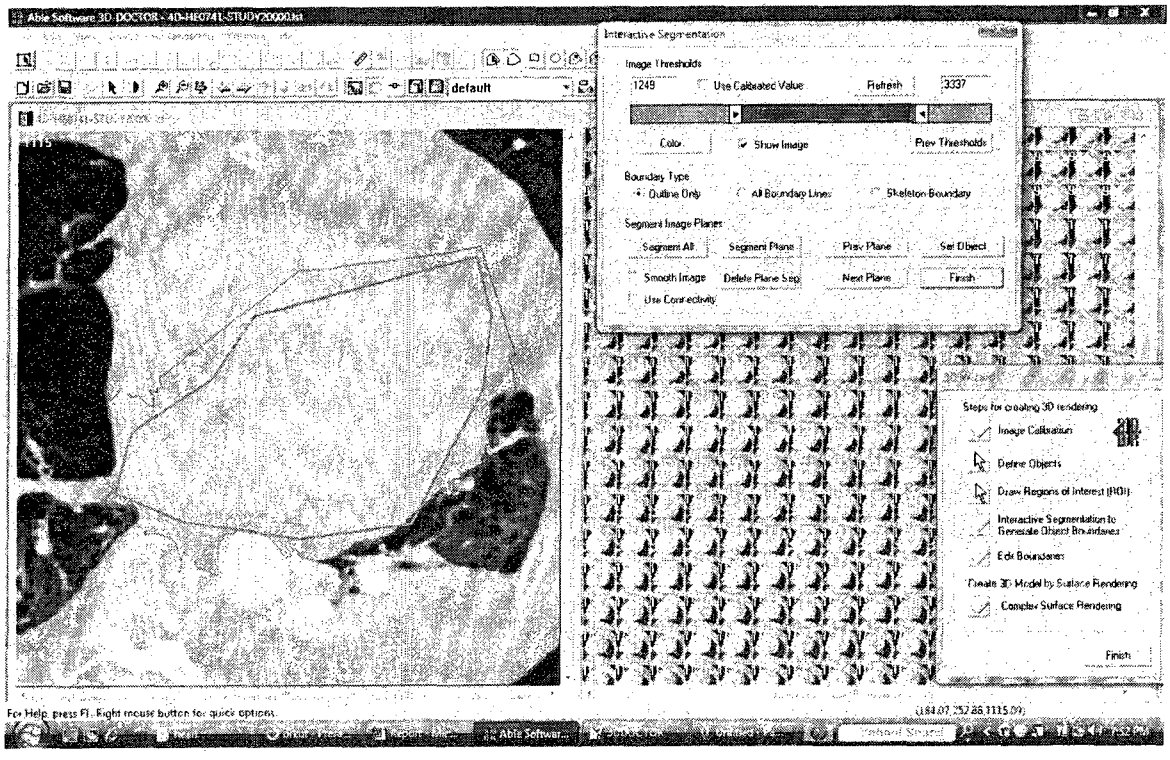

FIGURE 3. Procedure steps 3 and 4.

5. The 'edit boundaries' option can be used to edit the boundary lines of preliminary boundary provided by the 3D doctor automated option. Then use the different tools such as trace boundary, snap edges, delete node, add node, smooth lines, mirror, histogram etc. This step is the most time consuming and critical step to get the required accuracy. Follow the steps 3 and 4 for all the number of slices per instance (usually 1200 to 1500 slices per instance)

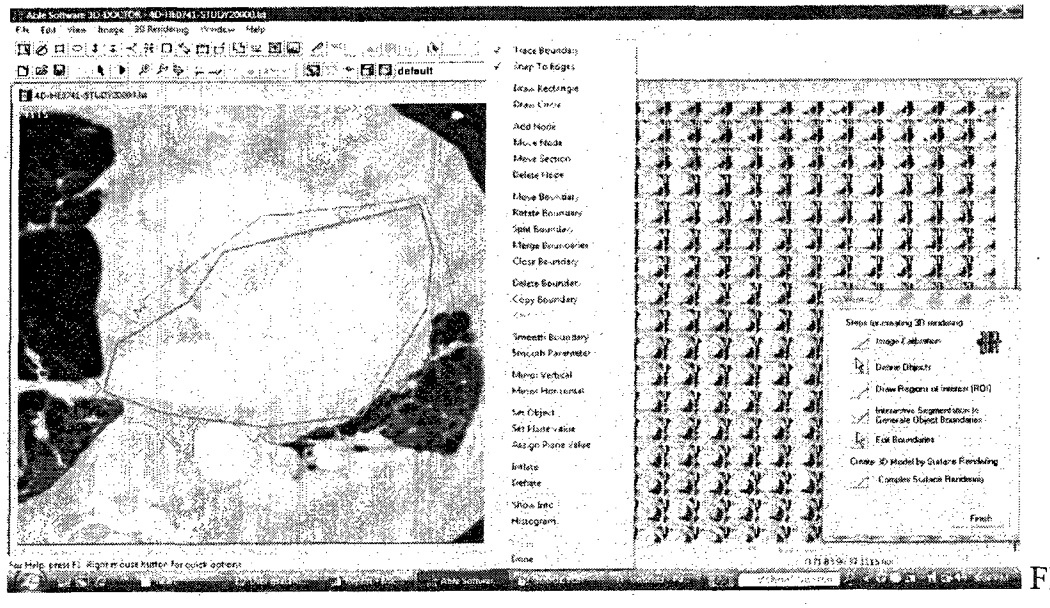

FIGURE 4. Procedure step 5.

6. Once all the slices (images) were completed, use the option complex surface rendering to combine all those slices to get surface polygons. Then enter X, Y and Z values in the complex rendering command window. The selection of these values will be based on the complexity of the object and the required accuracy.

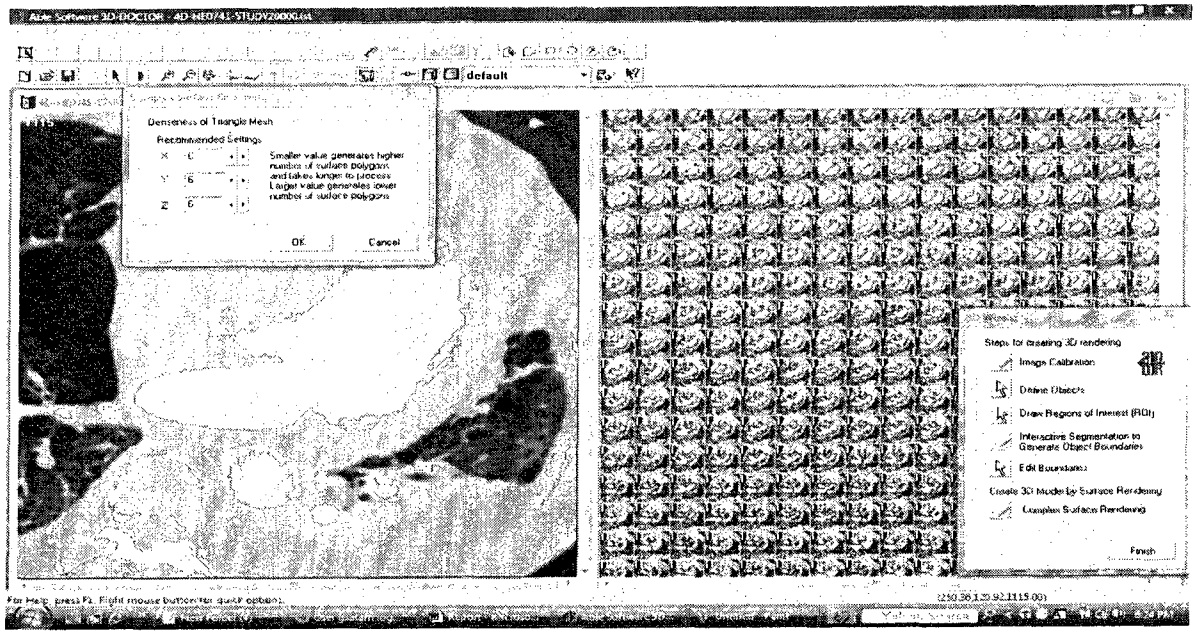

FIGURE 5. Procedure step 6.

7. The initial 3D model of the object with given parameters can be generated by using the 'ok' command. The continuous surface model is usually desired for the accurate anatomical analysis but the surface generated by 3D doctor is not a continuous surface but it is made up of millions of small surfaces.

8. Once the 3D object is formed, the command 'export object' on toolbar can be used to convert this model file in to .DXF file (point cloud file of the object in 3D).

9. Use the imageware software to open the .DXF file created in 3D doctor. The .DXF file is opened as point cloud as shown in the figure. By using the edit point cloud option select the required part of the point cloud. The figure shows the left ventricle of the heart as the selected point cloud.

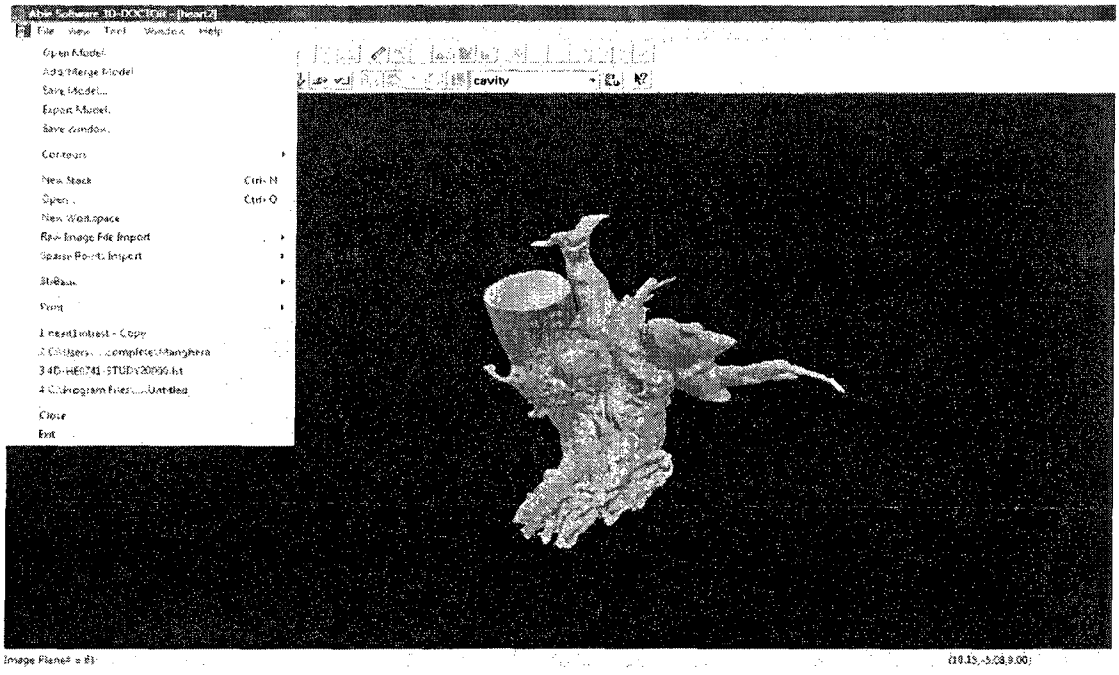

FIGURE 6. Procedure steps 7 and 8.

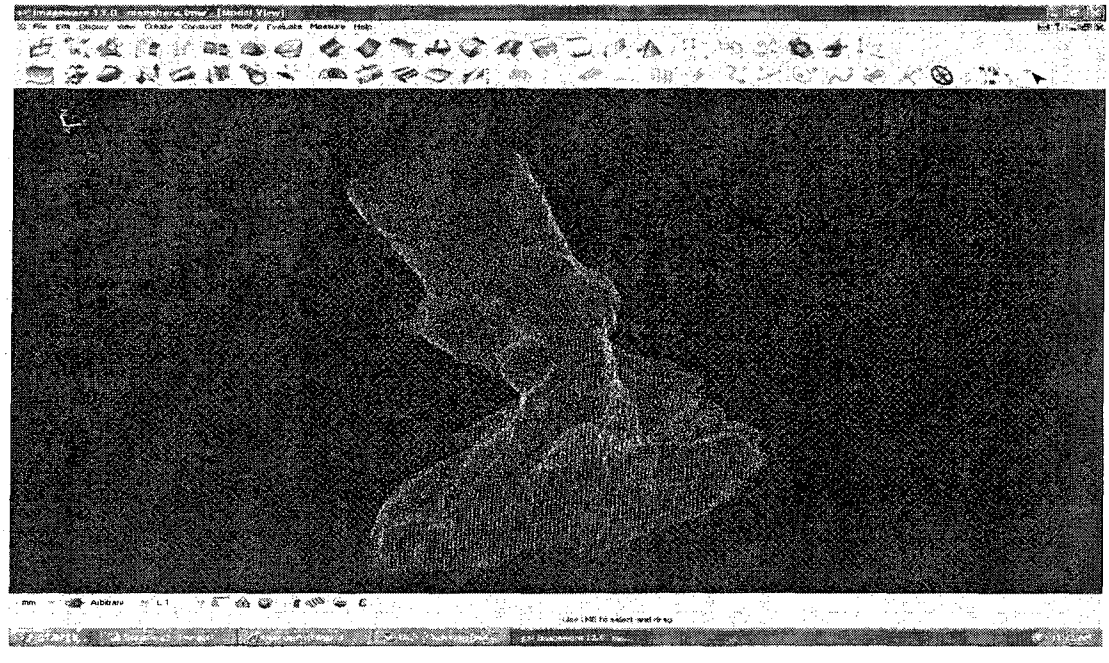

FIGURE 7. Procedure step 9.

10. Clear all the extra points on the cloud. Then select the edit option on the toolbar and reduce the density of the clouds as per the required accuracy.

11. Select the 'construct' option from the toolbar to draw the 3D curve along the orientation of the heart. Then make sure that the curve is in proper alignment with the point cloud on every view and isometric view.

12. Click on the 'construct' option on the toolbar to create the cross sections on the point cloud along the curve drawn in the previous step. Then select the number of cross sections depending on the smoothness on the object and complicity of it. Once you have the cross section drawn on the point cloud select the construct curve to draw the curve on the created cross sections. The number of control points can be used to align the curve as per the shape of the cross sections and make sure all the cross sectional curves are exactly perpendicular to the 3D curve drawn in the step 10. Figure below shows the desired curves created.

13. Click on the create surfaces command inside the construct menu to create the surfaces along the 3D curve created in the step 10. The surface using the cross sectional curves will be created. Then click on the 'evaluate' option on the toolbar menu and select the 'point cloud to surface' evaluation option so that the percent values will be displayed to give the accuracy of the created surface with respect to original point cloud. If the value is above the desired accuracy then accept the surface or repeat the process in the same order to create the new surface.

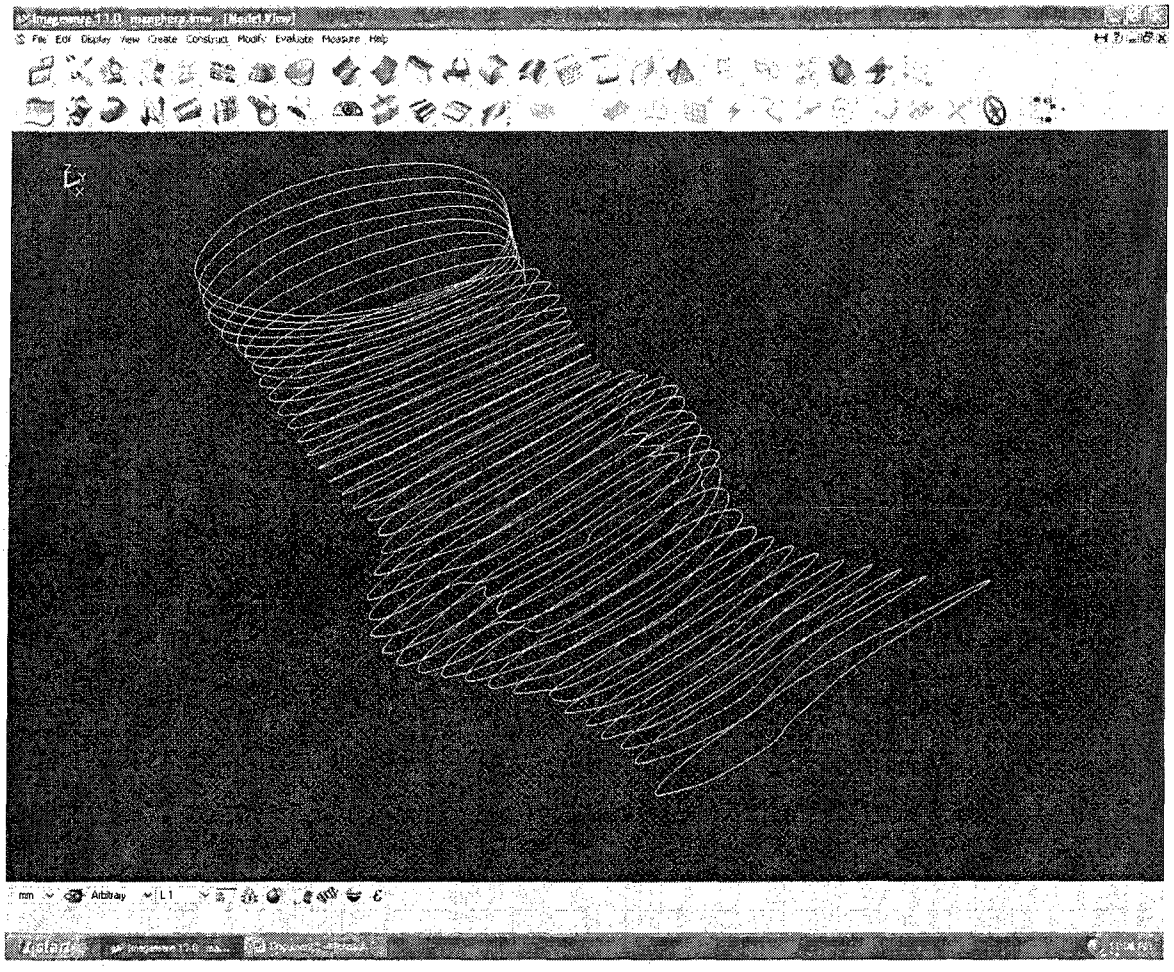

FIGURE 8. Procedure steps 11 and 12.

14. The imageware file has the extension .IMG which can be exported to NX 5.0 as .PRT file. Using the export feature of imageware curves and surfaces of the object will be exported into NX5.0 to create .PRT file. Then use the 'bounded plane' command to create the plane to close the surface and create solid model of the imageware file. Then use the cross sectional view command on NX to create cross section plane on the drawn curves.

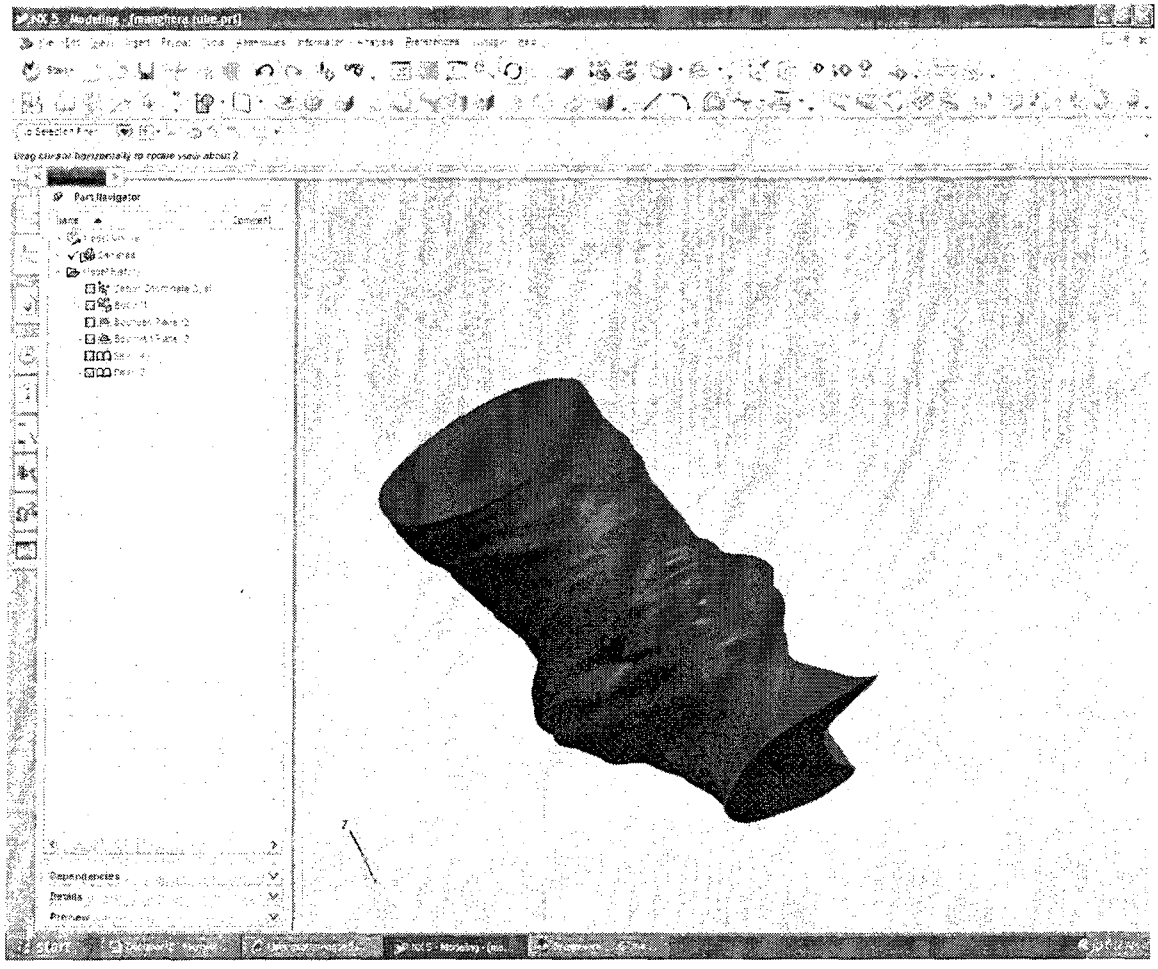

FIGURE 9. Procedure step 14.

15. Use the analysis option on the toolbar to analyze the created cross section. Then use the command in analysis menu to get the measurements such as area, angle of tilt, distance etcetera.

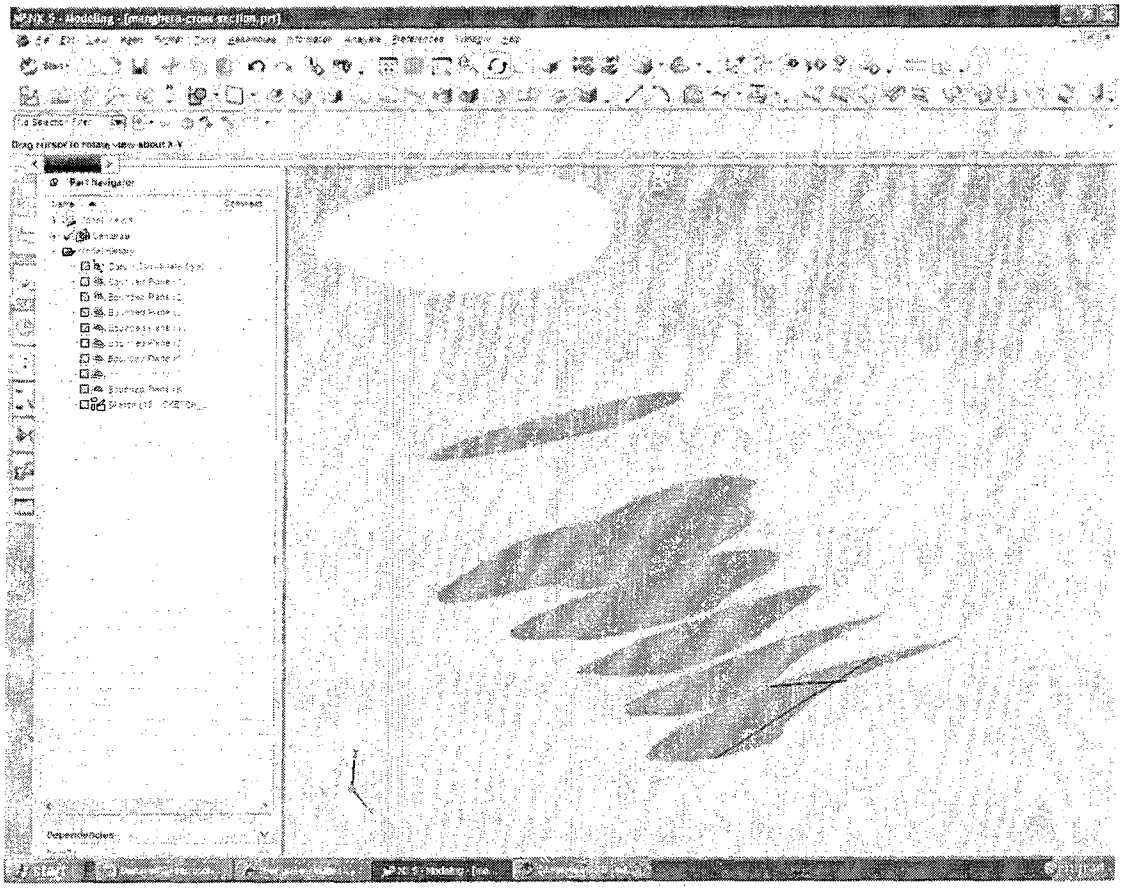

FIGURE 10. Procedure step 15.

CHAPTER 3

RESULTS

The procedure was developed to obtain the 3D model of the heart anatomy. This procedure is used for anatomical analysis of the aortic arch, aortic valve and left ventricular outflow tract (LVOT). The anatomical model at every major step such as initial 3D modeling in 3D doctor, solid surface modeling using imageware and measurement analysis using NX 5.0 are shown below.

1. Initial 3D model (LVOT).

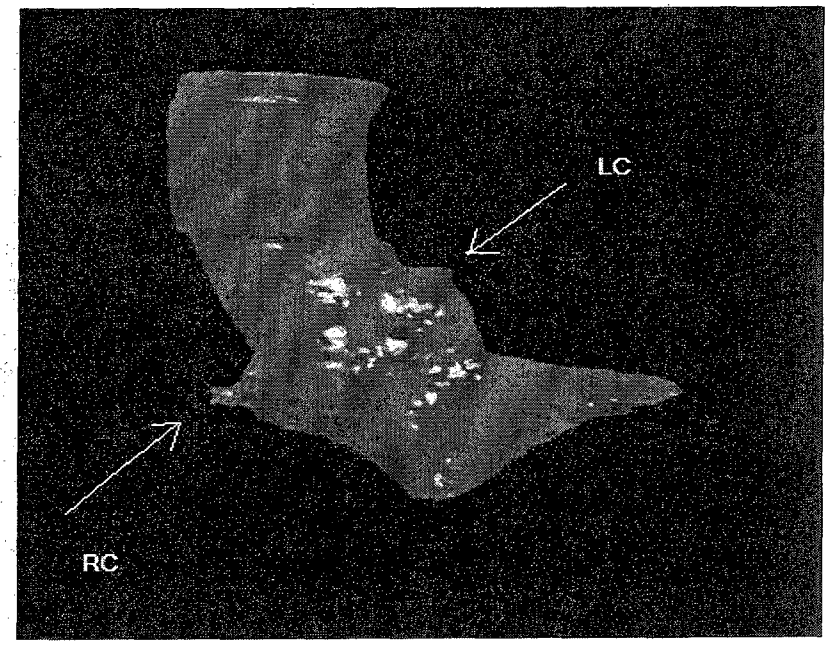

FIGURE 11. Three-D DOCTOR model.

2. Solid surface model in imageware (LVOT).

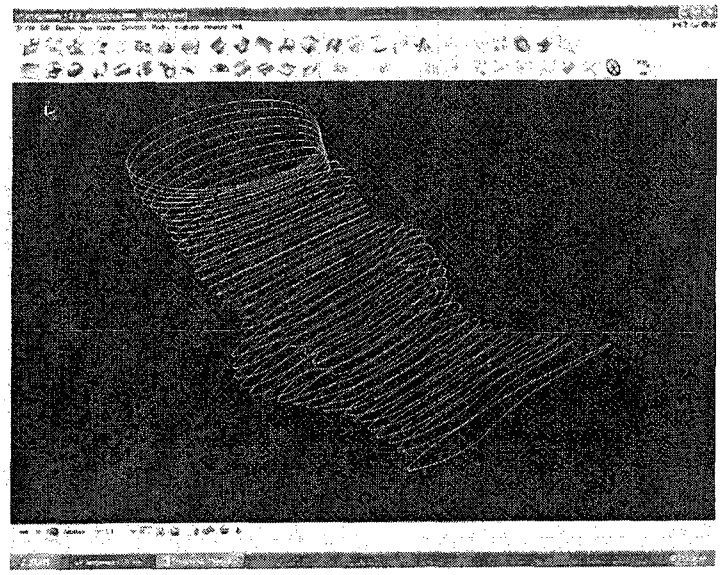

FIGURE 12. Three-D curve model in imageware.

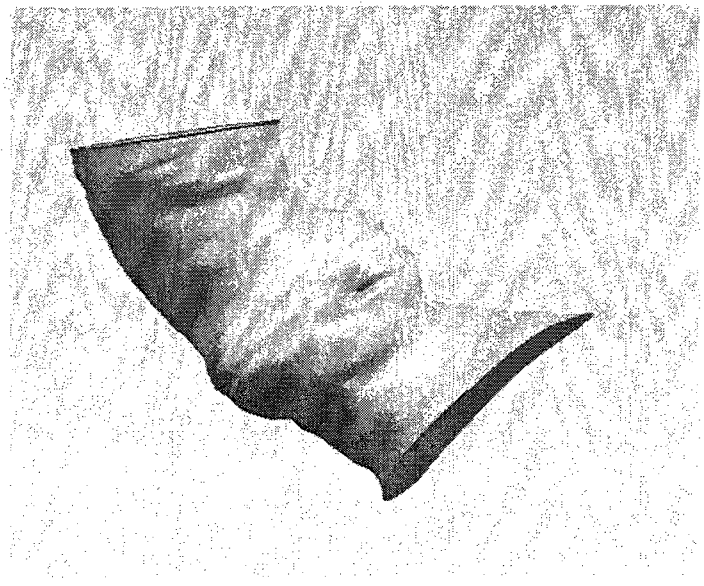

FIGURE 13. Three-D surface model in imageware.

3. Measurement analysis in NX 5.0 (LVOT).

FIGURE 14 Cross section of required location.

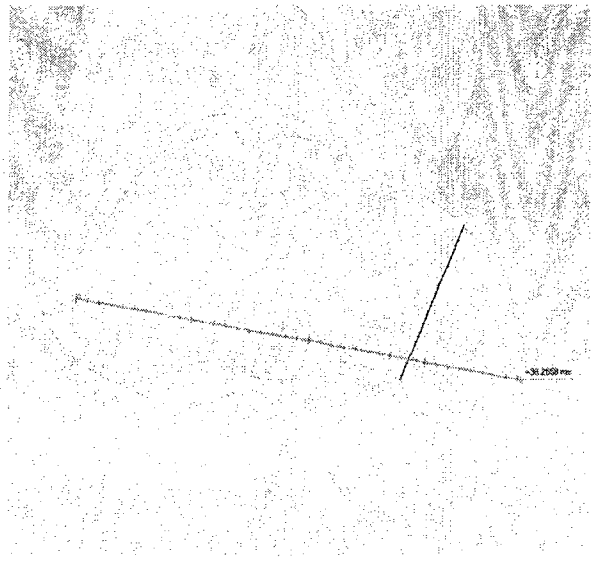

FIGURE 15. Measurement at each section.

FIGURE 16. Area at the desired cross section.

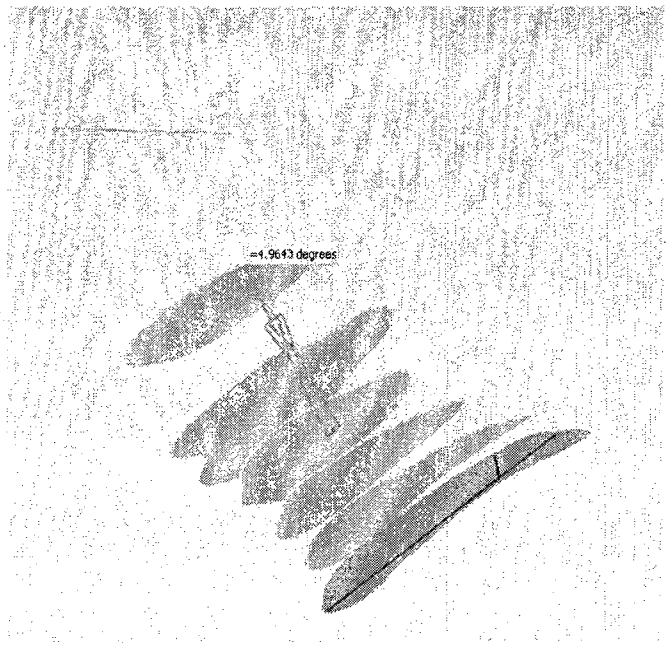

FIGURE 17. Angle of tilt.

The results obtained from the measurement analysis of LVOT, aortic valve and aortic arch is given below. The CT scan images of number of sets were analyzed. Some of them were analyzed for both diastole and systole. The definition for each measurement is provided before the plotted data.

LVOT Anatomical Measurement Analysis

LVOT: The region between the end of the aortic valve and initial part of the left ventricle of the heart.

Area at the cross section: It is the area measured using the NX5.0 on the desired cross section (as shown in figure 19).

Angle of tilt: It is the 3D angle measured between the plane at the start of the valve and respective plane to be measured (as shown in figure 20).

Minimum and Maximum distance: It is the minimum and maximum straight line distance on desired cross section (as shown in figure 18).

Distance: It is the perpendicular distance measured from the plane 5 mm below the annulus.

Area

TABLE 1. Area at the Cross Section

Distance/Sample	H1	H2	H3	H4	H5	H6	H7	H8
0mm	634	454	583	415	463	485	657	360
5mm	830	487	461	364	481	577	707	395
10mm	1158	646	461	357	573	766	1008	524
15mm	1340	960	564	478	788	919	1612	952

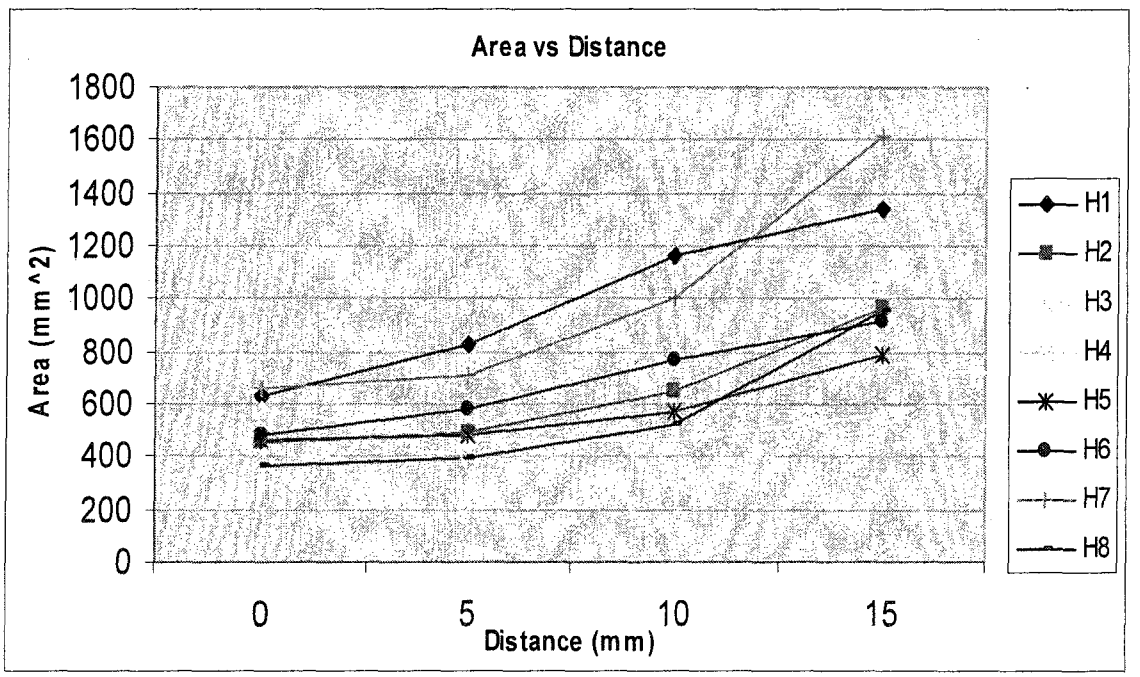

FIGURE 18. Area at the cross section at different distance.

Angle of Tilt

TABLE 2. Angle of Tilt (degree)

Distance/Sample	H1	H2	H3	H4	H5	H6	H7	H8
0mm	7	8	8	16	5	13	6	14
5mm	10	10	6	17	6	17	7	9
10mm	13	10	5	17	8	19	10	6
15mm	16	12	5	18	10	21	14	5

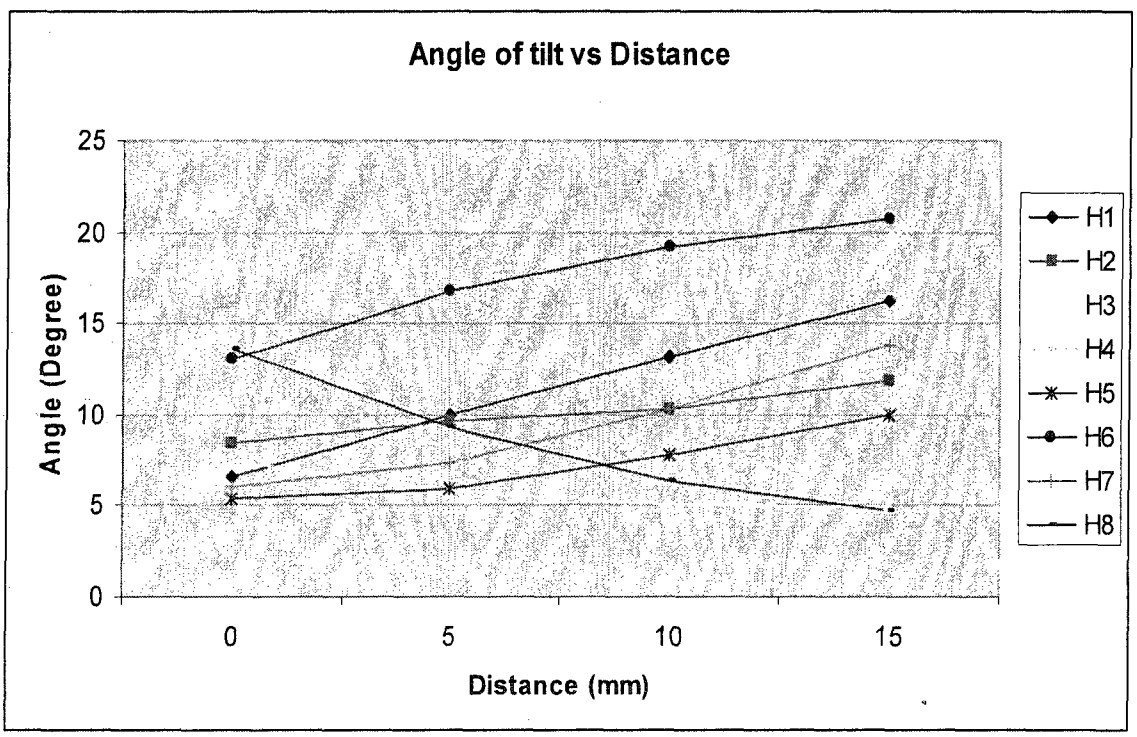

FIGURE 19. Angle of tilt of the cross section at the different distance.

Maximum and Minimum distance

TABLE 3. Maximum Distance on Cross Section Plane

Distance/Sample	H1	H2	H3	H4	H5	H6	H7	H8
0mm	39	26	30	26	28	29	35	23
5mm	47	29	30	26	29	45	33	29
10mm	52	35	34	29	37	45	39	33
15mm	54	45	38	33	46	51	45	44

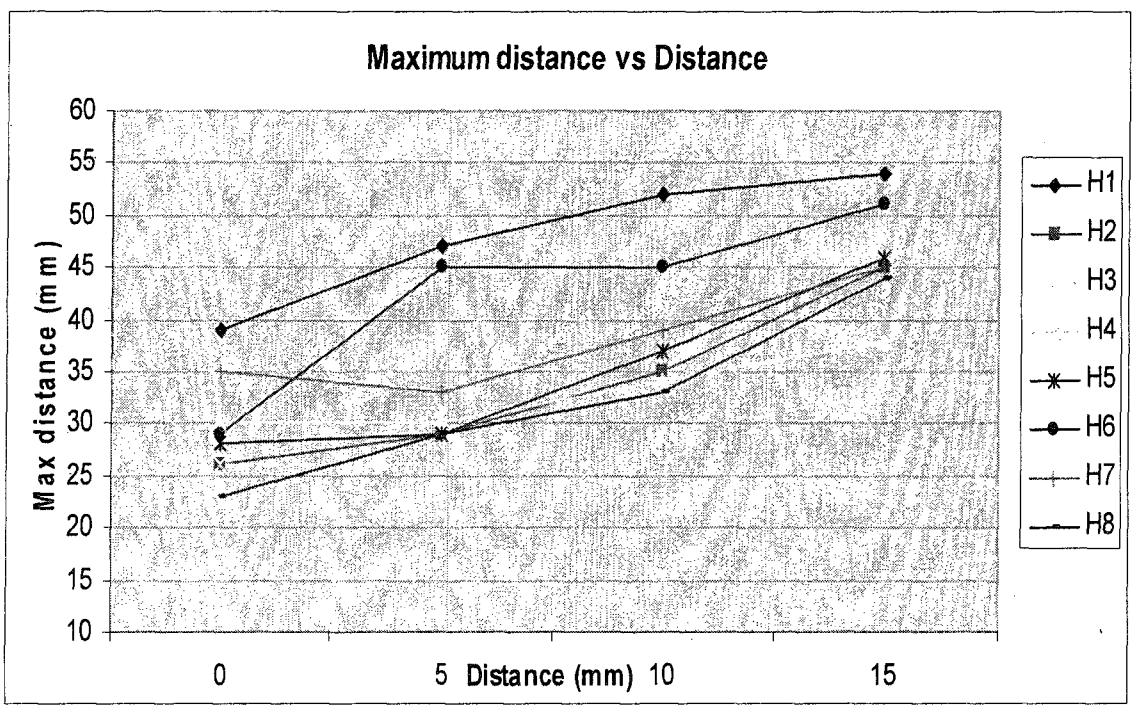

FIGURE 20. Maximum distance on the cross section at the different distance.

TABLE 4. Minimum Distance on Cross Section Plane

Distance/Sample	H1	H2	H3	H4	H5	H6	H7	H8
0mm	20	16	24	15	14	18	14	17
5mm	18	14	14	13	16	20	19	14
10mm	18	13	10	9	17	16	19	13
15mm	19	15	12	10	19	16	19	16

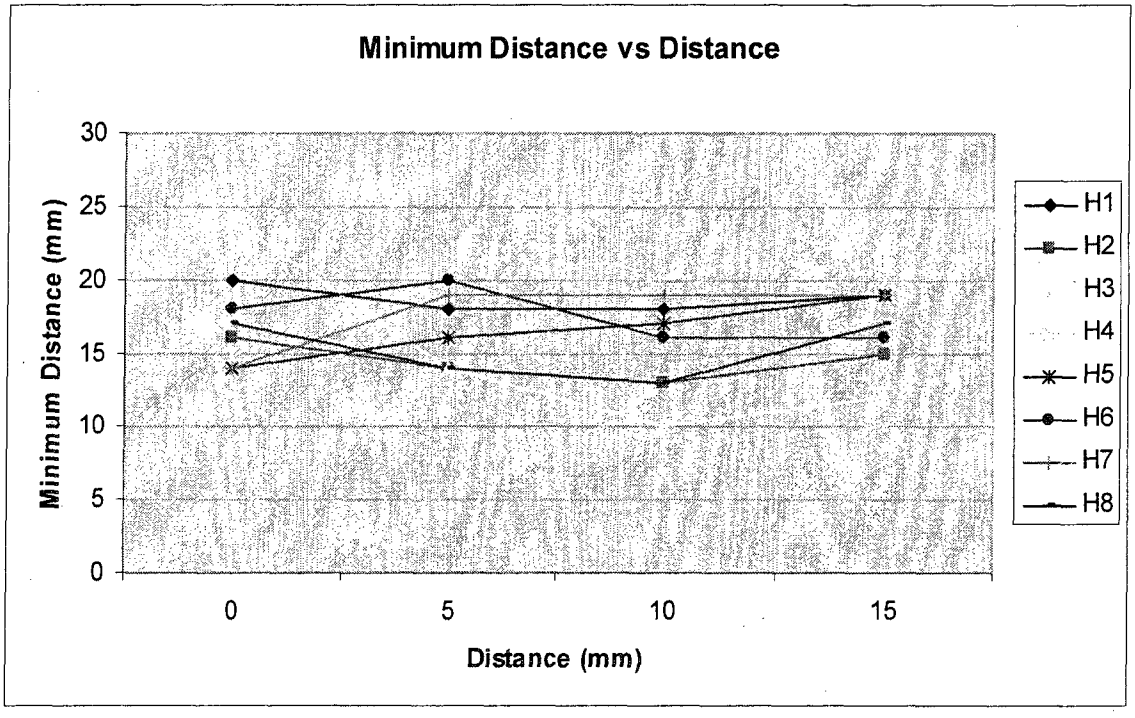

FIGURE 21. Minimum distance on the cross section at the different distance.

Aortic Valve Measurement Analysis

The diameter of the annulus and aorta are defined and measured as shown below.

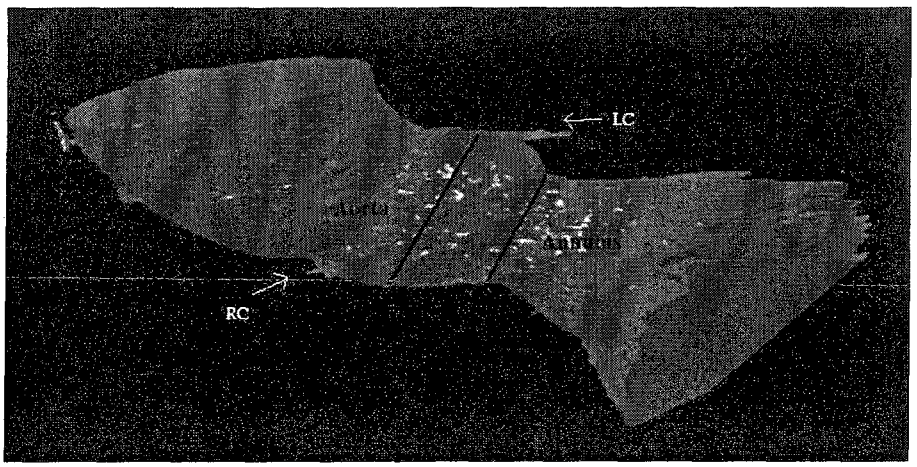

FIGURE 22. Definition of the aortic valve diameter.

TABLE 5. Diameter in Diastole Phase

Diastole	H1	H2	H3	H4	H5	H6	H7	H8
Annulus (mm)	22	20	19	18	24	21	22	23
Aorta (mm)	30	27	38	32	34	33	33	36

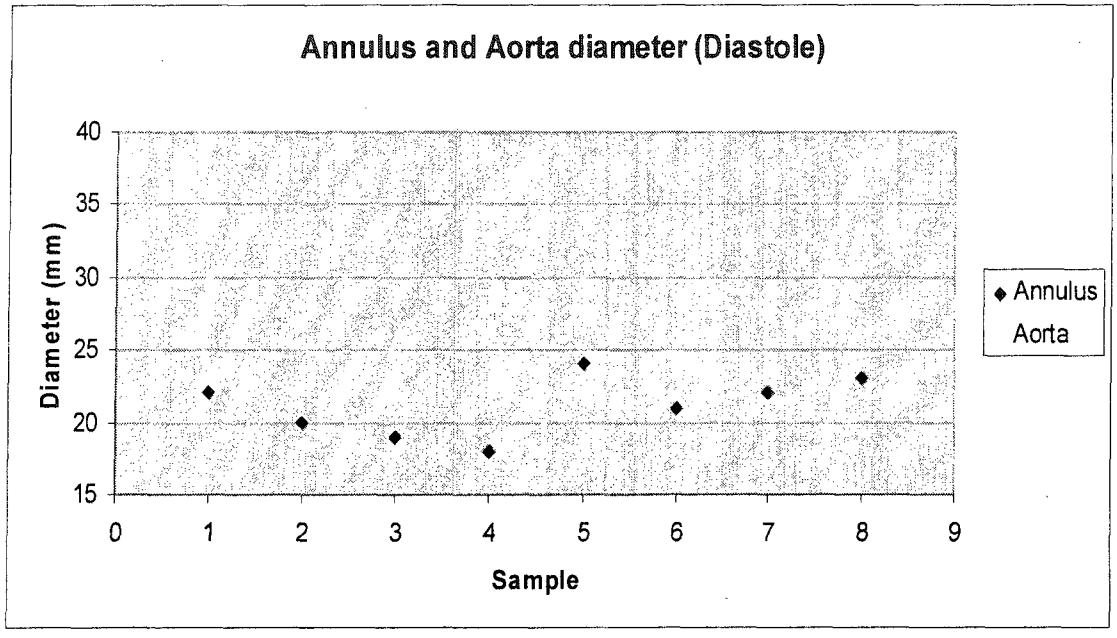

FIGURE 23. Diameter in diastole phase.

TABLE 6. Diameter in Systole Phase

Systole	H1	H2	H3	H4	H5	H6	H7	H8
Annulus (mm)	23	22	23	20	25	22	23	24
Aorta (mm)	33	31	37	33	39	33	31	35

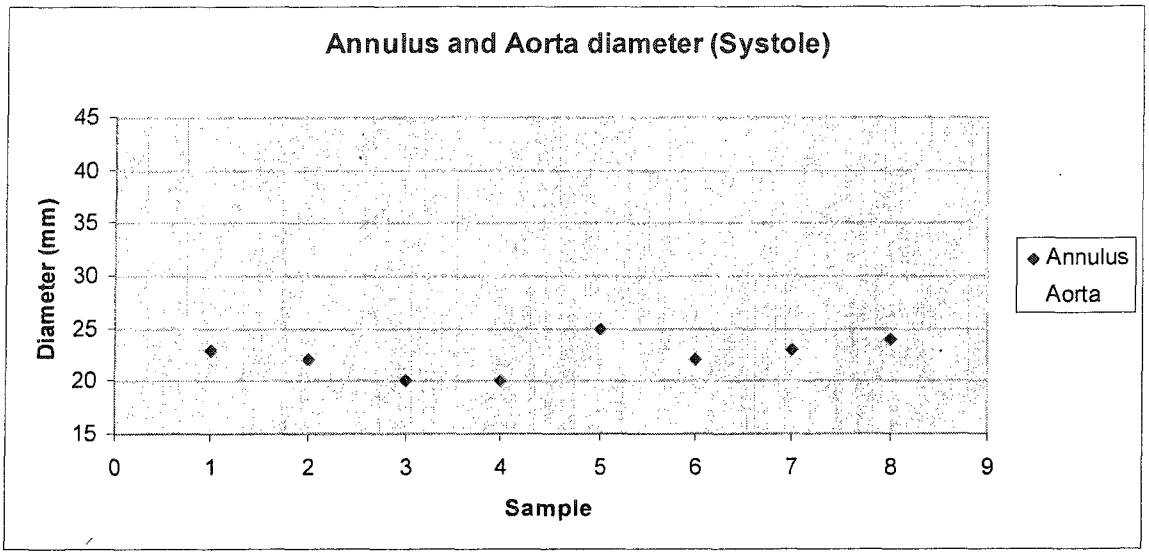

FIGURE 24. Diameter in systole phase.

Aortic arch

The radius of the curvature for the aortic arch is defined as shown below.

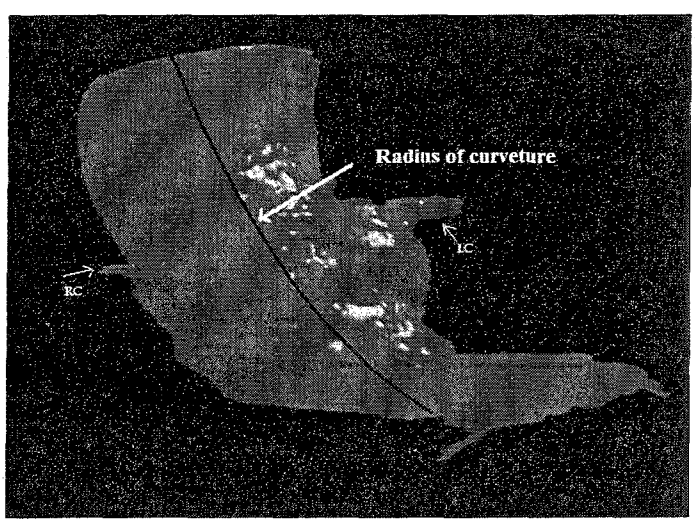

FIGURE 25: definition of the radius of the aortic arch.

TABLE 7. Radius of Curvature

Diastole	77	39	103	58	64	67	122	78
Systole	100	66	91	115	68	130	99	59

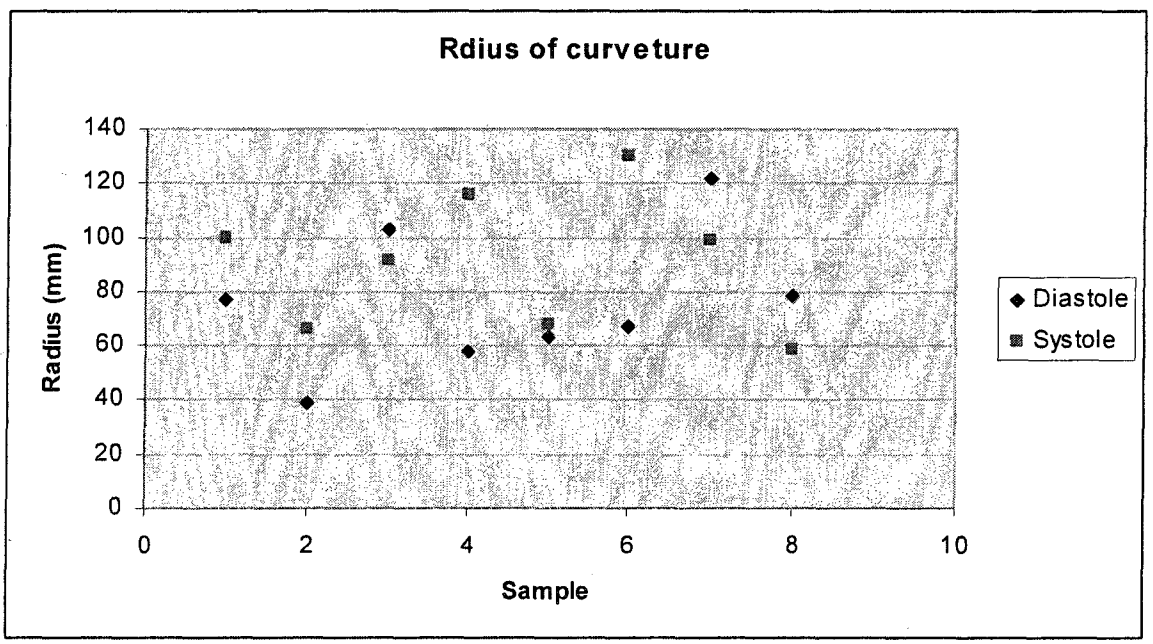

FIGURE 26. Radius of curvature at diastole and systole.

CHAPTER 4

DISCUSSION

The method developed using the mechanical engineering approach has given the better result than the 2D measurement technique. The method can be modified easily for the required accuracy. The 3D model developed using 3D DOCTOR software has given the better idea about the desired region. The solid model developed using IMAGEWARE has smooth surfaces which are easy to prototype. The cross sections at the desired section of the model were taken for further analysis. The cross section taken using this developed method was used to obtain the measurement analysis results.

Cross Sectional Area

The normal distribution plots of the measured areas were plotted. The area at 0 mm plane showed more consistence result with the mean of 506.4 mm^2 and the standard deviation of 106.7. The areas at 5 mm, 10 mm and 15 mm cross section planes increased as the distance increased. Also, the standard deviation values increased with increase in the distance. The area of the cross section can be predicated up to certain distance after which it became difficult to predict.

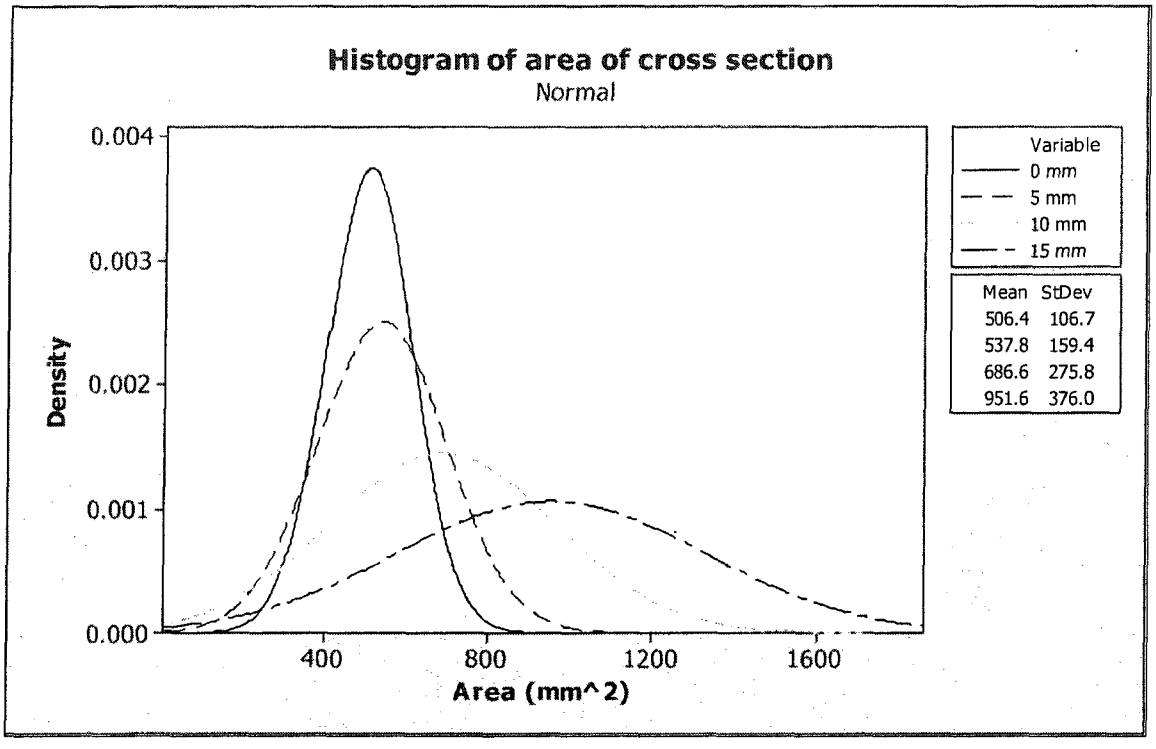

FIGURE 27. Histogram of area of cross section (Normal distribution).

Angle of Tilt

The normal distribution plot of the angle of tilt at different distances was plotted. It can be observed that mean of the angle of the tilt remained constant with the tolerance of ± 2 degree but the standard deviation increased with the distance.

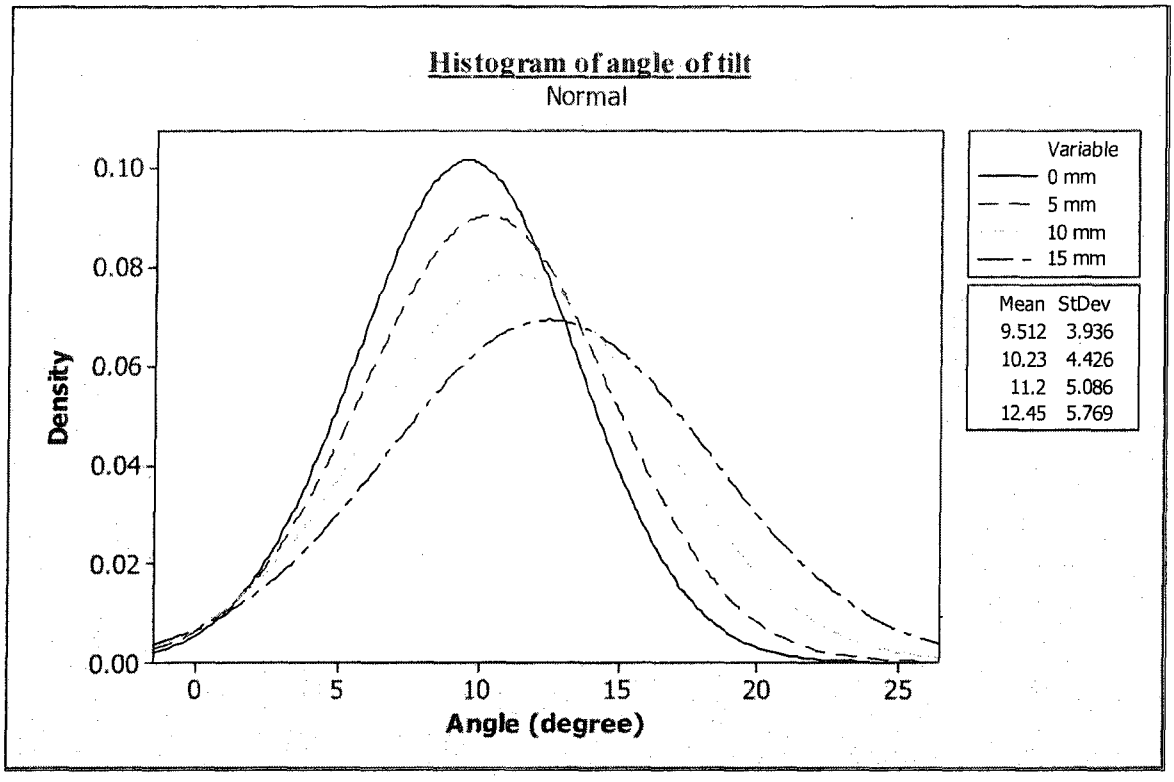

FIGURE 28. Histogram of angle of tilt (Normal distribution).

Maximum and Minimum Distance at The Cross Section

The normal distribution plot of the maximum and minimum distances was plotted at different location. The mean of the maximum distance on cross section increased with distance whereas the mean minimum distance on cross section decreased with distance. The standard deviation of the maximum and minimum distance at particular cross section varied randomly and no visible trend was observed.

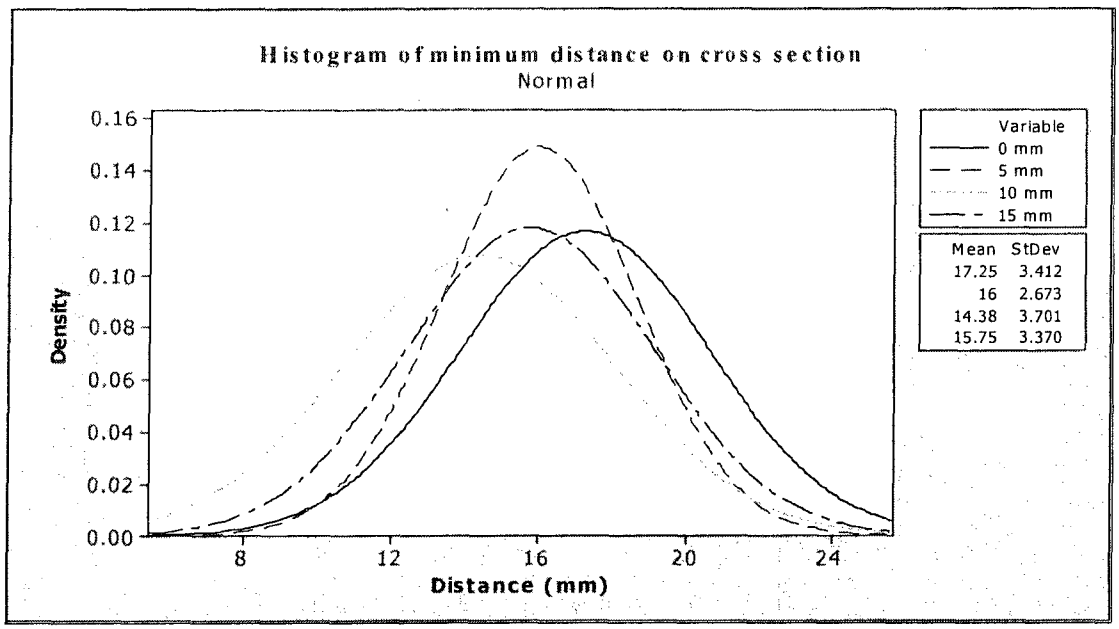

FIGURE 29. Histogram of minimum distance on cross section (Normal distribution).

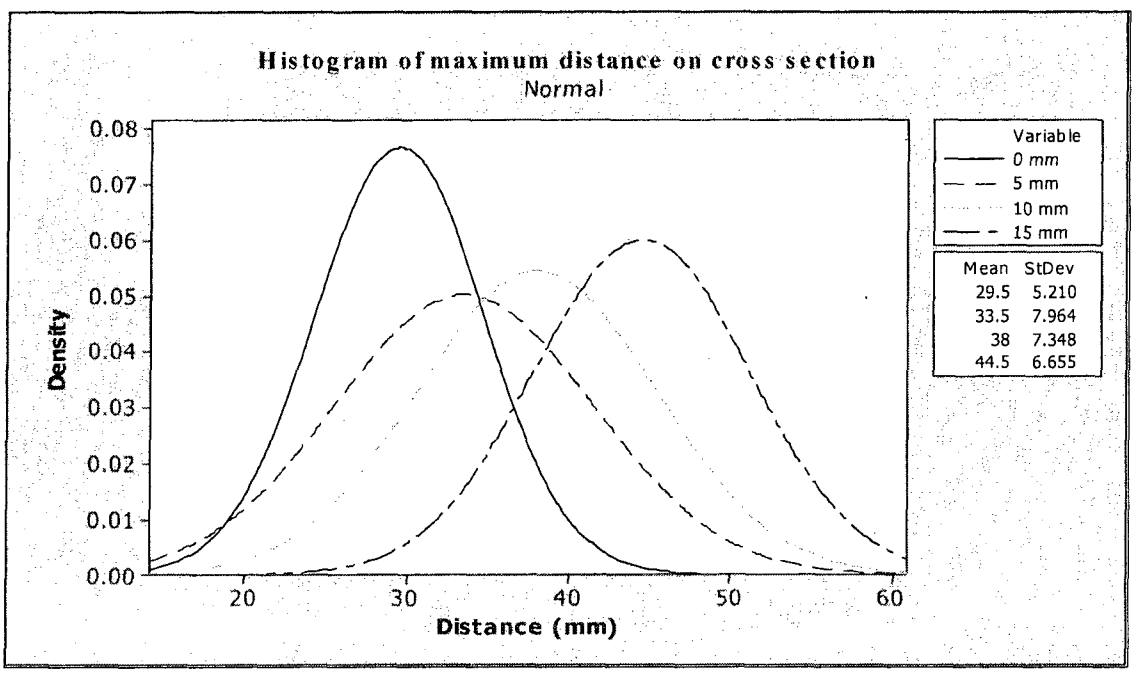

FIGURE 30. Histogram of maximum distance on cross section (Normal distribution).

Valve Measurement

The normal distribution plot of the annulus and aortic diameter were plotted at the diastole and systole phase. It was observed that mean annulus diameter has the difference of approximately 2.5 mm with a standard deviation of almost 2 during both the phases. In case of aorta, the difference between the mean values is almost the same as annulus but the standard deviation increased compared to annulus. The mean value of percentage difference in annulus and in aorta diameter is almost the same. The standard deviation of the percentage difference is more in aorta compared to annulus.

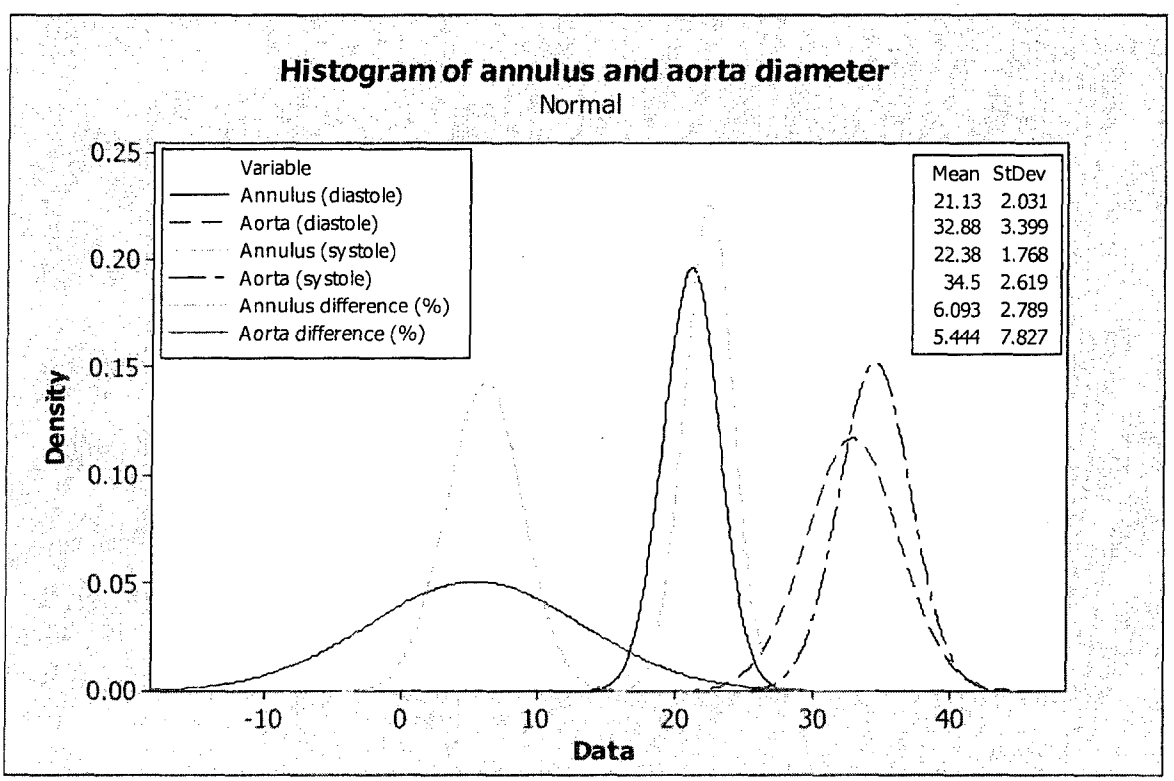

FIGURE 31. Histogram of annulus and aorta diameter (Normal distribution).

Radius of Curvature of The Aortic Arch

Mean value of the radius of curvature showed a significant difference during the phase change from diastole to systole. The mean value of the percentage change in the radius of curvature is 30 with the standard deviation of 51.

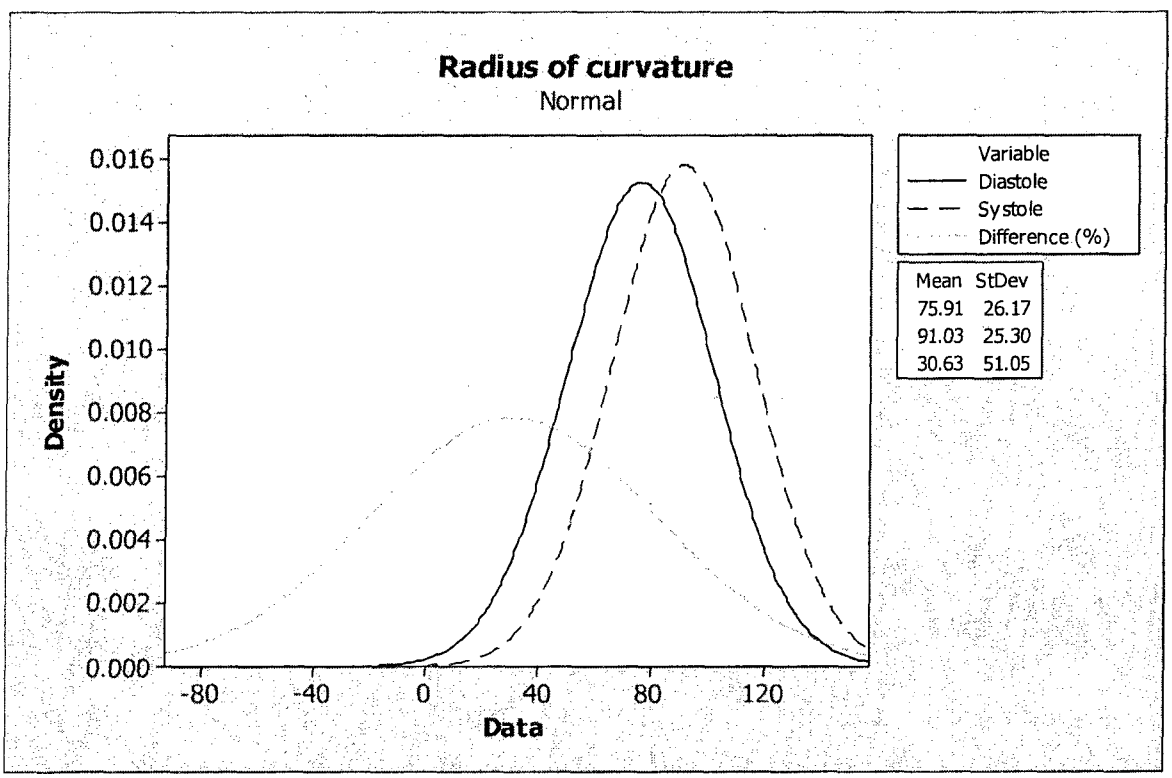

FIGURE 32. Histogram of Radius of curvature of the aortic arch (Normal distribution).

CHAPTER 5

CONCLUSION

In conclusion, the mechanical engineering approach was used to develop three dimensional modeling procedures and to measure the heart anatomy. The method developed using this approach has given the better result than the 2D measurement technique. The method was modified to obtain the required accuracy. The measurement analysis of the LVOT gave reasonably accurate estimate of the region. The statistical analysis of the data obtained gave good idea to predict overall trend at each cross section. The arch models of the Aortic valve were developed. The diameter of the Annulus and the Aorta were quantified during diastole and systole and had significant difference. The statistical analysis of the data made it easy to predict the changes during the phase change. The radius of curvature of the aortic arch was measured during the diastole and systole to get the change in the radius.

The 3D model developed using 3D DOCTOR software has given the better idea about the desired region. The solid model developed using IMAGEWARE has smooth surfaces which are easy to prototype. The cross sections at the desired section of the model were taken for further analysis. The cross section taken using this developed method was used to obtain the measurement analysis results.

The studied literature knowledge and data can be validated or modified with statistical data obtained by the measurements. The developed procedure can also be

used to quantify the leaflet calcification, to develop the customized models for minimally invasive surgery procedure. This research finding is a very valuable tool to bridge the gap between vitro and vivo procedures.

REFERENCES

REFERENCES

1. Reul H, Vahlbruch A, Giersiepen M, Schmitz-Rode T, Hirtz V, Effert S. The geometry of the aortic root in health, at valve disease and after valve replacement. Journal of Biomech. 1990; 23(2):181-91.

2. Laurens F. Tops, MD, David A. Wood, MD, Victoria Delgado, MD, Joanne D. Schuijf, MSC, John R. Mayo, MD, Sanjeevan Pasupati, MD, Frouke P. L. Lamers, MD, Ernst E. van der Wall, MD, PHD, Martin J. Schalij, MD, PHD, John G. Webb, MD, Jeroen J. Bax, MD, PHD, FACC. Noninvasive Evaluation of the Aortic Root with Multislice Computed Tomography Implications for Transcatheter Aortic Valve Replacement. J Am Coll Cardiol Img, 2008; 1:321-330.

3. Attila Nemes, MD, PhD, Tjebbe W. Galema, MD, Marcel L. Geleijnse, MD, PhD, Osama I.I. Soliman, MD, Sing-Chien Yap, MD, Ashraf M. Anwar, MDb, Folkert J. ten Cate, MD, PhD. Aortic valve replacement for aortic stenosis is associated with improved aortic distensibility at long-term follow-up American heart J 2007 153, (1) 147-151

4. Joseph C. Greenfield, Jr. and Dali J. Patel. Relation Between Pressure and Diameter in the Ascending Aorta of Man. Circulation Research the journal of the American Heart Association. 1962; 10; 778-781.

5. Kit V. Arom, M.D. Ph.D., Robert W. Emery, M.D. The Aortic Valve.

6. Kazui T, Izumoto H, Yoshioka K, Kawazoe K. Dynamic Morphologic Changes in the Normal Aortic Annulus during Systole and Diastole. J Heart Valve Dis. 2006 15(6):843.

7. Scott B. Capps, MS, Ronald C. Elkins, MD, David M. Fronk, MS. Body Surface Area As A Predictor Of Aortic And Pulmonary Valve Diameter. J Thorac Cardiovasc Surg 2000; 119:975-982.

8. E Nagel, M Stuber, B Burkhard, S.E Fischer, M.B Scheidegger, P Boesiger and O.M Hess. Cardiac rotation and relaxation in patients with aortic valve stenosis. European Heart Journal 2000 21(7):582-589

9. Todd R. Zwink, Ian G. Burwash, Carolyn Y. Miyake-Hull and Catherine M. Otto. Changes in Aortic Annulus Diameter During the Cardiac Cycle and its Effect on Predicting Aortic Valve Prosthesis Size. Journal of Diagnostic Medical Sonography 1994; 10; 262-267

10. W. Milton Swanson and Richard E. Clark. Dimensions and Geometric Relationships of the Human Aortic Value as a Function. Circ. Res. 1974;35;871-882

11. Padial LR, Oliver A, Sagie A, Weyman AE, King ME, Levine RA. Two-dimensional echocardiographic assessment of the progression of aortic root size in 127 patients with chronic aortic regurgitation: role of the supraaortic ridge and relation to the progression of the lesion. Am Heart J. 1997 134, 814-21

12. Lus R. Padial, MD, a Alvaro Oliver, MD, Alex Sagie, MD, Arthur E. Weyman, MD, Mary Etta King, MD, and Robert A. Levine, MD. Two-dimensional echocardiographic assessment of the progression of aortic root size in 127 patients with chronic aortic regurgitation: Role of the supraaortic ridge and relation to the progression of the lesionEuropean Heart Journal 2000 21(7):582-589

13. Kalath S, Tsipouras P, Silver FH. Non-invasive assessment of aortic mechanical properties. Ann Biomed Eng. 1986;14(6):513-24.

14. Groenink M; de Roos A; Mulder B J; Spaan J A; van der Wall E E. Changes in aortic distensibility and pulse wave velocity assessed with magnetic resonance imaging following beta-blocker therapy in the Marfan syndrome.
The American journal of cardiology 1998;82(2):203-8.