COO-2208-6
AVAILABLE SPACE FOR A TOTALLY IMPLANTABLE
CARDIAC PROSTHESIS

ANNUAL PROGRESS REPORT

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ABSTRACT

Methods have been developed for generating an integrated, statistical model of the anatomical structures within the human thorax, relevant to artificial heart implantation. These methods involve measurement and analysis of anatomy in four areas: chest wall, pericardium, vascular connections, and great vessels.

A model for the prediction of thorax outline from radiograms is finalized. These models have been combined with 100 radiograms to arrive at a size distribution representing the adult male and female populations.

A final method has been developed for generating a shape model of the pericardium. Inputs for this shape model were derived from published tomographic data, original transverse sections of the thorax, and actual cadavers. The pericardial outlines of thirty abnormal heart patients have been partially analyzed. The method for developing a vascular connection "spatial" model has been determined, and data is being processed. Preliminary results indicate the "Spatial" model is disease dependent, requiring further investigation.

Great vessel determination in the critical regions is being analyzed, using angiograms.

A parallel effort to determine the anatomical and physiological tolerance of 80 kg calves to implanted models of the thermal converter was completed after over one year of study in 5 calves. The retroperitoneal infrarenal location appears most feasible.

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1.0

STATEMENT OF EFFORTS

Dr. Y. Nose, the Principal Investigator has devoted approximately ten percent of his time to this contract. This same level of effort is anticipated for the remainder of the contract period.

ACKNOWLEDGEMENT

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2.0

CURRENT STATUS OF THE PROGRAM

The program originally had two objectives, both under the general topic of "Available Space."

Calf Studies. The first was aimed at defining the calf anatomy for the blood pump space, shape, and vascular connections. This has been completed and reported in COO-2208-2. The second calf study was to examine the anatomical and physiological tolerance to implanted models of the thermal converter in various trial locations in calves. The methods and initial results were reported in COO-2208-3. This study was completed in the last year and is reported in this document.

Human Studies. The human studies relative to the blood pump are concerned at present with the thorax to define the shape and statistical size distribution, including vascular connections and great vessel location. Since it is imperative that the data be accurate and reliable, a very careful multi-data-source study is being conducted. The hard structure definition is essentially complete. The vascular connections and critical potential problem areas are in process of being quantitatively defined. Recently identified was the variability due to heart disease, which must be studied, since these cases are the very candidates for the artificial heart.

Yet to be initiated is the important and possibly more difficult task of defining the location and method of implanting the thermal converter. Also to be considered is the implantation of the total system as a single operating assembly in the human.

To our knowledge, the studies being reported here are unique in that they are quantitative. The extreme relevance to the clinical use of the artificial heart warrants this study in conjunction with the development of the system.

3.0

PROGRESS IN THIS REPORTING PERIOD

Since the last report (*), the major effort was directed in two areas. The first was to continue to define the size and shape of the human thorax for implantation of the blood pump. The second area was to determine the anatomical and physiological tolerance of calves to implants of models of the thermal converter. Both these efforts are described in detail in the following sections.

* COO-2208-3, Available Space for a Totally Implantable Cardiac Prosthesis. Annual Progress Report, Department of Artificial Organs, Cleveland Clinic Foundation, July 1, 1972 - March 31, 1973.

3.1 ANATOMICAL AND PHYSIOLOGICAL TOLERANCE OF THE THERMAL CONVERTER IN CALVES

The AEC totally implantable artificial heart is composed of two separate components -- the blood pump and the thermal converter.

A report on the initiation of the experimental study to locate acceptable spaces for the thermal converter was included in the last annual progress report (COO-2208-3), and this effort has been concluded since then. Actual implantations of the thermal converter model were performed in calves during the period of July and August of 1972. Experimental materials, methods, animals and operative procedures were described in detail in the last report. Silastic reproductions of the converter model supplied by the AEC, having a volume of 820 cm³ and a weight of 1200 gm, were made for implantation. Figure 1 shows the size and shape of the model. Three units were constructed with stainless steel balls in the Silastic model to duplicate the 1200 gm weight.

Calves weighing about 80 kg each were used for these experiments. The duplicate model was implanted in the extrapleural subcostal, in the retroperitoneal infrarenal, or in the intraperitoneal space. The implantations performed are tabulated in Table 1.

Case 1 (Extrapleural Subcostal Implantation) and Case 2 (Retroperitoneal Infrarenal Implantation) were reported in the last progress report to have been in perfect condition after implantation and to be normal on physical, biochemical, and histological examinations at the eighth month after implantation, at which time they were sacrificed.

Case 3 (Retroperitoneal Infrarenal Implantation)

The animal recovered from the operation without any difficulty and had grown to over 300 kg in weight. The animal was in perfect condition 11 1/2 months after the implantation. The model seemed to be wrapped by

FIGURE 1

THERMAL CONVERTER PROPOSED BY USAEC/WESTINGHOUSE

TABLE 1

LOCATION OF IMPLANTATION, IDENTIFICATION OF THERMAL CONVERTER MODEL
AND PROGNOSIS OF CALVES

Calf No.	Implantation Site	Thermal Converter Model	Prognosis
1	Extrapleural, Subcostal	S-S-D	Sacrificed (8 months) for autopsy
2	Retroperitoneal, Infrarenal	S-S-D	Sacrificed (8 months) for autopsy
3	Retroperitoneal, Infrarenal	S-S & W-D	Sacrificed (11-1/2 months) for autopsy
4.	Intraperitoneal	S-S & W-D	Sacrificed (9-1/2 months) for autopsy
5	Retroperitoneal, Infrarenal	S-S & W-D	Sacrificed (15 months) for autopsy

S-S-D: Duplicating the size and shape of the original.

S-S & W-D: Duplicating the size, shape and weight of the original.

surrounding tissues and was not palpable over the skin.

Blood was sampled immediately before sacrifice for autopsy at 11 1/2 months after implantation. The data showed no particular changes in routine hematology, kidney and liver function.

The animal was sacrificed with intravenous administration of KCl solution. The model was found positioned in the right retroperitoneal infrarenal space. It protruded into the abdominal cavity with the wide base adhering firmly with the right kidney and with the free apex toward the intraperitoneal cavity. The whole model was encapsulated by thick, fibrous connective tissues and was completely isolated from the other organs (Figure 2). No signs of inflammation were noticed. There was no detectable macroscopic or microscopic abnormality in the internal organs.

Case 4 (Intraperitoneal Implantation)

The animal had been doing well after operation. The model, which had migrated and positioned itself at the lowest level in the intraperitoneal cavity immediately after completion of the operation, was not palpated over the skin.

Blood was sampled immediately before sacrifice for autopsy at 9 1/2 months after implantation. Hematology data were normal. Serum protein fraction was properly balanced. Blood chemistry showed no kidney or liver dysfunction.

The animal was sacrificed with KCl solution. The abdomen was opened through a midline incision and the stomachs were exteriorized outside the body. The model appeared completely encapsulated with a thin fibrous sheath which adhered to the right colon. The model appeared to be fixed by surrounding tissues, still keeping some extent of freedom of mobility.

The encapsulated model was easily separated from surrounding tissues (Figure 3). There were no noticeable macroscopic or microscopic changes in any internal organs.

Case 5 (Retroperitoneal Infrarenal Implantation)

There had been no difficulty during the course of convalescence after surgery, and the animal had grown to over 350 kg by the time of autopsy. No macroscopic changes were detected in any internal organs at autopsy. The implanted model was found in the right retroperitoneal infrarenal region with the apex pointing toward the latero-ventrocaudal direction. The base was adhering firmly with a lower pole of the right kidney. Anchoring of the model was with Dacron fringes adhering to the dorsal muscles. The implant was encapsulated with a fibrous sheath which was thinner than that seen before in the previous cases. Laboratory examination showed no particular changes in hematology and blood chemistry during the postoperative period.

Conclusions

The intrathoracic cavity, the extraperitoneal intrapelvic space, the subcutaneous anterosternal space, and the retrovertebral space were discussed in detail in the last report with recommendation that these not be considered.

The implantation in the retroperitoneal infrarenal or in the intraperitoneal space did not cause any physical disorders, which was also supported by hematological, biochemical and histological examinations. It is interesting to note that serum protein fraction has been kept within normal ranges in all experimental animals, even with the Silastic models implanted. This probably suggests that the Silastic is inert enough to

FIGURE 2
AUTOPSY OF CASE 3 (RETROPERITONEAL INFRARENAL IMPLANTATION)

FIGURE 3
AUTOPSY OF CASE 4 (INTRAPERITONEAL IMPLANTATION)

the living body as a covering material of the artificial heart components.

A conclusion of this study is that all of the spaces examined appear somewhat tolerable. However, the retroperitoneal infrarenal space is preferable for implantation of the thermal converter, not only from an anatomical space availability, but also from the physiological view of minimal possible sacrifice of function of the neighboring tissues or organs. This is supported by the fact that the retroperitoneal infrarenal implantation did not cause any physical disorders, as shown by the normal examination findings. Also, for fixation of the unit, the dorsal muscles are adequate for anchoring. Figure 4 shows the convenient connection between the converter and blood pump.

FIGURE 4
RECOMMENDED CALF IMPLANT CONFIGURATION

3.2 DEFINITION OF THE HUMAN THORAX

3.2.1 Introduction and Motivation.

Anatomical mismatches between the animal and the heart prosthesis have been an all too frequent cause of death in implant experiments for all the investigators working in the area of total heart replacement. It is hoped that one result of this effort will be a minimization of these problems when the time for human total heart replacement arrives.

The problem can be broken down into two main areas according to the mode of geometrical mismatch between the mechanical heart and the recipient. After excising the natural heart, the surgeon is presented with four vascular connection points with varying distances and orientations (direction of a vector parallel to blood flow in the vessel) between them. The first category (mode 1) of failure can occur if either the distances between the connection points of the artificial heart are incorrect, or if the orientation of a connection point on the prosthesis does not match the orientation of the corresponding blood vessel. This results in stretching (and possible tearing) or kinking at the anastomosis points, ending in either a fatal experiment or sharply curtailed blood flow.

A second mode of failure can occur even if perfect joints are made; this happens when the heart, hanging from its four bonds, encounters either relatively hard structures (chest wall, aorta) or soft structures (vena cava). The first failure mode defines dimensional relationships between connection points on the surface of the blood pump, while the second failure mode dictates constraints on the external boundaries of the device.

In Figure 5 is shown a transverse section of the thorax at the

approximate level of the mitral and tricuspid valves. This is also a close estimate to the connection points for the mechanical heart, since it is anticipated that as much natural atrium as possible will be retained in actual implants. Also shown (in hatched region) is the lower edge of the lung hilus area. As can be seen, overly large dimensions for the anterior wall of the prosthesis will result in a mode two failure, in which the heart is forced posteriorly against the two atria, decreasing the effective volume and possibly cutting off flow altogether (heavy arrows). In Figure 6 is pictured the same failure in the lateral view. Again, excessive dimensions in the anterior direction will either compress the sensitive hilus region or possibly cause a counterclockwise rotation, pivoting around this same point. Figure 7 indicates a mode two failure occurring in the lower region of the chest. Here, an abnormally large heart will be forced backwards (heavy arrow), perhaps compressing fatally the inferior vena cava. Aortic compression, while highly unlikely due to its relative rigidity, could occur if blood pump dimensions are excessive.

To summarize, two failure types must be concentrated on:

1. Kinking or twisting caused by a mismatch at the connection points.
2. Compression of vital soft structures due to abnormally large anterior boundary of the mechanical prosthesis.

Consequently, the region where most of the effort should be directed is enclosed between the dotted lines and the chest wall, as shown in Figures 5 and 6. Structural relationships outside of this area, though not so important, are relevant in that two additional phenomena may occur:

TRANSVERSE SECTION IN UPPER REGION OF PERICARDIUM
(Heavy arrows indicate possible compression)

FIGURE 5

SAGITTAL SECTION AT LEFT ROOT OF LUNG
(Heavy arrows indicate possible compression)

FIGURE 6

TRANSVERSE SECTION IN LOWER REGION OF HEART
 (Heavy arrows indicate possible compression)

- A. Extension of the blood pump's flexible artificial atrium beyond the normal pericardium will result in a decreased atrial compliance (the pliant wall will simply acquire the compliance of surrounding tissue). In such a case, its elasticity will be a function of how far into the lung the atrium extends, and the average lung compliance, which in turn is governed by the lung inflation. Too great a decrease in atrial compliance severely reduces its effectiveness as an accumulator buffering a pulsatile pump.
- B. Excessive pressure on the lung by a pump protruding beyond the pericardial limits may cut into the lung's residual volume. In addition, pinching of the lung tissue between the thorax wall and the pump may cause necrosis of the lung parenchyma (Fig. 5).

3.2.2 Overview of Method for Solving Problem

3.2.2.1 Previous Work. In actuality, very little previous work applies directly in a quantitative manner to the anatomical problems inherent in the implantation of an artificial heart. Radiograms of the only pump ever used in a human patient⁽¹⁾ show the device reasonably well situated completely within the pericardial sac, with just a slight bulge noticeable in the left superior cardiac outline. This patient, however, had a noticeably enlarged left ventricle and left atrium prior to the operation.

Other work (especially in the fields of radiology and anatomy), though not directly applicable to the problem, has been indirectly helpful, both in formulating a solution and as quantitative inputs for certain sections of the final model. Text books in radiology present an approach oriented primarily toward diagnosing various forms of heart disease from pericardial

outlines. The description in one of these x-ray diagnostic text books⁽²⁾ on early investigators' attempts at deriving quantitative data from radiograms has been useful for eliminating unusable techniques. Also, certain ratio information (e.g., ratio of left to right maximum pericardium dimensions) can be used to check the validity of much of our raw data.

Most useful have been anatomy texts in which original transverse sections of the human thorax are presented⁽³⁻¹²⁾. Even though no absolute dimensions are available from these sections, ratio and shape information has proved very useful when combined with large amounts of data from radiograms. Published tomographic data, especially that of Takahashi⁽¹³⁾, has also been useful for obtaining the same kind of ratio and shape data.

Absolute dimensional measurements have proved extremely rare in both anatomy and radiography literature. Exceptions are studies concentrating on very specific sections of the cardiovascular system; e.g., the inferior vena cava^(14, 15), or the left atrium^(16, 17), which have proved somewhat helpful.

To summarize, the requirements for determining design constraints imposed on an artificial heart are specific dimensions, both between intended vascular connection points to the heart, and from these same points to nearby hard or soft structures. This kind of data is practically nonexistent in the literature.

3.2.2.2 Description of Method. Because reliable dimensional information is lacking in the literature, some method must be devised for avoiding mode one and two failures discussed earlier. The approach used must generate not only a set of average dimensions for both the vascular connection points and external boundary of the heart, but tolerances as well, so that the final pump chosen will fit a majority of prospective candidates.

The method finally used was based on the assumption that most organs and structures in the human body have similar configurations, and variations of a particular organ from person to person are due mainly to differences in size. This implies that if these size differences were normalized out of the specific organ under investigation, the organ's "shape," or geometrical configuration would be the same from person to person. For instance, if various size ellipses displayed symmetrically on the same set of cartesian coordinates (cylindrical coordinates have fewer degrees of freedom), are normalized in both the x and y directions, a single circle with its center at zero and passing through the (1,0) and (0,1) points results. This means that this particular shape, an ellipse in this case, can be characterized by a circle after normalization. Further, the average size of an entire family of ellipses can be expressed by this circle and the average of the maximum x and maximum y dimensions of the ellipses under investigation.

In Figure 8 is shown the application of this concept to the left-posterior boundary (solid line) of a typical transverse section of the human thorax. Maximum x and y values in this quadrant are approximately 8.0 cm and 5.0 cm respectively. The curve, after discretization, consists of a series of points; i.e., (1, .7), (2, 2.4), (3, 3.9), etc. Dividing the coordinates of each of these points by the maximum x and y values respectively (called "normalizing parameters" in this report), results approximately in the middle curve in Figure 8. In the particular case of a thorax section, these "normalizing parameters" were carefully chosen to be observable dimensions in either lateral or P-A radiograms. Specifically, maximum y value in the example appears in lateral view, while greatest x dimension is observed in P-A photo. Note that the

NORMALIZATION AND INTERPOLATION OF RAW DATA

FIGURE 8

maximum x value is the largest dimension in the entire left half of the chest, and may appear in either the posterior or anterior quadrant. For this reason, the end point may not pass through the (1,0) point. This normalized curve, then, represents the "shape" of the left-posterior thorax section after size variability has been eliminated. In order to verify this, a statistically significant number of these normalized curves must be averaged together. However, normalization of a second left-posterior curve may not result in identical x values, making direct averaging impossible. To avoid this problem, the normalized curve is interpolated to yield a y value for each incremental x value, as shown in the lower curve of Figure 8. A quadratic interpolation scheme that successively straddled each x value in increments of .1, up to 1.0, was found to give excellent results. Following interpolation, an average "shape" for any number of samples can be calculated by averaging all y values corresponding to each incremental x value (typical example is Fig. 9). If the standard deviation for this curve is sufficiently small, then it can be said to constitute the "shape model" for this particular quadrant of the chest.

Having finalized a configuration for each quadrant, at each level in the chest, the investigator can now measure the "normalizing parameters" from a large number of A-P and lateral radiograms. Using average values of these parameters in conjunction with the shape model allows the reconstruction of a truly average thorax.

The above is a simple example of a concept that is applied throughout the entire program. A small sample (10) of hard-to-get data is used to determine the form of an organ or structure in terms of normalizing parameters that are easily observed on standard radiograms, a relatively

FIGURE 9

abundant source of data. Final results yield a meaningful average, along with a variability factor (i.e., standard deviation) that can be used for design purposes.

In Figure 10, within the dotted line, appears a general block diagrams of the thought processes involved in arriving at a final result. As can be seen, the end product (blood pump shape) is a function of both hard structure (thorax wall) and soft structure (pericardium, great vessels) information. Figure 11 illustrates the application of normalization to acquiring both kinds of information. Average thorax wall definition is generated by combining statistical distributions of "normalizing parameters" (A, B, and C, obtained from A-P and lateral x-ray photographs) with a shape model derived from silastic thorax molds poured in human cadavers. A typical soft structure, the pericardium, is shown to be a function of parameters: level, D, E, F, and G. (Level is the percent vertical distance between an upper and lower reference point located within the thorax⁽¹⁸⁾). Specifying chest levels in this manner is intended to normalize out variations in chest height encountered from patient to patient. Using certain portions of the ribs to locate high and low reference points follows from the clinical practice of locating heart valves and aspiration points via the rib dependent intercostal spaces⁽¹⁹⁾.

Notice the model box in Figure 11 with a question mark within it. This corresponds to the as yet unfinalized "shape model" for locating soft structure other than pericardium. The question that must be answered is: "What observable points or structures in two-dimensional radiograms should be used as input for a model to predict vascular connections and location of relevant great vessels (both invisible) with respect to the

PROGRAM TO DETERMINE SPACE FOR BLOOD PUMP

FIGURE 10

**METHOD FOR RELATING TWO DIMENSIONAL
MEASUREMENTS TO THREE DIMENSIONAL OBJECTS**

FIGURE 11

pericardial sac and the chest wall?" Solutions to this problem will be presented in later sections.

A breakdown of the total problem is shown in Figure 12. This includes four basic areas of investigation: chest wall, pericardium, valve, and great vessel anatomy. Valves are studied only insofar as they indicate the approximate connection point with the artificial heart. Except for the great vessels, each area is further subdivided into a "shape model" and pertinent normalizing parameters. Dimensions H, I, J, and K are not normalizing parameters in the true sense of the word and will be explained in the detailed section on the valve model.

The form of a final integrated model used for design is portrayed in Figure 13. Average values for chest wall, pericardium, valves and great vessels (aorta and vena cava) will be shown with their corresponding tolerances at specified levels in the chest. Vascular connection points in these transverse sections also have vertical tolerances. A complete, reconstructed thorax is generated by stacking each of these sections on top of one another. Distance between sections is simply the average vertical chest length (distance between upper and lower reference points) divided by 10. Location of sections with respect to each other is determined by positioning the chest reference point (most anterior portion of vertebra) of each section on the typical curve of a spinal column. This curve is generated from both our own data and published results⁽²⁰⁾.

As a means of validating the final integrated model, a dummy pump incorporating the derived dimensional constraints will be constructed and implanted in human cadavers (Figure 12).

3.2.2.3 Possible Artifacts in the Method. One of the final goals is the variability of anatomical relationships with the thorax. There

COMPONENTS OF MODEL FOR GENERATING EXTERNAL
DESIGN CONSTRAINTS OF HUMAN ARTIFICIAL HEART

FIG. 12

FORM OF FINAL RESULTS AT A PARTICULAR LEVEL IN THE CHEST

FIGURE 13

are two sources of this variability: One is the actual, random differences between patients, and the second is error inherent in the method of analyzing the anatomical structures.

Dissimilarities in the thorax region between individuals are significant and qualitatively well documented. Pericardial sac differences alone can be quite remarkable. The sac in an asthenic individual (very low diaphragm) is long and narrow, while that of the sthenic (high diaphragm) is short and broad. Somewhere in between is a so-called "average" individual^(2, 21). Similarly, there can be great variation in the layout of the great vessels, and an individual can still be considered quite normal⁽²²⁾.

Sources of variability that might be termed artifact, in that they don't reflect purely genetic differences between individuals, may enter the analysis simply because the system under investigation is highly dynamic. This can happen especially in radiological measurements. Cardiac silhouette is known to be highly dependent on respiration phase; hence, standard radiographic procedure dictates that all photos be taken during full inspiration. There may be, however, many different patient views on what constitutes "full inspiration." Cardiac phase has a negligible effect on results for both the cardiac silhouette and valve location^(21, 23). However, accidental breathholding by the subject results in the classical valsalva maneuver, resulting in decreased blood inflow to the heart and subsequent marked reductions in cardiac size.

A third source of variability -- disease -- can be considered either an artifact (in dealing with normals), or an important correlation parameter if one is deliberately studying patients with abnormal hearts, prime candidates for an artificial blood pump. The effects of abnormal hemo-

dynamics on pericardial size, valve location and, to some extent, vena cava location, is marked and non-negligible. A detailed discussion of such effects is beyond the present scope of this report, but excellent source material can be found in references 2, 21, 22, and 24.

Errors in shape models will most likely enter either from the usual problems with pouring molds into semi-amorphous material such as human tissue, or from inherent differences between cadavers and living systems.

In the following sections, the detailed methods used in investigating each of the four main areas outlined in Figure 12 will be discussed. At the same time, the current status of each, and specific methods for detecting errors in the results (if applicable) will be presented.

3.2.3 DEFINITION OF THE HUMAN CHEST WALL

The purpose of this work is to define the chest cavity of an adult human. This effort is only the first stage in accomplishing the ultimate goal, that of defining not only the chest cavity, but the relative location of pertinent soft structures within this cavity in the human. In order to accomplish these goals, a special technique has been developed.

A shape model was made from data taken from transversely sectioned molds of the chest cavity of human cadavers (Figure 14). The normalized shape and curvature of the human chest cavity was determined by analysis of this data on a computer.

The shape model was then combined with the measurements of dimensions on a large number of human plane chest radiographs to determine a distribution of the size of the chest cavity as a function of the percentage of the population having these dimensions.

The ultimately developed technique of the modeling and analysis is also expected to be applicable to clinical cases of artificial heart

METHOD FOR MOLDS SLICING

FIGURE 14

**NORMALIZING PARAMETERS FOR
A TYPICAL MOLD CROSS SECTION**

FIGURE 15

implantation where standard chest radiographs of the proposed recipient will insure that the prosthesis will fit in the particular patient.

3.2.3.1 Generation of Model. A detailed description of the essential concepts in the model development are included in an earlier report⁽¹⁸⁾. Briefly, shapes generated from molds cast in cadaver thorax cavities were used to determine chest wall curvature after individual size variations had been normalized out of the data (using normalizing parameters A, B, and C, Fig. 15). Nine male molds and two female molds have been analyzed and the resulting data used to generate a vertically dependent model. This model consists of a normalized curve for each quadrant (i.e., left anterior, left posterior, etc.) at a known level in the thorax. The vertical level under investigation is specified in terms of the percent vertical distance between two reference points identifiable on the radiograms. Because the individual vertebrae were not distinct in the films, these reference points are specified in terms of rib number and certain x-ray dimensions. They are located roughly at the T4 and T10 regions of the chest (Fig. 16). A typical normalized curve is shown in Figure 17. This curve represents the model (± 1 standard deviation) for the left anterior portion of a transverse section at approximately the T10 region. Data for this curve is shown at the top of Table 2 under "left anterior." Comparison of Figure 17 with Figure 18 demonstrates graphically the reduction in error when a vertically dependent model is used. Data for the T6 and T4 regions is shown in Tables 3 and 4 respectively. A comparison of the left and right anterior and posterior sections of all model data averaged in the vertical direction is shown in Figures 19 and 20 and clearly demonstrates symmetry of the thoracic wall shape.

Example of Model Use. Assume that the Atlas projections shown in

PROCEDURE FOR
LOCATING TOP AND LOWER REFERENCE POINTS

- 1) Measure B_{LT} and B_{Lb}
- 2) Upper reference point is intersection of Rib 4 and $B_{LT}/2$
- 3) Lower reference point is intersection of Rib 10 and $B_{Lb}/2$

FIGURE 16

FIGURE 17

FIGURE 18

FROM SPEC. # 3.00 TO SPEC. # 9.00

LEFT SIDE

ANTERIOR

SLICES USED IN AVERAGE= 7.00

XINT	AVG	STDEV	PRCT
0.0000	0.9796	0.0281	2.8736
0.1000	0.9951	0.0111	1.1140
0.2000	0.9989	0.0040	0.3995
0.3000	0.9849	0.0095	0.9620
0.4000	0.9644	0.0149	1.5497
0.5000	0.9370	0.0208	2.2165
0.6000	0.8897	0.0234	2.6251
0.7000	0.8160	0.0309	3.7872
0.8000	0.7075	0.0355	5.0118
0.9000	0.5268	0.0478	9.0778
1.0000	0.0623	0.0777	124.7309

FROM SPEC. # 3.00 TO SPEC. # 9.00

LEFT SIDE

POSTERIOR

SLICES USED IN AVERAGE= 7.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.1257	0.0400	31.8348
0.2000	0.5089	0.1189	23.3615
0.3000	0.8067	0.1082	13.4112
0.4000	0.9322	0.0680	7.2980
0.5000	0.9942	0.0212	2.1358
0.6000	0.9851	0.0205	2.0777
0.7000	0.9282	0.0634	6.8308
0.8000	0.7777	0.1122	14.4215
0.9000	0.5168	0.1777	34.3829
1.0000	0.0000	0.0000	0.0000

FROM SPEC. # 3.00 TO SPEC. # 9.00

RIGHT SIDE

ANTERIOR

SLICES USED IN AVERAGE= 7.00

XINT	AVG	STDEV	PRCT
0.0000	0.9882	0.0106	1.0771
0.1000	0.9934	0.0058	0.5882
0.2000	0.9953	0.0078	0.7881
0.3000	0.9900	0.0110	1.1108
0.4000	0.9724	0.0185	1.9067
0.5000	0.9330	0.0237	2.5399
0.6000	0.8812	0.0273	3.1027
0.7000	0.8020	0.0380	4.7368
0.8000	0.6904	0.0551	7.9826
0.9000	0.5014	0.0651	12.9829
1.0000	0.0215	0.0367	171.1594

FROM SPEC. # 3.00 TO SPEC. # 9.00

RIGHT SIDE

POSTERIOR

SLICES USED IN AVERAGE= 7.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.0905	0.0474	52.3826
0.2000	0.4789	0.0820	17.1162
0.3000	0.8222	0.0459	5.5851
0.4000	0.9428	0.0232	2.4653
0.5000	0.9884	0.0077	0.7760
0.6000	0.9800	0.0220	2.2412
0.7000	0.9169	0.0426	4.6479
0.8000	0.7677	0.0594	7.7394
0.9000	0.5022	0.1148	22.8625
1.0000	0.0000	0.0000	0.0000

VERTICALLY
DEPENDENT MODEL
AT T10 REGION
(LEVEL 9.0 TO 13.0)

TABLE 2

LEFT SIDE

ANTERIOR

SLICES USED IN AVERAGE= 9.00

XINT	AVG	STDEV	PRCT
0.0000	0.9703	0.0180	1.8602
0.1000	0.9918	0.0130	1.3139
0.2000	1.0019	0.0056	0.5564
0.3000	0.9928	0.0077	0.7748
0.4000	0.9703	0.0172	1.7728
0.5000	0.9339	0.0275	2.9398
0.6000	0.8856	0.0397	4.4808
0.7000	0.8109	0.0555	6.8409
0.8000	0.7087	0.0707	9.9781
0.9000	0.5481	0.0781	14.2568
1.0000	0.1214	0.0875	72.0709

FROM SPEC. # 1.00 TO SPEC. # 9.00

LEFT SIDE

POSTERIOR

SLICES USED IN AVERAGE= 9.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.1635	0.0495	30.2595
0.2000	0.5039	0.1058	20.9877
0.3000	0.8107	0.0790	9.7497
0.4000	0.9525	0.0353	3.7034
0.5000	0.9971	0.0075	0.7498
0.6000	0.9694	0.0097	0.9969
0.7000	0.8607	0.0315	3.6547
0.8000	0.6721	0.0698	10.3852
0.9000	0.3467	0.1070	30.8625
1.0000	0.0000	0.0000	0.0000

FROM SPEC. # 1.00 TO SPEC. # 9.00

RIGHT SIDE

ANTERIOR

SLICES USED IN AVERAGE= 9.00

XINT	AVG	STDEV	PRCT
0.0000	0.9769	0.0193	1.9746
0.1000	0.9936	0.0105	1.0533
0.2000	0.9959	0.0066	0.6655
0.3000	0.9882	0.0053	0.5317
0.4000	0.9606	0.0170	1.7672
0.5000	0.9171	0.0293	3.1920
0.6000	0.8527	0.0440	5.1565
0.7000	0.7800	0.0447	5.7313
0.8000	0.6744	0.0534	7.9174
0.9000	0.4869	0.0629	12.9124
1.0000	0.0410	0.0873	213.0066

FROM SPEC. # 1.00 TO SPEC. # 9.00

RIGHT SIDE

POSTERIOR

SLICES USED IN AVERAGE= 9.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.1701	0.0273	16.0353
0.2000	0.5550	0.0868	15.6374
0.3000	0.8415	0.0573	6.8071
0.4000	0.9581	0.0419	4.3766
0.5000	0.9943	0.0094	0.9470
0.6000	0.9670	0.0214	2.2081
0.7000	0.8738	0.0391	4.4784
0.8000	0.6894	0.0628	9.1161
0.9000	0.3747	0.0799	21.3225
1.0000	0.0000	0.0000	0.0000

VERTICALLY
DEPENDENT MODEL
AT T6 REGION
(LEVEL 3.0 TO 6.0)

TABLE 3

FROM SPEC. # 1.00 TO SPEC. # 9.00

LEFT SIDE

ANTERIOR

SLICES USED IN AVERAGE=12.00

XINT	AVG	STDEV	PRCT
0.0000	0.9890	0.0151	1.5275
0.1000	0.9872	0.0153	1.5502
0.2000	0.9768	0.0260	2.6569
0.3000	0.9511	0.0383	4.0255
0.4000	0.9107	0.0482	5.2951
0.5000	0.8567	0.0566	6.6048
0.6000	0.7904	0.0628	7.9407
0.7000	0.7068	0.0693	9.8097
0.8000	0.5996	0.0754	12.5707
0.9000	0.4424	0.0781	17.6478
1.0000	0.0539	0.0891	165.3323

FROM SPEC. # 1.00 TO SPEC. # 9.00

LEFT SIDE

POSTERIOR

SLICES USED IN AVERAGE=12.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.1267	0.0517	40.8214
0.2000	0.4759	0.1042	21.9033
0.3000	0.7603	0.0913	12.0087
0.4000	0.9239	0.0557	6.0337
0.5000	0.9855	0.0237	2.4021
0.6000	0.9808	0.0155	1.5771
0.7000	0.9084	0.0451	4.9602
0.8000	0.7786	0.0895	11.5013
0.9000	0.5366	0.1686	31.4188
1.0000	0.0369	0.0870	235.9217

FROM SPEC. # 1.00 TO SPEC. # 9.00

RIGHT SIDE

ANTERIOR

SLICES USED IN AVERAGE=12.00

XINT	AVG	STDEV	PRCT
0.0000	0.9853	0.0174	1.7685
0.1000	0.9824	0.0225	2.2945
0.2000	0.9695	0.0348	3.5867
0.3000	0.9453	0.0436	4.6169
0.4000	0.9077	0.0450	4.9519
0.5000	0.8611	0.0476	5.5254
0.6000	0.7988	0.0545	6.8254
0.7000	0.7200	0.0646	8.9760
0.8000	0.6182	0.0789	12.7604
0.9000	0.4661	0.1070	22.9528
1.0000	0.0782	0.1184	151.3348

FROM SPEC. # 1.00 TO SPEC. # 9.00

RIGHT SIDE

POSTERIOR

SLICES USED IN AVERAGE=12.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.1208	0.0648	53.6008
0.2000	0.4587	0.1295	28.2308
0.3000	0.7475	0.0901	12.0465
0.4000	0.9027	0.0524	5.8018
0.5000	0.9776	0.0250	2.5585
0.6000	0.9822	0.0186	1.8953
0.7000	0.9194	0.0382	4.1509
0.8000	0.7888	0.0679	8.6062
0.9000	0.5439	0.1324	24.3376
1.0000	0.0808	0.1293	159.9669

VERTICALLY
DEPENDENT MODEL
AT T4 REGION
(LEVEL -0.5 TO 3.0)

TABLE 4

FIGURE 19

FIGURE 20

Figures 21 and 22 represent the actual structure of a patient under investigation for a possible prosthesis. The transverse section shown in Figure 21 is labeled with a set of axes determined by one reference point on the vertebral column and another on the distal point of the inner side of the sternum. The dimensions A, B, and C represent those measurements of the chest cavity visible on the radiogram (Fig. 23 a). These simulated x-ray dimensions are shown at the top of Table 5 as A', B', and C'. Assuming T10 region of the symmetrical model is used, x-y coordinates of the predicted thorax are generated by simple multiplication; i.e., for the left anterior quadrant, the normalized x values (X_n) are multiplied by B'. The total predicted curve for this simulated patient is shown in black squares in Figure 21. Additional comparisons of the model with some classical transverse thorax sections⁽³⁾ are shown in Figures 24 through 26. Greatest errors are in the anterior region of the chest, on either side of the sternum. Fortunately, it results in an underestimation rather than an overestimation of available space. Source of the error probably stems from the fact that this is precisely the region where the cadaver chest wall section was removed in order to empty the thorax and pour in the silastic. Even though the section was replaced during curing, some error could be present in repositioning the section. Additional factors that may affect the standard deviation of the thorax model are illustrated in Figure 23 b. These include absolute values of the normalizing parameters, ratio of certain normalizing parameters, and qualitative data, such as mesomorph or ectomorph designations. These correlations have not been pursued, since pericardium and valve data were considered more important.

9th THORACIC VERTEBRA

FIGURE 21

FIGURE 23a

FIGURE 23b

TABLE 5

TRANSFORMATION OF SIMULATED X-RAY MEASUREMENTS FROM FIGURE 21
INTO THE PREDICTED THORAX CAVITY

Simulated X-ray Dimensions: $A_i = 4.6$ cm
 $B_i = 8.6$ cm
 $C = 9.6$ cm

Note: Y_n below is the model for approximately the T9 region

X_n	Left Anterior			Left Posterior		
	$X_n \cdot C'$	Y_n	$Y_n \cdot B'$	$X_n \cdot B'$	Y_n	$Y_n \cdot A'$
0	.0	.979	8.42	0.0	0.0	0.0
.1	.96	.995	8.56	.86	.126	.58
.2	1.92	.999	8.60	1.72	.509	2.34
.3	2.88	.985	8.47	2.58	.807	3.71
.4	3.84	.964	8.29	3.44	.932	4.29
.5	4.8	.937	8.06	4.30	.994	4.57
.6	5.76	.889	7.64	5.16	.985	4.53
.7	6.72	.816	7.02	6.02	.928	4.27
.8	7.68	.708	6.09	6.88	.777	3.57
.9	8.64	.527	4.53	7.74	.517	2.38
1.0	9.6	.062	.53	-	-	-

UPPER THORAX

COMPARISON OF MODEL WITH ACTUAL SECTION

FIGURE 24

MIDDLE THORAX

COMPARISON OF MODEL WITH ACTUAL SECTION

FIGURE 25

LOWER THORAX

COMPARISON OF MODEL WITH ACTUAL SECTION

FIGURE 26

To determine a statistical distribution of thorax sizes for the adult population, average values for A, B, and C at each level in the thorax must be determined from a reasonably large sample of x-ray measurements. The procedure used to extract this data from 80 male and 20 female radiograms is described next.

3.2.3.2.1 Measurements on Chest Radiographs. One hundred radiographs were read and measured. Eighty of them were chosen from males and twenty from females, since comparison between the male and female chest cavity regarding the shape as well as the size was considered useful. All radiographs were obtained from outpatients of the Cleveland Clinic and were diagnosed "no findings" as far as the thorax was concerned. Their ages ranged between 40 and 55.

Figures 27 and 28 show the front and side view radiographs and the measuring points used. Appendix A gives the details of the measuring method. Approximately 80 measurements are made from each set of radiographs. Some of the data pertains to the location of the outside surface of the heart. The heart dimensions, from these normals, will be examined in detail in the near future, but only the chest wall location was analyzed in depth in this reporting period.

Several assumptions were made relative to the radiograph measurements. These assumptions were necessary to solve the problem while not compromising the result.

1. A magnification effect of 10% was assumed at all portions of the radiographs. An average magnification effect is calculated to be 10% by the Department of Radiology at the Cleveland Clinic. Theoretically, it varies according to location on the body relative to the film.

FIGURE 27

P-A RADIOGRAPH SHOWING DIMENSIONS MEASURED

FIGURE 28

LATERAL RADIOGRAPH SHOWING DIMENSIONS MEASURED

2. The chest cavity is assumed symmetric on a postero-anterior radiograph. The chest is not perfectly symmetrical, as is usual in other structures of the living body. If all vertebrae clearly appear on a radiograph, a midline can be pointed out without difficulty. Very often, however, some of the thoracic vertebrae, particularly those overlapped with the heart silhouette, are not shown clearly. Therefore, a midline was obtained, not anatomically, but by dividing the width of the chest cavity by two.
3. All bones are covered with relatively radiotransparent, soft tissues. On radiographic measurements, dimensions are obtained as distances between two radiopaque bony structures. However, the mold data yields smaller inside dimensions due to the thickness of these tissues.
4. It was assumed that all patients held a deep inspiration and were standing perpendicular to the floor when the radiographs were made. This is usually the instruction given to the patient. Level of the diaphragmatic dome changes depending upon respiratory phase, while configuration of the chest changes depending upon posture. This again accounts for differences between cadavers and living patients.

3.2.3.2.2 Data Processing. At each level (where a level represents 10% of the distance between the two reference points), the average value and standard deviation was calculated. Also the standard deviation, expressed as a percent of the average, is shown. Tables 6 and 7 summarize this data for males and females, respectively. Distance between the two reference points was 16.57 ± 1.31 for males, and $15.77 \pm .73$ for females.

TABLE 6

SUMMARY OF MALE X-RAY DATA

Level	Normalizing-Parameter								
	B			C			A		
	Avg.	σ	$\frac{\sigma}{\text{Avg.}} \times 100$	Avg.	σ	$\frac{\sigma}{\text{Avg.}} \times 100$	Avg.	σ	$\frac{\sigma}{\text{Avg.}} \times 100$
-2	4.74	0.69	14.7	1.03	0.68	66.5	1.80	0.00	0.0
-1	7.14	1.42	19.9	4.91	2.62	53.4	3.36	1.39	41.5
0 Ref	9.18	1.02	11.1	7.84	2.11	26.9	4.70	0.79	16.9
1	10.52	0.88	8.3	9.79	1.81	18.5	4.97	0.72	14.4
2	11.26	0.84	7.5	10.97	1.61	14.7	5.15	0.64	12.3
3	11.70	0.80	6.8	11.84	1.62	13.7	5.28	0.60	11.3
4	12.13	0.77	6.3	12.47	1.74	13.9	5.41	0.59	11.0
5	12.38	0.78	6.3	12.87	1.83	14.2	5.53	0.61	11.1
6	12.63	0.83	6.6	13.13	1.91	14.6	5.65	0.63	11.1
7	12.86	0.83	6.5	13.23	2.02	15.3	5.77	0.63	11.0
8	13.08	0.89	6.8	13.22	2.11	15.9	5.89	0.65	11.0
9	13.23	1.04	7.9	13.07	2.13	16.3	5.99	0.68	11.4
10 Ref	13.65	0.95	7.0	12.85	1.98	15.4	6.04	0.70	11.5
11	13.91	0.83	6.0	12.48	1.99	16.0	6.12	0.69	11.3
12	14.05	.87	6.2	12.12	1.90	15.7	6.19	0.79	12.8

TABLE 7
SUMMARY OF FEMALE X-RAY DATA

Level	Normalizing Parameter								
	B			C			A		
	Avg.	σ	$\frac{\sigma}{\text{Avg.}} \times 100$	Avg.	σ	$\frac{\sigma}{\text{Avg.}} \times 100$	Avg.	σ	$\frac{\sigma}{\text{Avg.}} \times 100$
-2	3.92	0.45	11.4	0.45	0.00	0.0			
-1	6.50	1.62	15.7	2.97	1.74	58.4	1.79	0.66	36.7
0 Ref	8.52	0.83	9.7	6.32	1.80	28.4	3.31	0.48	14.6
1	9.71	0.73	7.5	8.51	1.28	15.0	3.78	0.40	10.6
2	10.33	0.73	7.0	9.63	1.33	13.8	4.12	0.44	10.7
3	10.61	0.73	6.9	10.31	1.50	14.6	4.37	0.45	10.4
4	11.00	0.75	6.9	10.91	1.48	13.5	4.58	0.46	10.0
5	11.12	0.75	6.8	11.11	1.52	13.7	4.76	0.49	10.3
6	11.22	0.79	7.1	11.13	1.44	12.9	5.00	0.51	10.3
7	11.34	0.82	7.2	11.07	1.51	13.6	5.18	0.59	11.3
8	11.45	0.89	7.7	10.86	1.53	14.1	5.28	0.64	12.1
9	11.51	0.87	7.6	10.71	1.64	15.4	5.36	0.61	11.5
10 Ref	11.58	0.87	7.5	10.16	1.65	16.2	5.42	0.62	11.4
11	11.76	1.08	9.2	9.52	0.97	10.2	5.36	0.66	12.3
12	12.13	0.70	5.8	8.69	0.28	3.2	5.57	0.59	10.6

3.2.3.3 Comparison of X-Ray and Mold Data. To check the assumption of dimensional symmetry in the thorax, as opposed to the symmetry of "shape" described earlier, left and right measurements for the normalizing parameters A and B were taken from the mold data and plotted against each other in Figures 29 and 30. Regression lines (solid) were calculated and are shown compared with the dotted identity line. Slopes of these regressions were .92 for A (y intercept = .51) and .83 for B (y intercept = 1.85). Perfect symmetry would have resulted in a slope of 1 and y intercept values of 0. This minor lack of symmetry, however, besides being within the expected error in the process of generating molds (they are used primarily for "shape" information rather than absolute measurements), would result in a negligible error in the overall predicted distributions.

Besides the dimensional symmetry check on the raw mold data, comparisons were made between x-ray and mold data at various vertical levels in the chest. The mold measurements should be approximately from the same statistical distribution as the x-ray data. Parameters A and B showed very close correlations between mold and x-ray data, although on the whole, mold dimensions were slightly less than corresponding radiogram measurements. This discrepancy probably reflects the fact that soft tissue between the actual chest cavity and the rib cage does not show up on x-ray film. Parameter C, shown in Figure 31, showed the largest difference (again the mold data smaller than x-ray data). The difference could be due to the fact that x-rays are taken during inspiration, while cadavers represent practically full expiration. Considering the "pump handle" action of the ribs during respiration, the somewhat larger difference is not surprising. Figures 32 through 34 demonstrate the quite marked difference between

COMPARISON OF NORMALIZING
PARAMETERS (A_R vs. A_L)
FROM MOLD DATA

FIGURE 29

COMPARISON OF NORMALIZING
PARAMETERS (B_R vs. B_L)
FROM MOLD DATA

FIGURE 30

COMPARISON OF MALE X-RAY AND MALE MOLD DATA
VENTRAL DIMENSION (C), SIDE VIEW AVG. ± 2 ST. DEV.

FIGURE 31

male and female chest dimensions. The smaller size, especially in the heart region, could be a limiting factor in the design of a universal cardiac prosthesis. Female results will be shown later when the x-ray data is combined with the female "shape model."

3.2.3.4 Integration of Chest Model and Radiograms (Male). Applying the vertically dependent model (summarized in Tables 2 through 4) to the x-ray data results in the statistical chest size distributions shown in Figures 35 through 37. These figures are to scale and represent the average x-ray parameters (plus and minus two standard deviations) for the upper, middle, and lower thorax regions. Hence, the inner and outer two dotted lines include 95% of the male adult population. Also shown are the percent values for that portion of the population smaller than the indicated curve. We anticipate that meaningful external design constraints for an artificial heart can be determined when these curves are combined with the relative location of vital soft structure.

Examination of Correlation between Normalizing Parameters (A, B, and C) Obtained from 80 Male X-Rays. In these final results, terms $A + 2\sigma$, $B + 2\sigma$, and $C + 2\sigma$ are combined. Similarly, points $A - 2\sigma$, $B - 2\sigma$, and $C - 2\sigma$ are also connected. This implies that there is a direct correlation between these three parameters; and hence the "shapes" outlined by these curves indicate actual statistical distributions. If there is no correlation between these parameters (and the data is normal), then the standard deviation still has meaning, but actual chest shapes may have any random shape between the plus and minus two standard deviation lines.

Plots of these transverse x-ray variables versus each other are shown in Figures 38 and 39. When these sections are reconstructed to

COMPARISON OF MALE AND FEMALE X-RAY DATA

DORSAL DIMENSION (A), SIDE VIEW AVG. ± 2 ST. DEV.

FIGURE 32

COMPARISON OF MALE AND FEMALE X-RAY DATA

LATERAL DIMENSION (B), FRONT VIEW AVG. ± 2 ST. DEV.

FIGURE 33

COMPARISON OF MALE AND FEMALE X-RAY DATA

VENTRAL DIMENSION (C), SIDE VIEW AVG. ± 2 ST. DEV.

FIGURE 34

FIGURE 35

FIGURE 36

FIGURE 37

DEPTH vs. WIDTH
LEVEL 10 MALE

FIGURE 38

C vs. B
LEVEL 10 MALE

FIGURE 39

form a generalized total thorax, $V_{\max}$ (chest height) will also have a tolerance assigned to it. Again, the meaning of connecting $V_{\max} + 2\sigma$ to $A + 2\sigma$, $B + 2\sigma$, etc., must be determined. Hence, plots of $V_{\max}$ vs. width (B), total depth ($C + A$) and the anterior depth (C) are shown in Figures 40 through 42. Very little correlation can be seen in any of the five graphs. Numerical values supporting this visual assumption of scatter follow:

For level 10, male (80 radiograms):

C vs A	$R^* = -.25$
B vs A	$R = .1897$
B vs C	$R = .1566$

In another test, where simple linear regressions were tried;

B vs C	Correl. = .2307	$B = 6.94$ $+ .48 \cdot C$
C vs A	Correl. = -.1998	$C = 7.79$ $- .0719 \cdot A$
B vs A	Correl. = .1766	$B = 4.765$ $+ .133 \cdot A$

the normality of A, B, and C was approached by determining if the skewness of the data was significant. Again, level 10, from the 80 male radiograms:

Results

Parameter	Data Points	Skewness	Significant
A	79	1.57	yes
B	68	.435	no
C	69	.063	no

the only parameter not normal was A, the posterior measurement. Since

* R = Spearman Rank correlation coefficient.

THORAX HEIGHT vs. WIDTH
LEVEL 10 MALE

FIGURE 40

THORAX HEIGHT vs. DEPTH
LEVEL 10 MALE

FIGURE 41

HEIGHT vs. C
LEVEL 10 MALE

FIGURE 42

this dimension is not relevant to the heart location, the lack of normality is not serious. As a result:

1. Data is normal, and hence the standard deviation has meaning.

However,

2. No correlation exists between the normalizing parameters A, B, and C. This means that the area enclosed by the $\pm 2\sigma$ lines in Figures 35-37 represents the limits of random curves, and that the closed curves shown have no real meaning; e.g., a curve going from $B + 2\sigma$ to $C + 2\sigma$ is just as probable as one going from $B + 2\sigma$ to $C - 2\sigma$. The same holds true for $V_{\max}$ vs A, B, and C. Figure 43 shows the male thorax size distribution superimposed on the cross section of the prototype AEC heart, at approximately the T6 region in the chest. Of course, the actual orientation and vascular connection remain to be determined, but this figure indicates the relative sizes involved.

3.2.3.4. Integration of Chest Model and Radiograms (Female). A model based on two molds was obtained for levels 0, 2, 4.5, 8, and 10. Though based on only two molds, horizontal variability was considerably less than the individual vertical variability of each mold.

Model data for levels 0, 5, and 10 are shown in Tables 8, 9, and 10. This model data was then combined with the x-ray data from 20 normal female radiograms (Table 7). These distributions, shown in Figures 44, 45, and 46, though based on a limited amount of data, can be compared with male distributions derived earlier, at the same levels.

Note that different shapes for both left and right sides were allowed for the female model. A comparison of the male and female distributions shows considerable differences. Implantation of the AEC heart within the

FIGURE 43

FROM SPEC. # 1.00 TO SPEC. # 2.00

69

LEFT SIDE

ANTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV	PRCT
0.0000	0.9944	0.0079	0.7901
0.1000	0.9930	0.0095	0.9567
0.2000	0.9827	0.0176	1.7915
0.3000	0.9637	0.0165	1.7079
0.4000	0.9347	0.0044	0.4710
0.5000	0.8898	0.0154	1.7325
0.6000	0.8357	0.0172	2.0589
0.7000	0.7703	0.0144	1.8753
0.8000	0.6851	0.0277	4.0391
0.9000	0.5523	0.0924	16.7224
1.0000	0.1379	0.1951	141.4214

FEMALE
VERTICALLY
DEPENDENT MODEL
(LEVEL -3.0 TO 1.0)

FROM SPEC. # 1.00 TO SPEC. # 2.00

LEFT SIDE

POSTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.1359	0.0017	1.2478
0.2000	0.4799	0.0365	7.6054
0.3000	0.8004	0.0311	3.8847
0.4000	0.9537	0.0063	0.6574
0.5000	0.9903	0.0031	0.3123
0.6000	0.9725	0.0325	3.3462
0.7000	0.8949	0.0667	7.4517
0.8000	0.7682	0.0628	8.1733
0.9000	0.5169	0.0521	10.0766
1.0000	0.0000	0.0000	0.0000

FROM SPEC. # 1.00 TO SPEC. # 2.00

RIGHT SIDE

ANTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV	PRCT
0.0000	1.0000	0.0000	0.0000
0.1000	0.9972	0.0060	0.6063
0.2000	0.9844	0.0039	0.3984
0.3000	0.9637	0.0032	0.3354
0.4000	0.9375	0.0121	1.2892
0.5000	0.9045	0.0207	2.2846
0.6000	0.8663	0.0216	2.4976
0.7000	0.8024	0.0488	6.0757
0.8000	0.7300	0.0903	12.3747
0.9000	0.6421	0.1508	23.4796
1.0000	0.1167	0.1650	141.4214

FROM SPEC. # 1.00 TO SPEC. # 2.00

RIGHT SIDE

POSTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.1031	0.0198	19.2102
0.2000	0.4826	0.0507	10.5008
0.3000	0.8023	0.0641	7.9934
0.4000	0.9403	0.0199	2.1173
0.5000	1.0008	0.0012	0.1185
0.6000	0.9886	0.0043	0.4309
0.7000	0.9219	0.0109	1.1850
0.8000	0.8065	0.0046	0.5714
0.9000	0.5983	0.0440	7.3609
1.0000	0.1000	0.1414	141.4214

TABLE 8

FROM SPEC. # 1.00 TO SPEC. # 2.00
LEFT SIDE
ANTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV
0.0000	0.9646	0.0125
0.1000	0.9843	0.0001
0.2000	1.0011	0.0011
0.3000	0.9900	0.0060
0.4000	0.9580	0.0073
0.5000	0.9139	0.0091
0.6000	0.8599	0.0280
0.7000	0.7904	0.0548
0.8000	0.6763	0.1103
0.9000	0.4988	0.1997
1.0000	0.2124	0.1752

PRCT

1.2974
0.0097
0.1054
0.6071
0.7608
0.9945
3.2542
6.9388
16.3139
40.0438
82.4958

FEMALE VERTICALLY DEPENDENT MODEL (LEVEL 3.5 TO 6.5)

FROM SPEC. # 1.00 TO SPEC. # 2.00
LEFT SIDE
POSTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV
0.0000	0.0000	0.0000
0.1000	0.1703	0.0015
0.2000	0.6651	0.0198
0.3000	0.8923	0.0000
0.4000	0.9850	0.0073
0.5000	0.9955	0.0132
0.6000	0.9320	0.0544
0.7000	0.8145	0.0690
0.8000	0.6230	0.0402
0.9000	0.3148	0.1026
1.0000	0.0000	0.0000

PRCT

0.0000
0.8964
2.9831
0.0052
0.7395
1.3238
5.8362
8.4712
6.4551
32.6012
0.0000

FROM SPEC. # 1.00 TO SPEC. # 2.00
RIGHT SIDE
ANTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV
0.0000	0.9572	0.0062
0.1000	0.9832	0.0139
0.2000	0.9960	0.0044
0.3000	0.9895	0.0093
0.4000	0.9606	0.0013
0.5000	0.9294	0.0026
0.6000	0.8853	0.0167
0.7000	0.8185	0.0358
0.8000	0.7386	0.0656
0.9000	0.5812	0.1438
1.0000	0.2539	0.2257

PRCT

0.6433
1.4137
0.4383
0.9402
0.1394
0.2745
1.8850
4.3694
8.8755
24.7431
88.8747

FROM SPEC. # 1.00 TO SPEC. # 2.00
RIGHT SIDE
POSTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV
0.0000	0.0000	0.0000
0.1000	0.1788	0.0345
0.2000	0.7796	0.0269
0.3000	0.9281	0.0007
0.4000	0.9871	0.0053
0.5000	0.9838	0.0101
0.6000	0.9320	0.0127
0.7000	0.8300	0.0229
0.8000	0.6332	0.0174
0.9000	0.2879	0.0450
1.0000	0.0000	0.0000

PRCT

0.0000
19.3105
3.4519
0.0737
0.5341
1.0261
1.3592
2.7552
2.7422
15.6316
0.0000

TABLE 9

FROM SPEC. # 1.00 TO SPEC. # 2.00

LEFT SIDE

ANTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV	PRCT
0.0000	0.9713	0.0055	0.5625
0.1000	0.9939	0.0013	0.1325
0.2000	0.9985	0.0030	0.3001
0.3000	0.9909	0.0129	1.2996
0.4000	0.9825	0.0149	1.5131
0.5000	0.9514	0.0118	1.2353
0.6000	0.9019	0.0232	2.5729
0.7000	0.8414	0.0153	1.8205
0.8000	0.7475	0.0191	2.5549
0.9000	0.6030	0.0059	0.9844
1.0000	0.0407	0.0575	141.4214

FROM SPEC. # 1.00 TO SPEC. # 2.00

LEFT SIDE

POSTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.0848	0.0093	10.9162
0.2000	0.3650	0.1450	39.7239
0.3000	0.8339	0.0118	1.4153
0.4000	0.9510	0.0115	1.2076
0.5000	0.9850	0.0024	0.2398
0.6000	0.9931	0.0000	0.0030
0.7000	0.9113	0.0011	0.1258
0.8000	0.7317	0.0257	3.5180
0.9000	0.4677	0.0189	4.0410
1.0000	0.0000	0.0000	0.0000

FROM SPEC. # 1.00 TO SPEC. # 2.00

RIGHT SIDE

ANTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV	PRCT
0.0000	0.9774	0.0063	0.6399
0.1000	0.9916	0.0124	1.2465
0.2000	0.9900	0.0039	0.3943
0.3000	0.9900	0.0131	1.3187
0.4000	0.9801	0.0068	0.6921
0.5000	0.9530	0.0107	1.1227
0.6000	0.9185	0.0097	1.0600
0.7000	0.8668	0.0101	1.1688
0.8000	0.7812	0.0078	0.9985
0.9000	0.6685	0.0012	0.1738
1.0000	0.2035	0.0307	15.0812

FROM SPEC. # 1.00 TO SPEC. # 2.00

RIGHT SIDE

POSTERIOR

SLICES USED IN AVERAGE= 2.00

XINT	AVG	STDEV	PRCT
0.0000	0.0000	0.0000	0.0000
0.1000	0.1244	0.0501	40.2937
0.2000	0.6691	0.0432	6.4541
0.3000	0.8770	0.0216	2.4630
0.4000	0.9634	0.0121	1.2573
0.5000	0.9949	0.0007	0.0707
0.6000	0.9790	0.0077	0.7832
0.7000	0.8768	0.0384	4.3772
0.8000	0.6941	0.0879	12.6709
0.9000	0.4378	0.0794	18.1317
1.0000	0.0000	0.0000	0.0000

FEMALE
VERTICALLY
DEPENDENT MODEL
(LEVEL 9.0 TO 13.0)

FIGURE 44

FIGURE 45

FIGURE 46

average female chest may be more difficult than in the larger male chest. More female x-ray data must be obtained to verify this conclusively.

3.2.4 Pericardium Definition.

Quantifying an unsymmetric object like the pericardium has proved to be quite a challenge. As with the thorax wall, the problem was approached by generating an accurate shape model from a limited amount of detailed data, then obtaining a large sample of the normalizing parameters characterizing the form of the pericardium. This is shown diagrammatically in Figure 47.

Before continuing, a couple of salient points should be made. First, in the thorax wall problem, the coordinate system and normalizing parameters defined at the beginning proved to be adequate, in that a sufficiently small standard deviation was obtained for the model. In this case, the "search" aspect of the problem did not appear. With the pericardium, however, a number of different referencing systems and corresponding normalizing parameters can be chosen; the final approach should be that scheme resulting in the smallest error for the shape model. Algorithms must be determined in two basic areas. One is the method of referencing the pericardium within the vertical coordinate system, and the second is the method of referencing the pericardium within a given transverse section.

3.2.4.1. Vertical Referencing Approach.

The simplest method for referencing the pericardium in the vertical direction was chosen first. This was then tested with normal data from 80 male and 20 female AP and lateral radiograms. Results showed that a different approach was necessary, and the method finally chosen will be described.

First tried was the following: Pericardium measurements D, E, F, and G (shown measured in Figures 27 and 28) were made at specified inter-

METHOD FOR PREDICTING PERICARDIUM
OUTLINE FROM A-P AND LATERAL RADIOGRAM

FIG. 47

vals between an upper and lower reference point (Fig. 16). Each interval was 10% of the distance between these two points. If the top and bottom of the pericardium always corresponded to a specific "level", then a shape model assumed to occur between these two levels could be used to characterize the pericardium. Data from 100 normal radiograms showed the top of the pericardium to occur very close to level 3.5 in the vertically normalized chest. The bottom of the pericardial sac, however, showed a wide range of end points. This could have been caused by variable levels of inspiration, basic differences between individuals, or the general obscurity of the heart silhouette in this region. (In many cases, the outline had to be estimated by a trained radiologist.) Data for the 80 normal males and 20 normal females is shown in Figures 48 through 51. Presented are averages plus or minus two standard deviations. Note that in the P-A views, the standard deviation increases abruptly at level 12 in both males and females, indicating the end points of some hearts have been reached. The same effect is even more remarkable in the two lateral views (Figs. 50, 51), where a sharp change in the average shape at level 11 (male) and level 10 (female) indicates the point where some hearts end. Farther down, where the short hearts are no longer contributing, F and G dimensions both decrease, followed at level 13, where these hearts then end.

Conclusions from these results indicate that heart height and location within the thorax do not correlate with overall thorax height, and a different vertical referencing scheme must be chosen.

The final method chosen was a direct result of these initial pilot studies and is shown in Figure 52, a diagram used to indicate valve reference points described in a later section. The top of the heart sil-

FEMALE PERICARDIAL VARIABILITY FROM
NORMAL A-P RADIOGRAMS

FIGURE 48

MALE PERICARDIAL VARIABILITY FROM
NORMAL A-P RADIOGRAMS

FIGURE 49

FIGURE 50

FEMALE PERICARDIAL VARIABILITY ($\pm 2\sigma$)
FROM NORMAL LATERAL RADIOGRAMS

FIGURE 51

**TWO POSSIBLE REFERENCING SYSTEMS
FOR VERTICAL LOCATION OF VALVES**

FIGURE 52

houette is considered as 0% and bottom of the heart as 100%, with the distance between these two points measured at $V_{H \max}$ (maximum heart height). The heart outline, then, has its own normalized vertical coordinate system and is referenced to the chest coordinate system by measurement V_R . Development of a pericardium shape model proceeds by searching for similarities in "shape" at identical percent distances between the top and bottom of the heart.

3.2.4.2 Pericardial Referencing System within a Transverse Section.

As with the vertical problem, it was hoped that within a given transverse section of the thorax, there would be a direct correlation between the chest wall outline and the pericardial outline (i.e., a constant ratio of chest depth to pericardium depth). A cursory examination of even normal data showed that heart outline was quite independent of the chest in which it was located. Subsequently, the following referencing method was chosen and will be used in generating the pericardial shape model using data from anatomical texts, published tomographic data and actual cadavers.

Shown in Figure 53 is a transverse section at a known normalized distance between the top and bottom of the heart. A coordinate system for the pericardium with respect to the chest ($\textcircled{X}$, $\textcircled{Y}$) is generated by dimensions X_R and Y_R , both observable in an x-ray film ($X_R = D$, $Y_R = F$). Also observable are the extreme points of the sac defining variables $X_{p_{\max}}$ and $Y_{p_{\max}}$ ($X_{p_{\max}} = D + E$, $Y_{p_{\max}} = F - G$). However, these points have no "tags" on them in normal radiograms and hence must be defined from the shape model. This information is provided by the ratios:

REFERENCING SYSTEM FOR PERICARDIUM MODEL

FIGURE 53

$$X_a/X_{p_{max}}$$

$$X_b/X_{p_{max}}$$

$$Y_a/Y_{p_{max}}$$

$$Y_b/Y_{p_{max}}$$

and constitutes the first component of the "shape" model.

In addition, the shape of the pericardium over each of the four regions defined by four secondary coordinate systems is normalized and constitutes the second component of the pericardial "shape" model. Each of these secondary coordinate systems is shown in Figure 53 and labeled by the section of the sac that it defines. For example, 1 IA outlines the left anterior portion of the right ventricle and is defined by a coordinate system originating at $X_a/X_{p_{max}}$. Additional sections are 2 LP which covers most of the left ventricle or left atrium depending on the vertical level, 3 RA which covers the remainder of the right ventricle not described by 1 IA, and 4 RP which outlines either the right atrium or right ventricle, again depending on the vertical level. Once the "shape" model is finalized, inputting the four observable data points on a radiogram, X_R , Y_R , $X_{p_{max}}$, and $Y_{p_{max}}$, allows the regeneration of the pericardial outline. Hence, a combination of this model with a large array of pericardium data (X_R , Y_R , etc.) from abnormal P-A and lateral radiograms will define this space available for an artificial heart (Figure 13, shown earlier). Note that to locate this average pericardium within the thorax, which has already been defined, correlations have to be determined between thorax normalizing parameters (A, B, and C) and pericardium normalizing parameters (X_R , Y_R , etc.).

3.2.4.3 Current Status. Raw data for implementing the above method for pericardium definition is being gathered and is partially analyzed.

Information for the shape model presently includes data from five anatomy atlases containing original transverse sections^(3, 4, 5, 6, 19), a complete set of published tomograms⁽¹³⁾, and pericardium outlines traced from slices of an intact cadaver (Case Western Reserve University, Department of Anatomy). Typical cadaver slices are shown in Figure 54, one with the AEC pump superimposed.

Data for the normalizing parameters (X_R , Y_R , etc.) presently includes 30 P-A and lateral radiograms of abnormal heart patients. A preliminary analysis of this data, which has been only partially digitized, indicates a correlation with the actual diagnosis may be necessary to arrive at a more meaningful model.

3.2.5 Vascular Connection Definition.

As discussed in Section 3.2.2.2, two types of failures (or a combination of both) can occur in an artificial heart implantation. These were termed "mode 1", for a mismatch between connection points, and "mode 2," for pump displacements caused by the incorrect distance between the vascular connection points and hard structures (chest wall). Consequently, one extremely important aspect of solving these two failure modes are measurements related to the intended vascular connection points for the prosthetic pump.

3.2.5.1 Method for Defining Vascular Connection Points. The approach to solving this problem is quite straightforward. As before, a small amount of detailed data was examined to develop a "shape" model, followed by the examination of a large amount of the "normalizing parameter" variables that characterize the shape model, resulting in a statistical distribution useful for design purposes. However, in this case the shape model

ACTUAL CADAVER SECTION

FIGURE 54

might well be more correctly called a "spatial" model, since the goal is to define the average location of a vascular connection point, rather than any particular shape. Problems of either mode 1 or mode 2 can be solved by the following technique, depending on what is done with the measured variables.

Basically, the method uses data from the radiograms of patients with one or more artificial valves. The important assumption made (in order to relate this data to a heart implantation) is that the vascular connection points will be just above the natural valve in order to retain as much natural tissue as possible (especially natural atria). Once valve spatial relationships are correlated with observable features on a normal radiogram (pericardium outline, chest wall, etc.), a statistical distribution can be determined for the final, integrated model (Figs. 12 and 13).

In order to determine these spatial relationships and corresponding correlations, a vertical and transverse referencing system must be chosen as in the pericardium case. In Figure 52 are shown the two possible vertical systems: one, referenced to the overall chest system, would examine the ratios $P_c/V_{\max}$, $A_c/V_{\max}$, etc., where P_c and A_c are the distances to the artificial pulmonary and aortic valves, respectively; a second (and the most probable at this time) will study the ratios $P_H/V_{H \max}$, $A_H/V_{H \max}$, etc., from a secondary coordinate system determined by the top and bottom of the pericardial sac. At a specified vertical distance, a reference system, shown in Figure 55, will most likely be applied to the corresponding transverse section. Ratios, determined from the x and y distances to each of the four valves divided by $X_{p \max}$ and $Y_{p \max}$, respectively, will be correlated with the particular normalized vertical distance within the

REFERENCING SYSTEM FOR VALVES AND GREAT VESSELS

FIGURE 55

pericardium. In addition, the ratio of the distance between valves and $X_{p_{max}}$, $Y_{p_{max}}$ will also be noted. Data such as this (and that from atlases, tomograms, and cadavers) will constitute the "spatial" model for the vascular connection problem. (It is expected that this model will be disease dependent.) Further useful measurements are direct distances between these artificial valves and the anterior portion of the chest wall.

Because the artificial valves, pulmonary and tricuspid, are somewhat rare, indirect means of locating these points in the heart may be necessary. One method presently being tested is the examination of P-A and lateral angiographs. A second, indirect method attempts to use published atrial size data (determined also angiographically)⁽¹⁶⁾ to estimate the distance from the posterior wall of the pericardial sac to the mitral valve.

To implement the above methods, raw data has been gathered from the lateral and P-A views of patients with artificial valves here at the Cleveland Clinic. The minimum amount of data for developing a model using any referencing system was determined and is shown on actual radiograms in Figures 56 through 63. Additional data, besides the parameters A - G described earlier, are dimensions H, I, and J in the P-A view and K in the lateral projection. H is the distance from the midline to the valve. J is the distance from the valve to the top of the pericardium. In the lateral view K is the distance from the chest reference point (most anterior point of vertebra) to the valve. As usual, superimposed on each radiogram is the normalized vertical coordinate system for the entire thorax.

In Figures 56 and 57 are shown the P-A and lateral radiograms of a

FIGURE 56

FIGURE 57

FIGURE 58

FIGURE 59

FIGURE 60

FIGURE 61

FIGURE 62

FIGURE 63

patient with an aortic prosthesis. In Figures 58 and 59 are also an aortic valve, except with a slightly different orientation (especially in the lateral view). This "orientation" information is also being recorded in order to successfully solve one of the aspects of "mode 1" failure. In Figures 60 and 61 are shown the measurements made on a typical mitral prosthesis. Figure 62 shows dimensions taken from a typical tricuspid valve. In Figure 63 is shown the lateral view of the same patient, with the K dimension this time taken from the mitral valve. Note the variations in the heart size and shape, comparing Figures 58 and 60.

3.2.5.2 Current Status. Data has been recorded from the P-A and lateral views of thirty patients with artificial valves. Additional data has been recorded from 7-P-A and lateral angiographs to supplement the valve information. This data is presently being analyzed in conjunction with the atlases, tomograms, and cadaver data to develop a valve "spatial" model that can be used with large numbers of standard radiograms to yield a statistical distribution for the vascular connection points.

3.2.6 Great Vessel Definition.

In section 3.2.2.2 the importance of vena cava location with respect to the artificial heart was demonstrated. Of minor significance is the location of the aorta. Location of blood vessels above the dotted lines shown in Figures 5 and 6 are, of course, irrelevant.

3.2.6.1 Method for Great Vessel Definition. Data for the vena cava location will most likely come from published sources^(14, 15), anatomical texts, cadaver data, and most importantly, lateral and P-A projections of venograms. Using the referencing system illustrated in Figure 53 -- that is, with vena cava data referenced to the pericardium coordinate system

and descending aortic locations referenced to the chest system -- certain ratios will be examined for a correlation with vertical distance. These are the vena cava x and y coordinates divided by C and B, respectively.

3.2.6.2 Current Status. Data has been recorded from 7 P-A and lateral angiograms, 1 cadaver, 4 atlas texts, and 2 published sources, and is currently being analyzed.

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APPENDIX A

RADIOGRAPH MEASUREMENT TECHNIQUE

MEASUREMENTS ON POSTERO-ANTERIOR RADIOGRAPHS (Fig. 27):

1. Define the median line (I), assuming that the chest is symmetric.
2. Locate the fourth and tenth ribs of both sides.
3. Draw the lines, which cross perpendicularly to (I) and pass through the points at which the fourth (II) and tenth rib (III) is farthest from line (I).
4. Draw a line from the mid-point of Line II, parallel to (I), to Point (IV) on the dorsal shadow of the fourth rib. Do the same and obtain Point (V) on the tenth rib.
5. Define the upper reference point (P_0) on Line (I) where a line perpendicular to Line (I) passes through Point (IV). Define the lower reference point (P_{10}) on Line (I) from Point (V).
6. Measure the distance between Point (P_0) and (P_{10}). This is V_{max} .
7. Divide V_{max} into ten divisions and name divisional points in an order of $P_0, P_1, P_2 \dots P_{10}$ and extend these points on Line (I) upward to $P_1, P_2 \dots$ and downward to P_{11}, P_{12} with the same divisional distance.
8. Measure distances $B_0, B_1, B_2 \dots B_{10}$ and $B_{-1}, B_{-2} \dots B_{11}, B_{12} \dots$ as many as exist in such a manner as B_n is a distance between Point (P_n) and a point at which a perpendicular to Line (I), passing through P_n , crosses the internal margin of the chest cavity on a radiograph.
9. Measure distances $D_0, D_1, D_2 \dots$ which are defined by the distances from $P_0, P_1, P_2 \dots$ to points at which lines perpendicular

Appendix A - 2

to Line (I) and passing through $P_0, P_1, P_2 \dots$ cross the right margin of the heart silhouette.

10. Measure distances $E_0, E_1, E_2 \dots$ which are defined as the same as $D_0, D_1, D_2 \dots$, but to the left margin of the heart silhouette.

An upper and lower limitation of the pericardial cavity are confirmed on a corresponding lateral view of chest radiograph.

If any upper and/or lower limitation of structures to be measured are not on exact divisions, half the divisional scale is set and indicated on a chart. (For example (3.5) in Column D in Table 1). The level of each side of the diaphragm is individually noted in Table 12 since very often it differs.

MEASUREMENTS ON LATERAL RADIOGRAPHS (Figure 28):

1. Locate and define the reference point (Q_0) on the anterior line of the vertebral column which has already been determined as the corresponding point (P_0) on a posteroanterior view. Point ($P_0 = Q_0$) usually positions itself at a lower rim of the third thoracic vertebra.

2. Define Point (R_0) which is marked on a posterior edge of the film and at the same horizontal level to (Q_0).

3. Make Point (R_{10}) on a posterior edge of the film with a distance of V_{max} from R_0 . Q_{10} can be marked by tracing a horizontal line passing through R_{10} on the anterior line of the vertebral column.

4. Divide the distance between R_0 and R_{10} into ten divisions and name divisional points in an order of $R_0, R_1, R_2 \dots R_{10}$ and extend these points upward to $R_{-1}, R_{-2} \dots$ and downward to $R_{11}, R_{12} \dots$ with the same divisional distance.

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5. Mark $Q_1, Q_2 \dots Q_9$ on the anterior line of the vertebral column so as to be at the same horizontal level to the corresponding points of $R_1, R_2 \dots R_9$.

6. Measure distances $C_0, C_1 \dots C_{10}$ in such a manner as C_n is defined by a horizontal distance between Q_n and the anterior internal margin of the chest cavity.

7. Measure distances $A_0, A_1 \dots A_{10}$ and $A_{-1}, A_{-2} \dots A_{-11}, A_{-12} \dots$ in such a manner as A_n is defined by a horizontal distance between Q_n and the posterior internal margin of the chest cavity.

8. Measure distances $\dots F_2, F_3 \dots F_5, F_6 \dots$ in such a manner as F_n is defined by a distance between Q_n and the point where a horizontal line through Q_n crosses an anterior line of the heart silhouette.

9. Measure distances $\dots G_2, G_3 \dots G_5, G_6 \dots$ in such a manner as G_n is defined by a distance between Q_n and the point where a horizontal line through Q_n crosses a posterior line of the heart silhouette. A typical case of the measurements is presented in Table A-1.

NO. 74

NAME: B.J.R.

SEX: Male

AGE: 54

	A	B	C	D	E	F	G
-5							
-4							
-3							
-2		(-1.5) 4.4	(-1.5) 0.5				
-1	3.0	6.8	8.0				
0	5.0	9.6	10.1				
1	5.4	11.6	13.2				
2	5.6	12.7	13.6				
3	5.8	13.3	13.6	(3.5) 2.0	(3.5) 2.2	(3.5) 7.8	(3.5) 7.8
4	6.1	14.0	13.8	2.6	2.2	10.8	6.5
5	6.5	14.1	13.5	3.0	2.4	12.5	4.1
6	7.2	14.6	13.2	3.4	3.1	13.2	3.1
7	7.5	14.7	12.9	3.6	4.2	12.9	2.8
8	7.5	14.8	12.5	4.3	6.1	12.5	2.5
9	7.6	14.8	12.4	4.5	8.0	12.4	2.5
10	7.6	15.4	12.4	4.5	9.0	12.4	3.2
11	7.6	15.4	12.4	4.5	10.0	12.4	5.0
12	7.6	^R (12.0) 9.0 ^L (12.0) 11.0	^R (12.0) ^L (12.0) 7.0 7.0	4.5	10.5		
13							
14							
15							
16							
Vmax	18.0						

() indicates a divisional scale.

Numbers indicate actual distance in cm.