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TITLE OF THESIS..... ECHOCARDIOGRAPHIC DETERMINATION OF CARDIAC OUTPUT USING THE ECHOGRAM OF THE ANTERIOR MITRAL VALVE LEAFLET AND AORTIC ROOT & THE RELATIONSHIP BETWEEN THE DYNAMICS OF MITRAL VALVE CLOSURE & AORTIC FLOW

UNIVERSITY... OF ALBERTA.....

DEGREE FOR WHICH THESIS WAS PRESENTED..... M.Sc.....

YEAR THIS DEGREE GRANTED..... 1976.....

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# ECHOCARDIOGRAPHIC DETERMINATION OF CARDIAC OUTPUT USING THE ECHOGRAM OF THE ANTERIOR MITRAL VALVE LEAFLET AND AORTIC ROOT AND THE RELATIONSHIP BETWEEN THE DYNAMICS OF MITRAL VALVE CLOSURE AND AORTIC FLOW

By

© Akbar V. A. Lalani, MB, BS

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR

THE DEGREE

OF MASTER OF SCIENCE (MEDICINE)

DEPARTMENT OF MEDICINE

EDMONTON, ALBERTA

SPRING, 1976

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled Echocardiographic Determination of Cardiac Output Using the Echogram of the Anterior Mitral Valve Leaflet and Aortic Root and the Relationship Between the Dynamics of Mitral Valve Closure and Aortic Flow, submitted by Akbar V.A. Lalani, MB, BS, in partial fulfilment of the requirements for the degree of Master of Science (Medicine).

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Supervisor

Professor 1. ..... J.M. Parkin .....

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Date March 12, 1976

ABSTRACT

The currently used echocardiographic method for measuring cardiac output has limitations in that it relies on obtaining satisfactory recordings of the minor axis diameter of the left ventricular cavity. It is based on assumptions pertaining to the shape (prolate ellipse) and uniformity of contraction of the left ventricle. In patients with dyskinesis or cardiac enlargement, these assumptions can lead to errors in the measurement of cardiac output by this method.

In this study, therefore, a different approach to measuring cardiac output, by echo, has been adopted. It is based on an adaptation of the hydraulic principle pertaining to the flow of fluids. Cardiac output = Aortic root cross-sectional area X Left ventricular ejection time X Mean aortic flow velocity X Heart Rate.

Using the Fick method, 34 measurements of cardiac output were made in 32 patients with normal aortic and mitral valves, with simultaneous echocardiographic recording of the aortic root, mitral valve, interventricular septum and posterior left ventricular wall. The manually derived systolic closure slope of the anterior mitral valve leaflet echogram was assumed to represent the mean aortic flow velocity. Aortic root area and left ventricular ejection time were derived from the aortic root and valve echograms. Heart rate was computed from the E.C.G. Stroke volume by the conventional echo method was derived from the difference between the cubes of the end-diastolic and end-systolic diameters.

Close correlation was found between ejection time by echo and that

measured from the aortic pressure tracings, which were obtained simultaneously in 17 of the subjects ($r = 0.95$, $p < 0.001$). Aortic root dimensions measured by echo and directly at surgery in 8 other subjects, in a separate study, also correlated well ($r = 0.97$, $p < 0.001$). Cardiac output by the Fick method and the proposed echo method showed good overall correlation ($n = 34$, $r = 0.90$, $p < 0.001$), and the close correlation held equally well when data from those patients with ($r = 0.94$, $n = 16$) and those without ($r = 0.87$, $n = 18$) asynergy was examined separately.

Cardiac output by the conventional echo method could be obtained in only 21 of the 32 patients (66%). Comparison of cardiac output by this method with that by the Fick method, showed good correlation ($r = 0.77$, $n = 13$, $p < 0.005$) in those patients without asynergy, but the correlation in those with asynergy ($r = 0.44$, $n = 8$, $p < 0.3$) was not significant. The overall correlation in the whole group was, however, significant ($r = 0.58$, $n = 21$, $p < 0.01$).

In order to verify the relationship between mitral valve closure slope and the mean aortic velocity, a separate study was carried out in 7 open-chest dogs. The close correlation obtained between these two parameters ($r = 0.94$, $n = 84$, $p < 0.001$) supported the original assumption.

Further studies were carried out in 3 other dogs to explore the relationship between derivatives of mitral valve closure slope and aortic velocity as measured by a catheter-tip electromagnetic velocity transducer. Peak mitral closing velocity, peak mitral closing acceleration and aortic acceleration were obtained by the

differentiation of the mitral and aortic signals, and compared with each other. It was found that peak mitral closing velocity correlated well with the manually derived closure slope ($r = 0.76$, $n = 30$, $p < 0.001$), peak mitral closing acceleration ($r = 0.84$, $n = 32$, $p < 0.001$), peak aortic acceleration ($r = 0.75$, $n = 31$, $p < 0.001$) and correlated moderately well with peak aortic velocity ($r = 0.59$, $n = 32$, $p < 0.001$). However, closest correlation was found between peak mitral closing acceleration and peak aortic acceleration ($r = 0.87$, $n = 30$, $p < 0.001$).

ACKNOWLEDGEMENTS

The successful completion of this project has been the result of help or advice, in one form or the other, from numerous people and I should like to recognise them in this section of my thesis.

Needless to say, the first and foremost of these must be Dr. Simon J.K. Lee. Ever since I first approached him with the initial idea, he has been selfless and generous in both the time and advice he has given me in this past year. In addition, it was under his guidance that the project got off the ground and culminated in this study. More than a supervisor, he has been a friend and a constant souce of encouragement.

My deep gratitude also goes to the staffmen who constitute the Division of Cardiology, in particular Dr. R.F. Taylor, Dr. C. Brooks and Dr. M. Haraphongse for the time and patience on their parts, both in and out of the cardiac cath laboratory.

Thanks are also due to the two surgeons, Dr. R.L. Fisk and Dr. E. Gelfand for helping me with the part of the study involving measurements made at open-heart surgery.

I am indebted to the various people from the Cardiac cath laboratory, Electronics Department and our Research labs for smoothing the many everyday problems that would otherwise have hampered this project. In particular, I wish to mention

Mrs. Glenda Hill and members of the cath lab team, Mr. Don McFarlane and Bert Van Mechelen of the Electronics Department, Mr. Lou Lacnicka, Miss Mary McNulty, Mr. Moeus Meeuse and Mrs. Marion Greenan of the Photography Department and Mr. Alan Wells and Mrs. Maureen Boudreau. It was a pleasure approaching these people at all times for their assistance or advice.

Thanks are also due to Dr. Garner King and Dr. George Meissner for their help with the animal studies, in terms of their generous help with either equipment or technical advice and assistance.

I should also like to acknowledge the considerable help I have received in bypassing administrative problems from Mr. E. Shell.

Finally, I should like to make special mention of the constant support, patience, understanding and encouragement I have received from my wife, Shamin. This thesis is in fact, a result of her initial suggestion.

Edmonton, Alberta
February, 27, 1976

Akbar V.A. Lalani, MB, BS

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# INTRODUCTION

The advent of echocardiography has introduced a useful non-invasive method for the measurement of cardiac output.

The echocardiographic method currently in use for this purpose is based on the studies of Feigenbaum[1], Popp[2] and others[3,4,5]. It relies on measurement of an internal dimension of the left ventricular cavity that approximates its minor axis diameter. The reliability of this method depends on the shape of the left ventricular cavity being a prolate ellipse and on uniformity of contraction of the left ventricular chamber[6]. Thus, the presence of non-uniform contraction of the left ventricle, frequently seen in patients with ischemic heart disease, or variations in the relationship between the major and minor axis diameters[7], can produce significant errors in the measurement of cardiac output using this method.

Another drawback of the method currently used is that it requires simultaneous recordings from the interventricular septum and the posterior left ventricular wall, which is often technically difficult, if not impossible.

The purpose of this study, therefore, was to adopt a different approach to measuring cardiac output by M-Mode echocardiography. The principle underlying the method proposed in this study utilizes a basic hydraulic formula pertaining to flow of fluids through a cylinder (Fig. 1). The proposed method is based on the measurement of aortic root diameter and left ventricular ejection time from the echocardiogram of the aortic valve and root. The principal assumption made in

this method is that mean aortic ejection velocity can be estimated from the systolic closure velocity of the anterior mitral leaflet.

In addition, further examination of the relationship between other characteristics of aortic ejection (namely, aortic acceleration and peak aortic velocity) and of mitral closure (peak mitral closing velocity and peak mitral closing acceleration) was also carried out in this study.

## BACKGROUND INFORMATION AND REVIEW OF THE LITERATURE

### Cardiac Output Measurement by Echocardiography

Edler was the first to note and recognise echoes arising from the interventricular septum and the posterior left ventricular wall[8]. He made the observation that the posterior wall echogram executed movements anteriorly with each ventricular systole and remarked that the magnitude of these excursions increased in those conditions that would lead to an increase in the cardiac output, such as aortic incompetence. However, no further attempts were made to quantitate left ventricular size or output, at that time.

The first attempt to measure left ventricular size and output was made by Feigenbaum[1]. He found an increase in the distance between the transducer artefact and posterior left ventricular wall echogram in those patients with cardiomegaly on the chest x-ray. The validity of this observation was subsequently verified angiographically in 52 patients, particularly in relation to the end-diastolic volume.

At about the same time, Zaky et al.[9] were examining the echoes originating from the base of the heart, specifically from the mitral annulus, with the purpose of assessing left ventricular function. These investigators observed that the pattern of motion executed by the mitral ring echo resembled an inverted ventricular volume curve. On the basis of this observation they postulated that the magnitude of its motion would bear some relationship to left ventricular stroke volume. As such, an empirical formula was devised, incorporating the distance from the anterior chest wall to the posterior left ventricular

wall as a measure of overall heart size and the magnitude of excursion of the mitral annulus echo as a measure of the change in volume of the ventricle from diastole to systole[1]. The results obtained by this technique related crudely with actual stroke volumes. This was primarily because the method used was fraught with two major drawbacks. Firstly, it was found that in those patients with right ventricular distension, or hypertrophy, their method gave poor results. This is not surprising because the measurement of overall heart size was in reality a composite of the sizes of both the left and the right ventricular cavities. Thus, changes in one would lead to gross errors in the estimation of the other. The second defect in this method was one of standardization owing to the multiplicity of echoes of varying amplitudes arising from the mitral ring area[9]. Despite these shortcomings, however, it was clear that echocardiography could become a feasible method for measuring stroke volume with the distinct advantage of being non-invasive.

A major step forward in the evolution of this technique came with the rediscovery of echoes arising from the interventricular septum. Although this structure was originally identified in 1961, it was not until 1969 that Popp[10] described the usefulness of echoes from the septum in the estimation of internal dimensions of the left and right ventricular cavities separately. The borders of each chamber were subsequently confirmed by simultaneous angiographic and echocardiographic studies[11].

A somewhat different approach to the one adopted by Zaky et al. was taken by Popp et al. in estimating cardiac output by echocardio-

graphy[2]. Based on data obtained by angiographic studies, this group assumed that the shape of the left ventricular cavity resembled a prolate ellipse and that the dimension measured by echocardiography represented the minor axis diameter of this ellipse. They further assumed that the relationship between the minor and major axes was constant in systole and diastole and that the latter was twice the former in magnitude. Based on these assumptions, this group proposed that the cube of the left ventricular internal dimension measured by echo, at end-diastole and end-systole, approximated the end-diastolic and end-systolic volumes. The difference between the two cubed values would therefore yield the stroke volume. Stroke volume obtained by this echocardiographic method bore close correlation to volume measurements made by angiography or by the standard Fick method. This observation was subsequently confirmed by several groups of investigators[3,4,5,12]. Currently therefore, this has become the accepted echographic method for estimating cardiac output[13,14].

It must be pointed out, however, that even in these early studies, several points were raised, which in the course of time have emerged as possible limiting factors to this method and its application. Fortuin[3] and Pombo[4] had both remarked that the echocardiographically derived cardiac output of some of the patients in their groups deviated widely from the data obtained angiographically. These patients had previously sustained myocardial infarctions and had areas of akinesis or compensatory hyperkinesis present. Since echographic measurements of internal dimensions were made from very limited areas of the ventricle, these investigators assumed, quite correctly, that segmental

irregularities of contraction probably were responsible for the erroneous results obtained. This observation has subsequently been shown to be true[15,16]. In fact, one recent study has taken this one step further and utilised the calculated discrepancy in cardiac output estimations by the echo and Fick methods in patients with dyskinesis, to estimate the size of the abnormally contracting segment[17].

Another limiting factor that was noted in the earlier studies was the variable degree of success in obtaining satisfactory echograms in the patients studied. This was found to vary between 60%[15] to 80%[5]. The major drawback appeared to be a technical one, of obtaining satisfactory recordings simultaneously from the endocardial surface of the posterior left ventricular wall and the interventricular septum[18].

The relationship between the major and minor axes of the left ventricle has recently been re-examined by Teichholz and his associates[16]. In 100 left ventricular angiograms examined retrospectively, they found considerable scatter in the major:minor ratio throughout the patient population studied. This scatter also occurred through the various stages of the cardiac cycle. The ratios obtained lay between approximately 3.5 and 1.1. They went on to confirm that these variations in the ratio led to falsely high or low results for the cardiac output values obtained.

Therefore, it appears that the presently accepted echocardiographic method for measuring left ventricular volumes and output, has three major limitations. These are:

(i) its inapplicability with any degree of accuracy, in patients with non-uniform left ventricular contraction,

(ii) its limited applicability in the presence of cardiac enlargement[6,7],

and (iii) the variability of the degree of success in obtaining satisfactory recordings.

A completely different echographic approach, which involved examination of the mitral valve echogram for the measurement of cardiac output, was proposed by Fischer et al. in 1972[19]. The premise on which their method was based was that the leaflets of the mitral valve responded passively to transmitral blood flow in a manner such that the degree and duration of separation of the anterior and posterior mitral leaflets would provide an index of diastolic inflow and hence of the stroke volume. The only pre-requisite for this method was the acquisition of an adequate echographic recording of both leaflets of the mitral valve. Initial results derived by this method showed excellent correlation between stroke volume obtained by the Fick method and the above-mentioned index. Aside from the primary assumption mentioned, the other assumptions inherent in this method were that the velocity of transmitral flow was constant throughout diastolic filling, that the mitral valve was normal and that the echocardiographically measured leaflet separation represented the true measure of this dimension. Many of these assumptions are, in fact, not entirely consistent with anatomic and physiologic realities and hence constitute theoretic barriers to the generalized utilization of this method.

Another mode of utilizing the mitral valve echogram for measuring stroke volume was proposed by two groups of investigators[20,21]. It was

suggested by these workers that the opening velocity of the anterior leaflet of the mitral valve might be an indicator of the velocity of flow of blood from the left atrium into the left ventricle, during diastole. Hence, using a hydraulic formula, total flow through the mitral orifice could be estimated by the product of mitral valve area (assumed in each case to be 5 $cm.^2$), diastolic filling period (taken from the echocardiogram as the period between mitral valve opening at the commencement of diastole and mitral valve closure at the start of ventricular systole) and mean transmitral flow velocity (derived from the DE slope of the anterior mitral valve leaflet echogram). Theodisou[21] compared cardiac output obtained by this method with that obtained by the Fick method at cardiac catheterisation. In the 20 subjects they examined, they obtained good correlation by this method ($r = 0.79$, $p < 0.001$).

Winsberg and his group[22] have examined the aortic valve echogram to estimate cardiac output. The theoretic basis for their method was that examination of the extent and duration of separation of the leaflets of the aortic valve recorded by echocardiography, would enable them to assess the volume of blood entering the aorta during the period of left ventricular ejection i.e. the stroke volume. Close correlation between measured stroke volume and the index derived from aortic leaflet separation was indeed found to exist. Unfortunately, however, absolute values for stroke volume could not be estimated as this method did not assess aortic flow velocity.

Currently, therefore, the standard echographic method for measuring cardiac output is the one involving measurement of cyclical changes of

internal dimensions of the left ventricular cavity, at end-systole and end-diastole. This method is based on sound physical principles but has definite limitations, particularly in the presence of irregularities of ventricular contraction or cardiac enlargement. The alternative methods available involve examination of the mitral or aortic valve echograms and deriving indices of stroke volume from the degree and duration of the separation of their leaflets.

Factors Affecting Mitral Valve Closure - The Role of Ventricular Contraction

The hemodynamic events that bring about mitral valve closure in late diastole-early systole are still under investigation. In particular, disagreement still exists over the relative roles, if any, played by atrial and ventricular contraction.

The classical experiments performed in 1912, by Henderson and Johnson[23] on excised animal hearts, led to the elucidation of two possible mechanisms leading to mitral valve closure. The first mechanism was mediated by the contraction of the atria. These workers postulated that with the forward acceleration of blood brought about by atrial systole, the mitral leaflets tended to be drawn into partial or complete apposition by the negative pressure created on the atrial side, i.e. by the Bernouilli effect. The role played by the second mechanism, ventricular contraction, according to these authors, was very much a secondary one of completing the process of valve closure, by the retrograde surge of blood flow produced by the action of the ventricle.

Four years later, Dean[24] carried out elegant experiments in the isolated, perfused cat heart and succeeded in recording the motion of the mitral valve using a delicate lever system. Essentially, he confirmed the earlier observations of Henderson and Johnson, i.e. that atrial systole is responsible for partial closure of the mitral valve but that ventricular systole is necessary for completion of closure. In addition, he introduced an important proviso, namely, that the relative contribution of atrial and ventricular contraction to valve closure depended largely on the time interval separating the systolic contraction of the two chambers.

The earlier studies of Sarnoff et al.[25] and the more recent work of Luisada and his group[26] has tended to favor the atrial mechanism as probably being the predominant factor involved in mitral valve closure.

The findings of Gordon et al. reported recently have, on the other hand, tended to underplay the importance of atrial systole in this process[27]. Their cineangiographic studies in dogs suggest that isolated atrial contractions, in the presence of 2:1 block or complete atrio-ventricular block, are ineffective in bringing about adequate valve closure, as opposed to those beats followed by normal ventricular contraction. These workers found that isolated atrial contractions resulted in only partial valve closure (45 to 90%) and that closing velocity was considerably slower (10 ± 4.5 cm. $sec.^{-1}$ as compared with 33 ± 13 cm. $sec.^{-1}$ in sinus rhythm) and of very short duration (10 to 30 msec.; 250 to 430 msec. in sinus rhythm). This evidence suggests that ventricular systole has a dominant role to play in ensuring rapid and effective valve closure. An additional mechanism involved in valve

closure has been invoked by Taylor[28] and Bellhouse[29a,29b]. This is the formation of vortices behind the valve leaflets further enhancing valve closure velocity.

The advent of echocardiography has made it possible to record movements of the mitral valve leaflets with accuracy. Pohost, Rubenstein and others[30,31] have confirmed, in both animal and human studies using echocardiography and hemodynamic parameters, that the former technique is indeed a reliable indicator of valve closure and opening. Results of their studies[31] have clearly shown that the advent of ventricular systole precedes the completion of mitral valve closure by 18 to 37 msec.

However, to date, the only studies that have attempted to correlate mitral valve motion with transmitral flow, have been those of Laniado and Yellin[32,33]. In essence, these investigators have established the important role of ventricular systole in influencing the characteristics of mitral valve closure. The basis of their thesis is that the surge of blood flowing into the left ventricle as a result of atrial systole, has momentum and inertia. This causes the leaflets to be flung open following atrial contraction and that these leaflets remain open until adequate decelerative forces are generated to halt the flow into the ventricles (Newton's Second Law of Motion). This decelerative force is provided by ventricular contraction. The developed ventricular pressure has, however, to be applied for a finite period of time before reversal of the pressure gradient across the mitral valve occurs. In addition, this reversed gradient also has to exist for a definite duration, before

flow is reduced and finally halted and valve closure can occur. The phase lag resulting from the inertiance properties of blood has been found to be of the order of 20 to 40 msec.[32]

The relative importance of ventricular and atrial systole in influencing the characteristics of mitral valve closure (including, presumably, velocity of closure) has become somewhat clearer with the echographic studies that have correlated valve closure with the length of the P-R interval on the E.C.G. Shah[34] and Craige[35] have suggested that in the presence of P-R intervals of less than 200 msec. atrial contraction does not result in adequate valve closure. Ventricular systole continues and completes the process of closure. However, in the presence of P-R intervals exceeding 200 msec., sufficient time exists for the atrial chamber to fully contract and relax, bring about adequate reversal of the pressure gradient - and hence complete valve closure. In these cases, ventricular systole merely seals an already closed valve. In those cases that the P-R interval exceeds 500 msec. however, the valve reopens following closure brought about by atrial systole. Here, once again, ventricular systole plays a major role in initiating and completing valve closure.

Therefore, from the evidence available so far, it appears that both atrial systole and ventricular contraction have a role to play in mitral valve closure and that the importance of each depends on the P-R interval. The more recent studies have, however, placed increasing emphasis on the role of ventricular contraction in determining mitral valve closing velocity and duration.

Velocity of Mitral Valve Closure

The measurement of mitral valve closing velocity, by various methods has yielded fairly consistent results. Yoshitoshi et al.[36] measured this parameter using a percutaneous ultrasonic Doppler technique and found that in the normal subjects they studied the peak Doppler shift frequencies they obtained corresponded to closing velocities of between 20 and 40 cm. $sec.^{-1}$, with a mean of 27 cm. $sec.^{-1}$.

A different approach was adopted in anesthetized dogs, by Gordon et al.[27]. These investigators sutured small radio-opaque markers to the mitral valve cusps and followed their motion using cineangiography. They found the peak closing velocity of the anterior mitral leaflet, in sinus rhythm, to be 33 cm. $sec.^{-1}$ ± 13 cm. $sec.^{-1}$.

Buynkozturk et al.[37] studied the influence of heart rate, age and sex on the movements of the mitral valve in normal subjects. They computed the closing velocity of the anterior leaflet of mitral valve from the manually-drawn slope corresponding to the AC or BC portion of the M-mode mitral echogram. The range of values they obtained in their normal subjects lay between 8 and 50.5 cm. $sec.^{-1}$ with a mean of 22.1 cm. $sec.^{-1}$ (± 9.13 cm. $sec.^{-1}$). In addition, this group found that heart rates upto 130 beats per minute and P-R intervals up to 190 msec., had no effect on mitral valve closure slope.

Instantaneous peak mitral valve closing velocity, derived by utilizing a digital tracking system with a dynamic range gate locked to the mitral valve echogram, was recently reported, in normal subjects, by Emerson et al.[38]. The system they used allowed them to track echoes

from the mitral valve every 8 milliseconds and hence compute the velocity attained at each stage of closure, at those intervals. Although the range of values this group reported (23 to 46.7 cm. $sec.^{-1}$) lay at approximately the same level as those reported by utilising the Doppler technique or manual computation from echocardiograms, the mean value obtained by this technique (34.6 ± 7.8 cm. $sec.^{-1}$) was definitely higher than that obtained by the other methods. This suggests that peak velocity obtained by the instantaneous analysis of the closure slope was somewhat different from the results obtained by manual derivation or Doppler examination.

The method we utilised in this study, included manual measurement of the closure slope and electronic differentiation of the mitral echogram. This method has not been reported by other investigators.

Factors Affecting Stroke Volume - Preload, Afterload and Contractility and the Role of Aortic Velocity and Acceleration

It is generally accepted that the primary factors affecting stroke volume are the degree of diastolic filling and the completeness of systolic emptying i.e., the ejection fraction. The former is affected by the filling pressure (preload) and compliance while the latter by the impedance encountered during ventricular ejection (afterload) and the contractile status of the ventricle (contractility).

Various studies[39,40,41] have shown that an increase in myocardial contractility can cause a concurrent increase in peak aortic velocity and acceleration. As to whether aortic acceleration is independent[42] or

not[41] of preload and afterload, is still a matter for debate. However, the mechanism whereby aortic acceleration probably affects stroke volume, is somewhat clearer. Increasing the preload conditions of the ventricle results in an increase in the portion of systole that is active, i.e. during which accelerative forces are applied to the ejected blood. This, in turn, produces a higher peak aortic velocity and greater momentum being imparted to the blood leaving the ventricle. These factors, taken in conjunction with the inertial properties of blood, permit a larger volume to be expelled during the passive phase of systolic flow. Hence, a larger volume of blood leaves the ventricle both during the active and passive portions of systole resulting in a larger stroke volume[42].

Similarly, it has been demonstrated by Wilcken et al.[43] that opening the aorta to the atmosphere and thus reducing aortic impedance (afterload), causes an increase in maximum aortic acceleration and thereby, probably affects stroke volume.

Alterations in contractility per se, will affect aortic acceleration and peak aortic velocity in the same direction, although not to the same degree[40]. The deciding factor as to whether changes in aortic acceleration and peak aortic velocity affect the stroke volume, probably is the duration of systole and the proportion of it during which positive acceleration and pressure gradient exist before the decelerative forces can come into full play.

## STATEMENT OF THE PROBLEM

### Principal Problems

(a) To ascertain whether the proposed echographic method, based on the hydraulic principles mentioned, could be used to reliably estimate cardiac output.

(b) If so, to examine whether the method would prove to be equally effective in measuring cardiac output in patients with segmental irregularities of ventricular contraction.

### Subsidiary Problems

(a) To experimentally verify whether there is a constant relationship between mitral valve closure slope measured by echocardiography and mean aortic velocity.

(b) To further examine the relationship, if any, between derivatives of mitral closure and aortic velocity, namely, peak mitral closing velocity and acceleration and peak aortic velocity and acceleration.

## METHODS AND PROCEDURE

This study was conducted in two parts:

(I) Human Study

(II) Animal Study

### (I) Human Study

This comprised two separate investigations:

(a) The first portion of the study was carried out in eight patients to compare the measurements of aortic dimensions obtained by echocardiography with those obtained by direct measurements obtained at surgery. The aim of this preliminary study was to verify the accuracy of echocardiography, in our hands, to obtain this measurement.

(b) The main part of the human study was carried out in 32 patients and involved determination of cardiac output using the proposed echo method and comparison of the results obtained with those obtained by the direct Fick method.

### (II) Animal Study

This portion of the study was also carried out in two parts:

(a) Seven dogs were studied to examine the relationship between echographically determined mitral valve closure slope and mean aortic flow velocity determined by using an electromagnetic flow catheter.

(b) In addition, three dogs were studied to further elucidate the relationship between the dynamics of mitral valve closure and aortic flow.

## HUMAN STUDY

### (a) Measurement of Aortic Diameter by Echo

Eight consecutive patients, admitted to the University of Alberta Hospital for open-heart surgery were studied.

The day prior to surgery, echocardiographic recordings were obtained from each subject, in the supine position, from the aortic root using the technique previously described by Feigenbaum[44]. When satisfactory recordings were completed, the external diameter of the aorta was measured from the echocardiogram - this was taken to be the distance between the outer surface of the anterior and posterior wall echoes on aortic root echogram.

The following day, at surgery, following sternotomy and after adequate exposure of the aortic root had been achieved, prior to putting the patient onto cardiopulmonary bypass, the surgeon measured the external circumference of the aortic root. This was done by placing a fine sterile silk ribbon snugly around the exposed aortic root, cutting off the appropriate length of the ribbon and measuring its length. Aortic root diameter was then calculated from the measured external circumference. This was then compared with the measurement obtained, the previous day, by echocardiography.

Aortic diameter was calculated from the measured circumference (C) using the formula:

$$\text{Calculated Diameter} = \frac{C}{\pi}$$

(b) Cardiac Output Study by Echo and Fick

In this portion of the study, 32 patients admitted for diagnostic cardiac catheterization and left ventricular and coronary angiography, were studied. Patients with aortic or mitral valve disease, either on clinical examination or found subsequent to the catheter study, were excluded from the study.

Catheterization and echographic studies were carried out with the patients in the fasting state. One hour prior to catheterization, each patient had received an oral premedication consisting of 10 mg. diazepam and 100 mg. secobarbital. All the studies were carried out with the patient in the supine position. For the echographic studies, patients were studied either flat in the horizontal position or tilted some 20° to 30° to the left side.

Following insertion of the right heart catheter into the main pulmonary artery via the femoral vein, the arterial catheter was introduced, similarly, via the femoral artery, into the root of the aorta, using the Seldinger technique in each case. At this stage, cardiac output determination by the direct Fick method was commenced.

Exhaled gas was collected from the patient over a period of 3 minutes, into a previously evacuated Douglas bag. During this procedure, three 5 ml. samples of blood were obtained, two from the pulmonary artery and one from the aorta via the catheters in situ. One of the pulmonary artery samples and the aortic sample were immediately examined for the oxygen saturation, using an American

Optical Reflection Oximeter. The third sample was sent off to the laboratory for hemoglobin estimation. The volume of gas (V) collected in the Douglas bag was determined using a calibrated gasometer. The expired gas was analyzed for oxygen and carbon dioxide using a Beckman E2 Oxygen Analyzer and a Godart Capnograph. Minute oxygen consumption and respiratory exchange ratio were calculated using the standard method[45].

The arterio-venous oxygen content difference (A - V $O_2$ difference) was determined utilizing the figures obtained for hemoglobin concentration, Hb gm. per 100 ml of blood, mixed venous (pulmonary artery), $S_{\bar{v}}$, and arterial (aortic), $S_{Ar}$, saturations and based on the assumption that the oxygen carrying capacity of hemoglobin is 1.34 ml. oxygen per gram at body temperature. Hence:

$$A - V\,O_2 \text{ Difference} = (S_{Ar} - S_{\bar{v}}) \times Hb \times 1.34 \quad \text{ml. \%}$$

Cardiac output by the Fick Method was then given by the Fick formula:

$$\text{Cardiac output} = \frac{\text{Minute Oxygen Consumption (ml.min.}^{-1}\text{)}}{A - V\,O_2 \text{ Difference (ml. \%)}} \times 10 \text{ L. min.}^{-1}$$

In each case, calculation of cardiac output by the echographic method was completed before calculation of cardiac output by the Fick method.

Echocardiograms were obtained using an SKI Ekoline 20A Ultrasonoscope and a 2.25 megahertz transducer, half an inch in diameter, prefocussed at 10 cm. and having a repetition rate of 1000 impulses per second. The ultrasonoscope was coupled to a Honeywell 1865

Stripchart recorder. All the recordings were obtained directly onto photosensitive Kodak Linagraph paper at a paper speed of either 50 mm. or 100 mm. $sec.^{-1}$

Recording was commenced in each case either during the period of gas collection for the Fick method or within five minutes of this. Most recordings were completed within a ten minute period. The technique used has been previously described[2]. Briefly, this involved placing the transducer in the 3rd, 4th or 5th left parasternal intercostal space. The choice of the ideal space was based on the criteria set out by Popp[46]. Echograms were obtained from the following structures:

(a) Anterior mitral valve leaflet, with the transducer angulated in a manner such that the posterior mitral leaflet just came into view and the anterior leaflet could be seen executing maximal amplitude of motion,

(b) Aortic root (which sometimes necessitated using a different intercostal space, usually one or two spaces above the previous one) and the aortic valve leaflets. Here, care was taken to adjust the Gain, Damp and Reject modes on the ultrasonoscope so that clear echoes from the inner aspect of the aortic root walls could be obtained. Similarly, the tilt of the transducer was varied until the clear box-like pattern described by the aortic leaflets could be recorded,

(c) Recordings were finally obtained from the endocardial surface of the posterior left ventricular wall and the left ventricular surface of the interventricular septum, so that the internal dimensions of the

left ventricular cavity could be subsequently measured.

In 17 patients, during the recording of the echogram from the aortic root and valve leaflets, simultaneous recordings of the aortic pressure tracing were obtained on an Electronics for Medicine D.R. 8 Multi-channel recorder, using the arterial catheter and a Statham P23b pressure transducer. These tracings were subsequently used to calculate the left ventricular ejection time.

The measurements made from the echocardiographic tracings obtained are summarized in Figure 2. They consisted of the following:

(a) Mitral Valve Tracing. The slope described by points BC on the anterior leaflet echo was drawn in manually. In those cases that point B could not clearly be identified, the maximum slope described by the AC portion of the echogram was drawn in. The steepness of the slope was computed using the time and distance markers on the tracing and measured in cm. $sec.^{-1}$. This slope was designated the Systolic Mitral Valve Closure Slope. In most cases, five clearly recorded consecutive beats were examined and their mean obtained.

(b) Aortic Tracing. Two measurements were obtained from the aortic root tracing:

(i) The internal diameter of the aortic root (D) was measured as shown in Figure 2. This measurement was taken approximately half-way through systole, during the anterior displacement of the aortic root.

(ii) The time interval between the separation and coaption points of the aortic valve leaflets was measured to obtain the left

ventricular ejection time (LVET).

(c) Left Ventricular Internal Dimensions. Measurements of the end-diastolic and end-systolic internal diameters of the left ventricular cavity were obtained, as described by others[4,10].

Calculation of cardiac output by the conventional and proposed echocardiographic methods was carried out as follows:

(a) Proposed Echo method. Using the hydraulic principle outlined in Figure 1., cardiac output was derived by the formula:

$$\text{Cardiac Output} = \text{Aortic Area } (cm^2) \times \text{LVET (sec.)} \times \text{Heart Rate (beats min.}^{-1}) \times \text{Systolic Mitral Closure Slope (cm. sec.}^{-1}) \times 10^{-3} \text{ L. min.}^{-1}$$

Aortic area was computed from the measured internal diameter. Heart rate was calculated from the E.C.G. tracing.

(b) Conventional Echo method. The widely used formula for deriving left ventricular volumes from the internal dimensions was used[2,4] and cardiac output derived as shown below:

$$\text{End-diastolic volume (EDV)} = (\text{End-diastolic diameter})^3$$

$$\text{End-systolic volume (ESV)} = (\text{End-systolic diameter})^3.$$

$$\text{Cardiac Output} = (\text{EDV} - \text{ESV}) \times \text{Heart Rate.}$$

Cardiac output obtained in each subject by the proposed and conventional methods were then compared with the results obtained by the direct Fick method.

In addition, comparison was also made between LVET measured from the aortic pressure tracing and that obtained from the echo tracing, in the 17 patients in whom simultaneous recordings were available.

## ANIMAL STUDY

### (a) Comparison of Mitral Valve Closure Slope and Mean Aortic Velocity

#### Experimental Procedure

Seven mongrel dogs were studied under general anesthesia which included an initial intravenous injection of 5% thiopentone sodium (20 mg. $kg.^{-1}$), followed by muscle relaxation induced by 5 to 10 mg. of intravenous succinylcholine. The dogs were immediately intubated with a cuffed endotracheal tube, the cuff inflated and the dogs were then placed on a mechanical ventilator. Anesthesia was maintained with a mixture of nitrous oxide and oxygen and in certain cases, with the addition of 1 to 2% halothane. E.C.G. electrodes were attached to the animal's chest wall and a single lead was constantly monitored.

A left paramedian abdominal incision was made and a functional splenectomy performed by tying off the efferent and afferent vascular bundles of that organ. A transverse thoracotomy was then performed at the level of the xiphisternum and the chest cavity was opened. The adoption of this approach minimized the problem of blood loss that is usually encountered with a midline exposure through a sternotomy. Self-retaining retractors were used to obtain and maintain adequate exposure of the heart while bleeding vessels were tied off to obtain hemostasis. Blunt dissection was carried out at the base of the heart and the aortic root was exposed. The pericardial sac was left intact and the exposed structures were constantly kept moist with sponges soaked in warm saline.

Fluid loss was replaced with an intravenous infusion of Hartmann's solution.

A skin incision was made to expose the right carotid artery and a stiff Biotronex Laboratory BL 9070 catheter-tip velocity transducer was introduced into the artery. The tip of the catheter was positioned approximately 4 cm. above the aortic valves. The position of the tip was confirmed by manual palpation of the aortic root through the thoracic incision. In addition, care was taken to ascertain as far as possible, that the catheter lay centrally within the lumen of the aorta, along its longitudinal axis. It was found that whenever the catheter tip approached the aortic leaflets or drifted sideways towards walls of the vessel, the waveform produced by the flow signal tended to change. The proximal end of the catheter at the carotid artery, was anchored by silk sutures and the distal end of this artery was tied off for the rest of the experiment. The velocity catheter, which had been calibrated and checked before-hand to give a linear output to velocities up to 300 cm. $sec.^{-1}$, was then connected to a Biotronex Laboratory BL 610 pulsed logic flowmeter and the Balance, Gain and Frequency Response modes were adjusted to give a signal of optimal amplitude.

Arterial pressure was monitored thorughout the experiment. A fluid-filled teflon catheter was placed in the femoral artery and connected to a previously calibrated Statham P23Db pressure transducer. This was then connected to an oscilloscope with a calibrated screen.

Echocardiographic recordings of the anterior leaflet of the

mitral valve were obtained using the ultrasonoscope and transducer used in the human studies. The transducer was held in direct contact with the epicardium of the anterior cardial wall to the left of the anterior descending coronary artery. An adequate amount of coupling gel (Aquasonic) was used to overcome the problem of intermittent loss of direct contact between the tip of the transducer and the anterior surface heart wall. The tilt of the transducer was varied until the excursion of the anterior mitral leaflet echo was found to be at its maximum. The signal from this structure was found, in each case, to lie at a depth of 3 to 6 cm. from the anterior cardiac wall. In most cases, the "M"-shaped configuration characteristic of the mitral echogram was not observed owing to the rapid heart rates encountered. However, it did occur in those experiments where the heart rate was observed to be less than approximately 100 beats per minute. This phenomenon was not entirely surprising, in view of the observation made by Taylor[28], in his animal experiments, that at fast heart rates the outlet area of the mitral valve remained unchanged throughout the diastolic filling period.

The echo signal arising from the anterior mitral leaflet was isolated using a time analog pre-amplifier module with a variable gate. The time delay in the ultrasound system was less than one millisecond and the inherent frequency response limitations did not occur below 500 hertz (information provided by Smith Kline Instruments Corporation).

The E.C.G., time analog mitral signal and the aortic velocity signals were recorded on a four-channel magnetic tape recorder (Hewlett Packard 3960 Instrumentation Recorder) and the signals stored for

subsequent replay on a pen recorder.

Recordings were obtained in all 7 dogs under resting conditions. In addition, one of the dogs had 3 additional sets of recordings. These were made following the administration of intravenous boluses of 5 μg. of isoprenaline, 2 mg. of propranolol and finally following the creation of a pulmonary embolus by injection of a preformed clot into the right atrium. In two other dogs, hemodynamic conditions were also changed - in one, by the administration of intravenous propranolol only while in the other, by the administration of isoprenaline alone, in the doses described above. Thus, in all, 12 sets of recordings were obtained in the 7 dogs.

Following completion of experiments on each of the dogs, the animals were sacrificed.

Signal Processing and Playback

The stored signals from the magnetic tapes were played back onto a four-channel Hewlett Packard Series 7700 heated-stylus recorder, at a paper speed of 100 mm. $sec.^{-1}$. The maximal frequency response of the magnetic and stylus recorders were well in excess of the maximal frequencies encountered in these experiments.

The aortic and mitral signals were processed initially by passing them through "active" low-pass filters (Krohn-Hite Model 3322, low-pass RC filter with a zero Db gain and an attenuation factor of 12 Db per octave). The cut-off frequencies selected for the mitral valve and aortic velocity signals were 30 Hz. and 55 Hz. respectively. These

frequencies were well above the maximal frequencies for the closure slope of the mitral valve and the upstroke of the aortic velocity signal[40].

Mean aortic velocity was computed from the aortic velocity curve by using a planimeter to measure the area under the velocity profile curve and dividing this by the duration of flow.

Mitral valve closure slope was obtained by manually drawing in the BC (or AC) slope, as for the human experiment.

Beat-to-beat analysis of 7 consecutive beats was made in each dog, for each hemodynamic intervention and the results obtained for mitral closure slope and the corresponding mean aortic velocity were subsequently compared and subjected to statistical analysis.

(b) Dynamics of Mitral Closure and Aortic Flow

In the second part of the animal study, 3 additional dogs were prepared as described above and once again, aortic velocity and mitral valve analog signals were obtained and stored on magnetic tape. However, in this case, the acquired signals were processed somewhat differently.

The mitral analog signal was filtered, as described before. It was then passed through an "active" differentiator made by our Electronics department for this purpose. The differentiator had a linear frequency-output response up to 40 hertz. First passage through the differentiator produced a waveform signal corresponding to the first derivatives of each portion of the original mitral valve analog signal, on a beat-to-beat basis. The maximal deflection

corresponding to the BC or AC slope which marked the closure of the mitral valve, was designated the Peak Mitral Valve Closing Velocity. Re-passage of the waveform corresponding to the first derivative of the original mitral signal through the differentiators resulted in yet another signal being produced corresponding to the second derivative of the mitral valve echogram. The peak of this signal corresponding to the peak mitral valve closing velocity, was designated the Peak Mitral Valve Acceleration.

The aortic velocity signal was processed by filtering and then passing it through a differentiator, as in the case of the mitral signals. The first derivative of the velocity signal corresponding to the ejection phase of the ventricle, was designated the Peak Aortic Acceleration.

Comparison, in these dogs, was made between the following parameters:

(i) Peak mitral closing velocity and systolic mitral closure slope,

(ii) Peak mitral closing velocity and peak mitral acceleration,

(iii) Peak mitral closing velocity and peak aortic velocity,

(iv) Peak mitral closing velocity and peak aortic acceleration,

and (v) Peak mitral acceleration and peak aortic acceleration.

Five consecutive beats were analyzed in each case, wherever possible, in the resting state, following intravenous isoprenaline or intravenous propranolol, or both, sequentially. In each case, the mitral and aortic beats analyzed corresponded to each other so

that a beat-to-beat comparison of these parameters was obtained. Where this was not feasible, the mean of five good beats was obtained and the means for each parameter were compared.

All the results obtained from the above experiments were subjected to statistical analysis using a Family Regression Analysis Program on a Hewlett Packard 9810A Calculator.

# RESULTS

## (I) Human Study

Representative examples of echocardiographic recordings obtained from the aortic root, mitral valve, the posterior wall of the left ventricle and interventricular septum are shown in Figures 3 and 4 respectively.

Patients studied ranged in ages from 14 years to 64 years (Mean age 49.2 years) and the group consisted of 10 female and 22 male subjects. Left ventricular angiograms were obtained in all the patients studied and coronary angiography was performed in all but two cases.

All the patients studied were in sinus rhythm and had P-R intervals on the E.C.G. of less than 0.2 seconds.

Eighteen of the 32 patients had significant coronary artery disease (i.e. more than 50% obstruction in one or more of the Left Main, Anterior Descending, Circumflex or Right Coronary arteries). Fourteen of these patients had sustained a previous myocardial infarction and 11 of them exhibited one or more areas of hypokinesis or dyskinesis on left ventricular angiography. Two other patients, who had significant coronary artery disease on the arteriogram but had no E.C.G. evidence of a previous infarction, also exhibited segmental irregularities of contraction. In addition to these, one of the patients (No. 18), whowas suspected of having cardiomyopathy, was found to have no significant obstruction of the coronary vessels but nevertheless exhibited generalised hypokinesis with a localised

areas of dyskinesis. Thus, of the entire group studied, 14 patients in all, had angiographic evidence of akinesis, hypokinesis or dyskinesis.

Thirty four determinations of cardiac output were obtained from the 32 patients. In one of the patients (No. 7) two additional recordings were obtained by varying the hemodynamic conditions by the administration of two separate doses of intravenous isoprenaline.

Table Ia summarizes the angiographic data of the patients studied. Table Ib illustrates the data obtained on each patient and the calculated cardiac output by the Fick method and the proposed (Echo 1) and conventional (Echo 2) echocardiographic methods.

Comparison of Aortic Diameter by Echo and Direct Measurement

The results obtained on comparison of aortic root diameter measurements by echocardiography and at surgery, in the 8 patients so studied, are tabulated in Table II.

Figure 5 illustrates the comparison between these two sets of measurements. These are summarized below:

| | Echo D (Y) | D at Surgery (X) |
|---|---|---|
| Mean | 3.64 cm. | 3.55 cm. |
| S.D. | ±0.51 cm. | ±0.49 cm. |

$n = 8$ $r = 0.97$ $p < 0.001$

$Y = 0.06 + 1.01\ X$

These results verified the accuracy of echocardiography in our hands for the measurement of aortic root diameter. It also confirmed the observations of other investigators[47,48].

Comparison of L.V.E.T. by Echo and Direct Measurement (Aortic Tracing) Methods

Table III summarizes the data obtained on the left ventricular ejection time (L.V.E.T.) in 17 patients. Comparison of left ventricular ejection time by echocardiography and as measured simultaneously from the aortic pressure tracings, is depicted in Figure 6. These are summarized below:

| | L.V.E.T. by Echo (Y) | L.V.E.T. Direct (X) |
|---|---|---|
| Mean | 304.88 msec. | 306.53 msec. |
| S.D. | ± 45.17 msec. | ± 46.72 msec. |

$n = 17$ $r = 0.95$ $p < 0.001$

$Y = 25.6 + 0.89\ X$

Thus, the accuracy of measuring L.V.E.T. using echocardiography was confirmed as has been done by others[49,50].

Comparison of Cardiac Output by Fick and Proposed Echo Methods (32 patients)

Direct comparison of the results obtained by these two methods is shown in Figure 7. Close correlation was noted between the two sets of results as is listed below, in the whole group studied:

| | Cardiac Output by Echo (Y) (Proposed Method) | Cardiac Output by Fick (X) |
|---|---|---|
| Mean | 4.78 L. $min.^{-1}$ | 5.45 L. $min.^{-1}$ |
| S.D. | ±1.73 L. $min.^{-1}$ | ±1.91 L. $min.^{-1}$ |

$n = 34 \quad r = 0.90 \quad p < 0.001$

$Y = 0.31 + 0.82\ X$

The overall results obtained in the 32 patients studied were then subdivided into those patients with (n = 16) and those without (n = 18) hypokinesis or dyskinesis. The results from these subgroups were analyzed separately as shown below:

| | Pts. with Asynergy | Pts. without Asynergy |
|---|---|---|
| Mean X | 5.42 L. $min.^{-1}$ | 5.48 L. $min.^{-1}$ |
| Mean Y | 4.56 L. $min.^{-1}$ | 4.96 L. $min.^{-1}$ |
| $S.D._X$ | ±2.24 L. $min.^{-1}$ | ±1.63 L. $min.^{-1}$ |
| $S.D._Y$ | ±1.99 L. $min.^{-1}$ | ±1.49 L. $min.^{-1}$ |
| n | 16 | 18 |
| r | 0.94 | 0.87 |
| p | <0.001 | <0.001 |
| | $Y = 0.63 + 0.79\ X$ | $Y = 0.31 + 0.82\ X$ |

Hence, almost equally good correlation was found between cardiac output measurements made by the proposed echo and Fick methods, both in the presence and absence of irregular segmental contraction of portions of the left ventricle.

Comparison of Cardiac Output by Conventional Echo and Fick Methods (21 patients)

Satisfactory recordings of the posterior left ventricular wall and the interventricular septum could be obtained by echo, in 21 of the

32 patients studied (66%). The overall correlation between these two methods from patients with (n = 18) and without (n = 13) dyskinesis or hypokinesis, treated together, was fairly good:

| | Cardiac Output by Echo (Y) (Conventional Method) | Cardiac Output by Fick (X) |
|---|---|---|
| Mean | 5.39 L. min.$^{-1}$ | 5.39 L. min.$^{-1}$ |
| S.D. | ±2.61 L. min.$^{-1}$ | ±1.79 L. min.$^{-1}$ |

n = 21 r = 0.58 p < 0.001

Y = 0.81 + 0.85 X

The above comparison is shown in Figure 8.

Data from patients with and without dyskinesis was then analyzed separately, as shown below:

| | Pts. with Asynergy | Pts. without Asynergy |
|---|---|---|
| Mean X | 5.54 L. min.$^{-1}$ | 5.29 L. min.$^{-1}$ |
| Mean Y | 6.74 L. min.$^{-1}$ | 4.56 L. min.$^{-1}$ |
| S.D.$_X$ | ±1.81 L. min.$^{-1}$ | ±1.85 L. min.$^{-1}$ |
| S.D.$_Y$ | ±2.88 L. min.$^{-1}$ | ±2.13 L. min.$^{-1}$ |
| n | 8 | 13 |
| r | 0.44 | 0.77 |
| p | <0.30 (N.S.) | <0.005 |
| | -- | Y = 0.88 X - 0.11 |

(N.S. = Not significant)

With the limitation that the number of patients in the subgroups were small, it was apparent that the correlation between the two methods, in the two groups, was quite different. In those patients with dyskinesis or hypokinesis, correlation between results by the Fick method and the conventional method did not reach the level of significance ($r = 0.44$). This was in contrast to the significant correlation ($r = 0.77$) obtained between the two sets of results from patients without abnormal left ventricular contraction. These results support the contention that the conventional echo method is not applicable in the presence of asynergy [7,16].

Comparision of Cardiac Output by Fick and Proposed Echo Methods (in the above 21 patients)

Results obtained by the proposed echo method were compared with those obtained by the Fick method in only those 21 patients in whom cardiac output could be determined by the conventional echo method as well. The correlation found in these 21 patients was similar to that found following analysis of results from the entire group of 32 patients as is shown in Figure 9. The overall results were:

| | Cardiac Output by Echo (Y) (Proposed Method) | Cardiac Output by Fick (X) |
|---|---|---|
| Mean | 4.77 L. min.$^{-1}$ | 5.39 L. min.$^{-1}$ |
| S.D. | ±1.55 L. min.$^{-1}$ | ±1.79 L. min.$^{-1}$ |

$n = 21$ $r = 0.90$ $p < 0.001$

$Y = 0.59 + 0.78\ X$

Results from patients with and those without abnormalities of left ventricular contraction are once again analyzed separately as shown below:

| | Patients with Asynergy | Patients without Asynergy |
|---|---|---|
| Mean X | 5.54 L. $min.^{-1}$ | 5.29 L. $min.^{-1}$ |
| Mean Y | 4.85 L. $min.^{-1}$ | 4.72 L. $min.^{-1}$ |
| $S.D._X$ | ±1.81 L. $min.^{-1}$ | ±1.85 L. $min.^{-1}$ |
| $S.D._Y$ | ±1.61 L. $min.^{-1}$ | ±1.57 L. $min.^{-1}$ |
| n | 8 | 13 |
| r | 0.94 | 0.87 |
| p | <0.001 | <0.001 |
| | $Y = 0.2 + 0.84\ X$ | $Y = 0.79 + 0.74\ X$ |

The results obtained suggest that the proposed echo method is equally accurate in patients with and without asynergy.

(II) Animal Study

(a) Comparison of Mitral Valve Closure Slope and Mean Aortic Flow Velocity

Figure 10 shows a representative sample of traces obtained from this experiment.

Eighty-four beat-to-beat analyses of mitral valve closure slope and the corresponding mean aortic velocity were obtained in the 7 dogs. These results are presented in Table IV. Comparison of these parameters

is shown in Figure 11 and the results obtained are summarized below:

| | Mitral Slope by Echo (Y) | Mean Aortic Velocity (X) |
|---|---|---|
| Mean | 19.38 cm. $sec.^{-1}$ | 18.08 cm. $sec.^{-1}$ |
| S.D. | ± 7.53 cm. $sec.^{-1}$ | ± 7.73 cm. $sec.^{-1}$ |

$n = 84$ $r = 0.94$ $p < 0.001$

$Y = 2.87 + 0.91 X$

These results provide experimental support for the original assumption made in the cardiac output study carried out in patients.

(b) Peak Mitral Valve Closing Velocity and Acceleration and Peak Aortic Velocity and Acceleration

Figure 12 illustrates the tracings obtained for the first and second derivatives of the mitral echo signal and Figure 13 shows the first derivative of the aortic velocity signal i.e. aortic acceleration. In order to match up the appropriate mitral and aortic beats corresponding to each other, the undifferentiated mitral echo signal and the aortic velocity signal were used as common markers in both sets of tracings obtained.

Tables Va, [redacted] and Vc show the detailed results obtained for mitral valve closure slope, peak mitral valve closing velocity, peak mitral acceleration, aortic velocity and acceleration, in the 3 dogs studied.

(i) Peak Mitral Closing Velocity and Systolic Mitral Closure Slope (Fig. 14)

Thirty beats were analyzed under different hemodynamic conditions in the 3 dogs. The results are as shown below:

| | Peak M.V. Closing Velocity (X) | Systolic M.V. Slope (Y) |
|---|---|---|
| Mean | 41.93 cm. $sec.^{-1}$ | 29.29 cm. $sec.^{-1}$ |
| S.D. | ±11.77 cm. $sec.^{-1}$ | ± 7.15 cm. $sec.^{-1}$ |

$n = 30$ $r = 0.76$ $p < 0.001$

$Y = 9.83 + 0.46\ X$

(ii) Peak Mitral Closing Velocity and Peak Mitral Acceleration (Fig. 15)

Closer correlation was obtained between these parameters, as shown below:

| | Peak M.V. Closing Velocity (X) | Peak M.V. Acceleration (Y) |
|---|---|---|
| Mean | 40.99 cm. $sec.^{-1}$ | 2387.7 cm. $sec.^{-2}$ |
| S.D. | ±11.97 cm. $sec.^{-1}$ | ± 838.8 cm. $sec.^{-2}$ |

$n = 32$ $r = 0.84$ $p < 0.001$

$Y = 58.8\ X - 22.72$

(iii) Peak Aortic Velocity and Peak Mitral Closing Velocity (Fig. 16)

In contrast to the close correlation noted between mean aortic velocity and mitral closure slope in the first part of the animal experiment, correlation between peak aortic velocity and peak mitral closing velocity was not as close, albeit, significant:

| | Peak Aortic Velocity (X) | Peak M.V. Closing Velocity (Y) |
|---|---|---|
| Mean | 209.8 cm. $sec.^{-1}$ | 40.99 cm. $sec.^{-1}$ |
| S.D. | ± 53.97 cm. $sec.^{-1}$ | ±11.97 cm. $sec.^{-1}$ |

n = 32 r = 0.59 $p < 0.001$

Y = 13.3 + 0.13 X

(iv) Peak Aortic Acceleration and Peak Mitral Closing Velocity (Fig. 17)

The correlation between these measurements was better than for peak aortic velocity and peak mitral closing velocity:

| | Peak Aortic Acceleration (X) | Peak M.V. Closing Velocity (Y) |
|---|---|---|
| Mean | 7669.97 cm. $sec.^{-2}$ | 41.49 cm. $sec.^{-1}$ |
| S.D. | ±3473.97 cm. $sec.^{-2}$ | ±11.83 cm. $sec.^{-1}$ |

n = 31 r = 0.75 $p < 0.001$

Y = 21.8 + 0.003 X

(v) Peak Aortic Acceleration and Peak Mitral Closing Acceleration (Fig. 18)

In analyzing this data, one of the points (marked * in Fig. 18) was excluded from the data analysis as it was found to deviate markedly from the statistical trends shown by the rest of the data.

The closest correlation was found to exist between these two parameters:

| | Peak Aortic Acceleration (X) | Peak M.V. Acceleration (Y) |
|---|---|---|
| Mean | 7772.87 cm. $sec.^{-2}$ | 2359.63 cm. $sec.^{-2}$ |
| S.D. | ±1102.04 cm. $sec.^{-2}$ | ± 805.03 cm. $sec.^{-2}$ |

$n = 30$ $r = 0.87$ $p < 0.001$

$Y = 802.1 + 0.2 X$

When data from each dog was examined separately, the close correlation, between these 2 parameters, held with correlation coefficient values of 0.88, 0.95 and 0.68 in the 3 dogs.

Table VI summarizes the correlation coefficients found when comparing the various mitral and aortic parameters.

## DISCUSSION

Echocardiography has now become an established diagnostic tool in the field of cardiology. Its uses in the rapid and non-invasive recognition of a vast range of anatomic cardiac abnormalities ranging from mitral stenosis and pericardial effusion to its applications in pediatric cardiology have, by now, become routine.

However, the major expansion in interest in this technique sprang in the latter part of the last decade with reports from various centres[1,2,3,4] that this tool could be used to estimate left ventricular volumes and cardiac output. The method proposed by these inveatigators is based on the measurement of the distance between the endocardial surface of the posterior left ventricular wall and the interventricular septum. The cubes of this dimension at end-diastole and end-systole are then assumed to represent end-diastolic and end-systolic volumes and stroke volume is then derived by obtaining the difference between these two volumes.

The assumptions on which this conventional echo method is based, pertain to the shape, size and uniformity of contraction of the left ventricular chamber. In particular, these assumptions are:

(a) that the shape of the left ventricular cavity can be represented by a prolate ellipsoid with a constant major:minor axis ratio of 2:1,

(b) that the major:minor axis relationship is the same throughout the population and within one individual, through the entire cardiac cycle,

(c) that the left ventricle contracts uniformly,

(d) that a major proportion of the stroke volume generated by the left ventricle can be accounted for by changes in the dimensions of the minor axis[51],

and (e) that the internal dimension measured by echocardiography approximates the true minor axis of the left ventricular cavity[3,52,53].

Unfortunately, the geometric assumptions made are not strictly or equally applicable in all cases and thus constitute potential sources of error in the estimation of ventricular volumes and cardiac output[54]. Hence, for example, errors can arise from the application of this method in those patients with cardiac decompensation and cardiomegaly, as has been pointed out by Fortuin and his associates[3]. These errors have been attributed to alterations in the shape of the ventricular cavity, from the usual ellipsoidal to a more or less spherical configuration. This tends to disrupt the major:minor axis relationship assumed in these calculations and thus invalidates the approximation, Volume = Cube of Minor Axis diameter.

Similarly, in the small ventricle with a long and narrow cavity, the major:minor axis ratio may be as high as 3:1, leading to an underestimation of the true volume. Teichholz et al. have recently shown that in a series of 100 patients, with a variety of cardiac lesions (and including 22 normal subjects), studied by left ventricular angiography, the major:minor axis ratio between end-systole and end-diastole varied very considerably from the assumed 2:1 figure[16]. This study confirmed similar findings previously reported by others[51,55].

A major shortcoming of the conventional method however, is its

inapplicability in the presence of segmental abnormalities of contraction, as is often encountered in patients with ischemic heart disease. In such cases, spuriously high or low readings of cardiac output are obtained, probably as a result of ultrasonic recordings being obtained from a localised area of compensatory hyperkinesis or hypo/akinesis[15,16].

Under these circumstances, therefore, an echocardiographic method that is (a) independent of the geometric assumptions listed above and (b) does not need to rely on the assumption that the entire ventricle contracts uniformly, should offer a superior approach to the conventional echographic method. The method proposed in this study fulfils the above criteria. Results obtained from the cardiac output study show that while there was good correlation between results obtained by the Fick method and by the conventional echo method in patients without asynergy, this correlation was not as close in the entire group taken as a whole. In addition, correlation in those patients with asynergy was not significant in this study, although, it is recognized that the numbers involved, were quite small. In contrast, there was little difference in the degree of correlation between the results obtained by the proposed echo method and the Fick method, both in the presence and absence of dyskinesis. This correlation was equally good in the same 21 patients in whom cardiac output estimation by the conventional echo method was possible. Thus, these results indicate that the new echo method proposed is more accurate than the conventional method in the patients studied and that the accuracy of the results obtained is unaffected by the presence of

asymmetric contraction.

In the method proposed in this study, the major assumption made was that the closure slope of the echogram from the anterior leaflet of the mitral valve and the mean aortic flow velocity were inter-related and that the former could be used to assess the latter. This assumption is an arbitrary one. The exact inter-relationship between the two parameters is unknown. In addition, these events take place in different phases of the left ventricular systolic cycle i.e. mitral closure takes place during the pre-ejection period while aortic flow occurs during the ejection phase. Nevertheless, it is reasonable to assume that the events that take place during pre-ejection period are probably quantitatively related to those occurring during the ejection phase, as the force of ventricular contraction will likely determine both these events. Previous studies have shown that a parallel relationship between parameters measured during isovolumetric contraction and those measured during the ejection phase of contraction does exist[56]. The importance of the role played by left ventricular systole in determining mitral valve closure has already been discussed. In addition, it has already been mentioned that the peak velocity and acceleration imparted to the blood entering the aorta are a function of ventricular systole, and that both these parameters of ejection have a role to play in determining the stroke volume ejected. It would therefore seem logical to extend the above discussion one stage further and suggest that, in the continuum of systolic events that commences with the build-up of left ventricular wall tension and pressure and culminates in the expulsion of blood into the aorta, quantitative inter-

relationships probably exist between each of the events that occurs, e.g. mitral valve closure, aortic valve opening and aortic ejection.

The results from the animal studies comparing mean aortic velocity and mitral closure slope have provided experimental support for this assumption. In fact, the degree of correlation obtained, appears to be surprisingly close between the parameters compared.

Examination of the results obtained in the latter studies performed in the 3 dogs shows that the velocity of mitral closure as determined by the manually-drawn slope consistently falls short of the peak closing velocity estimated by electronically differentiating the slope signal. However, the two values are, in fact, interrelated (Figure 14). Similarly, correlation was noted between peak mitral closing velocity and peak mitral closing acceleration ($r = 0.84$).

Comparison of peak mitral closing velocity with aortic flow parameters suggests that better correlation exists with peak aortic acceleration ($r = 0.75$) rather than with peak aortic velocity ($r = 0.59$). Best correlation was noted between peak mitral closing acceleration and peak aortic acceleration ($r = 0.87$).

Aortic acceleration has been proposed as a specific index of myocardial contractility[40,57]. The close correlation found between aortic acceleration and peak mitral closing velocity and acceleration, under different hemodynamic conditions, therefore, suggests that the factors that influence changes in aortic acceleration probably also affect mitral closure in a similar manner and to approximately the same degree. In the case of peak mitral valve closing velocity and acceleration, these factors would, specifically be preload and

contractility. Afterload almost certainly has no role to play in determining these parameters as mitral valve closure is completed before aortic ejection takes place. Other investigators have shown that aortic acceleration is indeed influenced by preload and afterload in addition to changes in contractility[41].

Thus it seems that mitral closure slope can probably be used, in patients with normal mitral valves, as an indicator of mean aortic flow velocity but that the peak acceleration and velocity of the anterior mitral leaflet are more closely related to the contractile properties of the left ventricle.

The principal advantages of the proposed method of estimating cardiac output are that:

(a) it circumvents the assumptions on which the conventional method relies for its accuracy,

(b) the results obtained are unaffected by the presence or otherwise, of non-uniform segmental contraction,

(c) it is a technically easier method to use,

and (d) the yield of successfully completed measurements, is higher.

The method does have limitations and shortcomings, however, and these can be summarized as follows:

(a) The method may not be accurate in the presence of mitral or aortic valve pathology;

(b) this method is probably inapplicable in patients with arrythmias or heart block, since, under these conditions, the closure velocity of the mitral valve may no longer be related to mean aortic velocity,

(c) this method directly estimates stroke volume but cannot measure ventricular volumes at the different phases of the cardiac cycle, unlike the conventional method,
and (d) the theoretic grounds for the assumption on which this method is based, need further elucidation.

The results of the limited studies carried out to examine the relationship between mitral valve velocity and acceleration reveal that these parameters probably bear some direct relationship to peak aortic ejection velocity and acceleration. If further studies bear out this relationship, then it seems quite possible that the echographically derived parameters of mitral velocity and acceleration could be useful for the non-invasive estimation of aortic acceleration and left ventricular contractility.

## CONCLUSIONS

(1) In the absence of aortic or mitral valve disease, atrial arrythmias or heart block, the manually-drawn closure slope of the anterior mitral valve leaflet, appears to be related to and estimates mean aortic ejection velocity through the systolic period,

(2) The mean velocity of flow derived as described above, when taken in conjunction with duration of left ventricular ejection time and aortic root area, both derived from echocardiograms of the aortic valve and root, can be used to calculate stroke volume,

(3) The above echo method gives reliable estimations of cardiac output both in the presence and absence of abnormal left ventricular contraction,

(4) This method, in our hands, gives more reliable results compared to the conventional method,

(5) Peak mitral closing velocity and acceleration show close correlation with peak aortic velocity and acceleration and are probably influenced similarly, by various disease processes or interventions. It is possible, that the former parameters could be used to evaluate the contractile state of the left ventricle, independent of the effects of afterload.

TABLE Ia

Anthropological and Angiographic Data on the 32 Patients in the Cardiac Output Study

| Patient No. | I.D. | Age (Yrs.) | Sex | C.A.D. | A.C.S. |
|---|---|---|---|---|---|
| 1 | MW | 29 | M | ? | – |
| 2 | KM | 56 | M | + (*) | + |
| 3 | MP | 60 | F | – | – |
| 4 | EM | 57 | F | + (*) | + |
| 5 | KP | 60 | M | + (*) | + |
| 6 | RH | 50 | M | + (*) | + |
| 7 | HS | 45 | M | + (*) | + |
| 8 | DB | 57 | M | – | – |
| 9 | PA | 64 | F | + (*) | + |
| 10 | JCh | 47 | M | + | + |
| 11 | BM | 31 | F | + | – |
| 12 | LE | 50 | F | – | – |
| 13 | GB | 50 | M | + | + |
| 14 | JCa | 57 | M | + (*) | – |
| 15 | JRe | 31 | F | ? | – |
| 16 | JM | 50 | M | + (*) | + |
| 17 | VL | 53 | F | – | – |
| 18 | EC | 53 | F | – | + |

(Continued Over)

TABLE Ia (Contd.)

| Patient No. | Patient I.D. | Age (Yrs.) | Sex | C.A.D. | A.C.S. |
|---|---|---|---|---|---|
| 19 | MF | 14 | M | - | - |
| 20 | WlD | 38 | M | - | - |
| 21 | WR | 48 | M | + (*) | + |
| 22 | EK | 51 | M | + (*) | + |
| 23 | AT | 37 | M | + (*) | - |
| 24 | FW | 63 | M | + (*) | - |
| 25 | PW | 54 | M | + (*) | + |
| 26 | WS | 52 | M | - | - |
| 27 | LG | 47 | F | - | - |
| 28 | JRa | 50 | M | + (*) | + |
| 29 | WW | 56 | M | - | - |
| 30 | WP | 59 | M | - | - |
| 31 | MS | 59 | F | + | - |
| 32 | WfD | 47 | M | - | - |

Abbreviations: I.D. = Identity; C.A.D. = Coronary Artery Disease; A.C.S. = Abnormally Contracting Segments.

Key: + = Present; - = Absent; (*) = Previous Myocardial Infarction; ? = Investigation not performed.

TABLE Ib

Results of Echocardiographic Measurements for the Calculation of Cardiac Output and Results of Cardiac Output Measurement by the Fick Method

| Patient No. | Echo Measurements | | | | | CO L. Min.$^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|
| | SMCS cm.sec.$^{-1}$ | Ao D cm. | LVET msecs. | EDD cm. | ESD cm. | Fick | $Echo_1$ | $Echo_2$ |
| 1 | 34.3 | 3.10 | 316 | 5.10 | 3.40 | 7.17 | 5.57 | 6.35 |
| 2 | 38.5 | 2.96 | 406 | 6.70 | 4.80 | 6.02 | 5.70 | 10.08 |
| 3 | 35.7 | 2.70 | 372 | 4.30 | 2.50 | 3.43 | 3.88 | 3.26 |
| 4 | 16.0 | 1.40 | 335 | - | - | 2.71 | 1.84 | - |
| 5 | 29.5 | 3.50 | 340 | 6.40 | 4.40 | 7.34 | 5.98 | 10.97 |
| 6 | 21.0 | 3.00 | 296 | - | - | 5.95 | 3.35 | - |
| 7 (a) | 22.9 | 3.70 | 260 | - | - | 4.08 | 4.50 | - |
| (b) | 24.6 | 3.80 | 275 | - | - | 6.85 | 6.01 | - |
| (c) | 27.1 | 3.90 | 245 | - | - | 10.70 | 9.20 | - |
| 8 | 32.9 | 3.70 | 297 | 5.25 | 4.40 | 5.37 | 5.38 | 3.21 |
| 9 | 20.7 | 3.25 | 224 | 6.00 | 5.20 | 3.67 | 3.50 | 6.86 |
| 10 | 36.4 | 3.10 | 315 | 5.60 | 4.30 | 5.84 | 5.54 | 6.24 |
| 11 | 49.9 | 2.45 | 302 | - | - | 5.93 | 5.38 | - |
| 12 | 30.0 | 3.00 | 356 | 4.20 | 2.80 | 5.02 | 4.34 | 3.02 |

(Continued Over)

TABLE Ib (Contd.)

| Patient No. | Echo Measurements | | | | | CO L. Min.$^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|
| | SMCS cm.sec.$^{-1}$ | Ao D cm. | LVET msecs. | EDD cm. | ESD cm. | Fick | Echo$_1$ | Echo$_2$ |
| 13 | 34.0 | 3.20 | 357 | 5.40 | 3.95 | 7.85 | 6.15 | 6.04 |
| 14 | 33.4 | 3.20 | 310 | 4.70 | 3.30 | 4.59 | 4.99 | 4.07 |
| 15 | 36.0 | 3.20 | 305 | 5.60 | 3.80 | 8.99 | 7.25 | 9.90 |
| 16 | 22.4 | 3.00 | 414 | - | - | 5.91 | 4.07 | - |
| 17 | 23.5 | 3.10 | 279 | 4.50 | 3.20 | 5.42 | 4.27 | 4.73 |
| 18 | 21.3 | 2.60 | 219 | - | - | 2.17 | 2.13 | - |
| 19 | 25.0 | 3.00 | 267 | - | - | 4.66 | 3.98 | - |
| 20 | 19.2 | 3.80 | 330 | - | - | 6.10 | 5.30 | - |
| 21 | 20.0 | 3.40 | 301 | 3.80 | 3.20 | 3.89 | 3.77 | 1.53 |
| 22 | 41.2 | 3.00 | 308 | 5.40 | 4.20 | 6.73 | 6.28 | 5.84 |
| 23 | 25.7 | 2.80 | 382 | 4.90 | 4.40 | 6.39 | 4.56 | 2.37 |
| 24 | 22.3 | 3.10 | 320 | 4.50 | 3.50 | 3.39 | 2.96 | 2.66 |
| 25 | 13.7 | 3.40 | 312 | - | - | 3.97 | 3.07 | - |
| 26 | 25.1 | 3.40 | 333 | - | - | 6.90 | 6.45 | - |
| 27 | 20.8 | 3.20 | 328 | 4.80 | 3.00 | 3.94 | 2.52 | 5.02 |

(Continued Over)

TABLE Ib (Contd.)

| Patient No. | Echo Measurements | | | | | CO L. Min.$^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|
| | SMCS cm.sec.$^{-1}$ | Ao D cm. | LVET msecs. | EDD cm. | ESD cm. | Fick | $Echo_1$ | $Echo_2$ |
| 28 | 14.0 | 3.90 | 264 | 6.60 | 5.70 | 2.99 | 1.85 | 6.34 |
| 29 | 29.6 | 3.55 | 290 | 4.25 | 3.10 | 5.21 | 6.03 | 4.55 |
| 30 | 27.5 | 4.00 | 396 | - | - | 6.22 | 6.98 | - |
| 31 | 22.1 | 2.80 | 376 | 4.20 | 2.60 | 2.42 | 2.45 | 3.16 |
| 32 | 34.4 | 3.54 | 273 | 5.30 | 3.90 | 7.46 | 7.21 | 6.99 |

Abbreviations: CO = Cardiac Output; SMCS = Systolic Mitral Closure Slope; Ao D = Aortic Diameter; LVET = Left Ventricular Ejection Time; EDD = End-diastolic diameter; ESD = End-systolic diameter; Fick = Fick Method.

Key: $Echo_1$ = Proposed Echo Method utilising Mitral and Aortic Echograms;

$Echo_2$ = Conventional Echo Method utilising Internal dimensions of the Left Ventricular cavity.

TABLE II

Aortic Root Diameter Measurement by Echocardiography and Results derived from Measurements made at Surgery

| Subject | Aortic Root Diameter (cm.) | |
|---|---|---|
| | By Echo | At Surgery |
| GR | 4.00 | 3.80 |
| RW | 4.05 | 4.00 |
| MB | 3.30 | 3.20 |
| AS | 3.00 | 3.10 |
| KM | 4.00 | 4.00 |
| EK | 2.90 | 2.80 |
| ES | 4.20 | 4.10 |
| DE | 3.70 | 3.40 |

TABLE III

Left Ventricular Ejection Time (LVET) by Echocardiography and from Aortic Pressure Tracings.

| Subject No. | LVET (msec.) | |
|---|---|---|
| | By Echo | Ao Pressure |
| 1 | 372 | 390 |
| 2 | 335 | 348 |
| 3 | 296 | 265 |
| 4 | 297 | 300 |
| 5 | 224 | 235 |
| 6 | 356 | 352 |
| 7 | 305 | 329 |
| 8 | 219 | 217 |
| 9 | 267 | 260 |
| 10 | 330 | 326 |
| 11 | 308 | 303 |
| 12 | 320 | 346 |
| 13 | 312 | 313 |
| 14 | 328 | 310 |
| 15 | 264 | 264 |
| 16 | 376 | 358 |
| 17 | 273 | 295 |

TABLE IV

Data from experiments on 7 dogs showing Manually-derived Systolic Mitral Closure Slope (SMCS) and Planimetrically-derived Mean Aortic Velocity (Mean Ao V)

| Beat No. | SMCS $cm.sec.^{-1}$ | Mean Ao V $cm.sec.^{-1}$ |
|---|---|---|
| | DOG 1 | |
| Baseline Recording | | |
| 1 | 21.0 | 16.7 |
| 2 | 20.3 | 16.9 |
| 3 | 18.9 | 17.6 |
| 4 | 16.7 | 16.5 |
| 5 | 18.4 | 16.2 |
| 6 | 19.3 | 15.8 |
| 7 | 18.1 | 16.1 |
| Isoprenaline after Baseline | | |
| 1 | 36.3 | 36.3 |
| 2 | 34.8 | 35.5 |
| 3 | 38.4 | 32.8 |
| 4 | 31.3 | 33.4 |
| 5 | 35.5 | 31.2 |
| 6 | 33.4 | 33.1 |
| 7 | 33.4 | 33.1 |
| Inderal after Isoprenaline | | |
| 1 | 26.1 | 28.5 |
| 2 | 27.6 | 25.8 |
| 3 | 30.0 | 28.6 |

(Continued Over)

TABLE IV (Contd.)

| Beat No. | SMCS $cm.sec.^{-1}$ | Mean Ao V $cm.sec.^{-1}$ |
|---|---|---|
| 4 | 26.1 | 25.5 |
| 5 | 29.7 | 25.2 |
| 6 | 32.6 | 26.3 |
| 7 | 26.1 | 29.0 |
| Following Embolism | | |
| 1 | 26.1 | 27.5 |
| 2 | 27.6 | 29.9 |
| 3 | 29.7 | 30.8 |
| 4 | 30.5 | 29.1 |
| 5 | 24.7 | 26.5 |
| 6 | 26.1 | 30.0 |
| 7 | 26.1 | 27.5 |
| | DOG 2 | |
| Baseline Recording | | |
| 1 | 19.0 | 20.8 |
| 2 | 19.0 | 21.5 |
| 3 | 17.7 | 20.9 |
| 4 | 19.0 | 19.6 |
| 5 | 17.7 | 20.4 |
| 6 | 21.7 | 20.4 |
| 7 | 22.3 | 20.4 |
| | DOG 3 | |
| Baseline Recording | | |
| 1 | 13.6 | 10.0 |
| 2 | 12.9 | 12.0 |

(Continued Over)

TABLE IV (Contd.)

| Beat No. | SMCS $cm.sec.^{-1}$ | Mean Ao V $cm.sec.^{-1}$ |
|---|---|---|
| 3 | 13.2 | 10.4 |
| 4 | 6.7 | 8.7 |
| 5 | 11.0 | 12.6 |
| 6 | 11.8 | 10.9 |
| 7 | 13.6 | 12.2 |
| | DOG 4 | |
| Baseline Recording | | |
| 1 | 12.5 | 13.8 |
| 2 | 13.8 | 15.0 |
| 3 | 13.6 | 14.5 |
| 4 | 14.3 | 13.2 |
| 5 | 14.9 | 14.8 |
| 6 | 14.2 | 15.2 |
| 7 | 12.7 | 15.3 |
| | DOG 5 | |
| Baseline Recording | | |
| 1 | 13.9 | 8.6 |
| 2 | 14.8 | 8.6 |
| 3 | 9.0 | 9.0 |
| 4 | 7.1 | 8.1 |
| 5 | 11.0 | 8.4 |
| 6 | 11.0 | 8.9 |
| 7 | 13.9 | 8.6 |
| | DOG 6 | |
| Baseline Recording | | |
| 1 | 19.6 | 16.7 |
| 2 | 21.4 | 16.4 |

(Continued Over)

TABLE IV (Contd.)

| Beat No. | SMCS $cm.sec.^{-1}$ | Mean Ao V $cm.sec.^{-1}$ |
|---|---|---|
| 3 | 22.7 | 16.8 |
| 4 | 24.2 | 16.7 |
| 5 | 23.9 | 16.6 |
| 6 | 14.7 | 15.1 |
| 7 | 15.4 | 16.4 |
| Inderal after Baseline | | |
| 1 | 14.3 | 10.9 |
| 2 | 15.0 | 10.7 |
| 3 | 15.3 | 11.7 |
| 4 | 12.8 | 11.4 |
| 5 | 12.6 | 9.5 |
| 6 | 10.6 | 9.8 |
| 7 | 10.9 | 10.3 |
| | DOG 7 | |
| Baseline Recording | | |
| 1 | 12.4 | 11.6 |
| 2 | 11.3 | 12.2 |
| 3 | 12.8 | 12.9 |
| 4 | 11.3 | 11.3 |
| 5 | 12.6 | 11.0 |
| 6 | 12.8 | 11.1 |
| 7 | 13.0 | 11.3 |
| Isoprenaline following Baseline | | |
| 1 | 20.2 | 18.7 |
| 2 | 18.8 | 17.9 |

(Continued Over)

TABLE IV (Contd.)

| Beat No. | SMCS $cm.sec.^{-1}$ | Mean Ao V $cm.sec.^{-1}$ |
|---|---|---|
| 3 | 22.4 | 16.7 |
| 4 | 20.2 | 17.5 |
| 5 | 21.7 | 18.2 |
| 6 | 23.2 | 17.6 |
| 7 | 21.2 | 17.5 |

TABLE Va

Data on Mitral Valve and Aortic Velocity Signals and their Derivatives in DOG 1

| Beat No. | SMCS $cm.sec.^{-1}$ | Peak MVCV $cm.sec.^{-1}$ | Peak MVAc $cm.sec.^{-2}$ | Peak Ao V $cm.sec.^{-1}$ | Peak Ao Ac $cm.sec.^{-2}$ |
|---|---|---|---|---|---|
| | | | BASELINE RECORDING | | |
| Mean of 5 Beats | 24.1 | 38.6 | 3957 | 135 | 4583 |
| | | | ISOPRENALINE | | |
| 1 | 33.4 | 54.7 | 3602 | 278 | 13636 |
| 2 | 36.6 | 54.7 | 3535 | 279 | 13841 |
| 3 | 35.5 | 54.7 | 3669 | 284 | 13295 |
| 4 | 36.3 | 60.0 | 3669 | 284 | 15272 |
| 5 | 31.9 | 59.4 | 3935 | 288 | 16160 |
| | | | PROPRANOLOL | | |
| 1 | 28.3 | 34.0 | 2068 | 206.1 | 6371 |
| 2 | 29.0 | 37.4 | 1868 | 206.1 | 7428 |
| 3 | 27.6 | 37.4 | 1934 | 201.9 | 6314 |
| 4 | 31.9 | 40.0 | 3002 | 195.3 | 5286 |
| 5 | 27.6 | 34.0 | 1734 | 203.6 | 6314 |

TABLE Vb

Data on Mitral Valve and Aortic Velocity Signals and their Derivatives in DOG 2

| Beat No. | SMCS $cm.sec.^{-1}$ | Peak MVCV $cm.sec.^{-1}$ | Peak MVAc $cm.sec.^{-2}$ | Peak Ao V $cm.sec.^{-1}$ | Peak Ao Ac $cm.sec.^{-2}$ |
|---|---|---|---|---|---|
| | | | BASELINE RECORDING | | |
| 1 | 21.9 | 31.1 | 1598 | 259 | 4147 |
| 2 | 19.8 | 30.5 | 1464 | 259 | 4[illegible] |
| 3 | 23.8 | 30.5 | 1354 | 241 | 4471 |
| 4 | 25.1 | 29.9 | 1220 | 257 | 4176 |
| 5 | 25.3 | 30.5 | 1440 | 241 | 4147 |
| | | | ISOPRENALINE | | |
| 1 | 41.0 | 55.9 | 2964 | 241 | 7794 |
| 2 | 41.8 | 55.9 | 2600 | 255 | 7765 |
| 3 | 37.1 | 55.3 | 2730 | 248 | 8029 |
| 4 | 40.2 | 56.6 | 3120 | 241 | 7441 |
| 5 | 38.7 | 55.9 | 2600 | 255 | 8000 |

TABLE Vc

Data on Mitral Valve and Aortic Velocity Signals and their Derivatives in DOG 3

| Beat No. | SMCS cm.sec.$^{-1}$ | Peak MVCV cm.sec.$^{-1}$ | Peak MVAc cm.sec.$^{-2}$ | Peak Ao V cm.sec.$^{-1}$ | Peak Ao Ac cm.sec.$^{-2}$ |
|---|---|---|---|---|---|
| | | BASELINE RECORDINGS | | | |
| Mean of 5 Beats | 22.4 | 59.3 | 3253 | 181.0 | 9160 |
| | | PROPRANOLOL | | | |
| 1 | 19.2 | 30.0 | 1826 | 169.5 | 4390 |
| 2 | 17.4 | 28.2 | 1660 | 165.0 | 4536 |
| 3 | 15.3 | 30.0 | 1660 | 144.0 | 4756 |
| 4 | - | 25.7 | 1660 | 154.5 | - |
| 5 | - | 28.2 | 1793 | 150.0 | 4207 |
| | | ISOPRENALINE | | | |
| 1 | 32.0 | 38.2 | 2324 | 142.5 | 8817 |
| 2 | 26.2 | 31.5 | 1843 | 126.0 | 8561 |
| 3 | 30.0 | 38.2 | 2324 | 150.0 | 8488 |
| 4 | 30.2 | 31.5 | 1975 | 135.0 | 8049 |
| 5 | 29.0 | 34.0 | 2025 | 138.0 | 8159 |

Abbreviations: SMCS = Systolic Mitral Closure Slope; MVCV = Mitral Valve Closing Velocity
MVAc = Mitral Valve Acceleration; Ao V & Ao Ac = Aortic Velocity & Acceleration

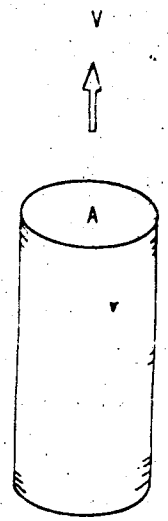
TABLE VI

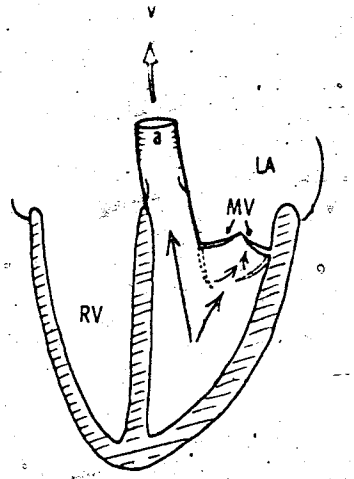
Table summarising the Correlation Coefficients obtained by comparing the Mitral Closure Slope and it First and Second Derivatives with Aortic Velocity and its First Derivative, i.e. Aortic Acceleration

| | Systolic Mitral Closure Slope | Peak Mitral Valve Closing Velocity | Peak Mitral Valve Acceleration |
|---|---|---|---|
| Peak Mitral Valve Closing Velocity | 0.76 | - | 0.84 |
| Peak Aortic Flow Velocity | - | 0.59 | - |
| Peak Aortic Acceleration | - | 0.75 | 0.87 |

NOTE: In each of the above cases, $p < 0.001$

Figure 1 Hydraulic Principle underlying flow of fluids through a Cylinder and its application to the Heart in vivo




Systole

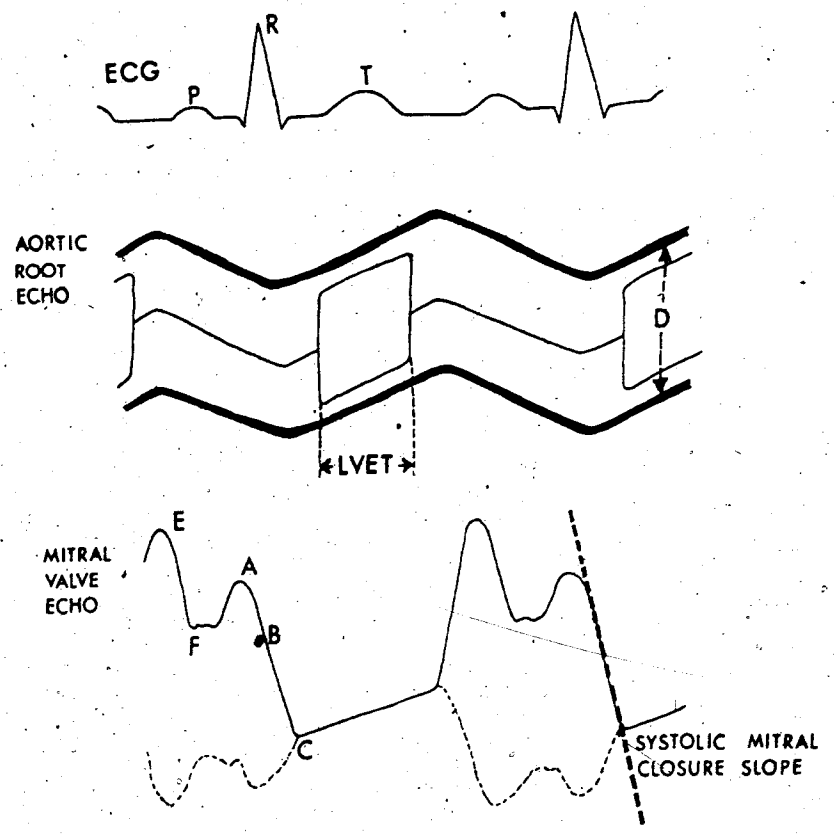
Continuous Flow : $Q = V \times A$

Q = Flow rate
V = Mean flow velocity
A = Cross-sectional Area

Phasic Flow: $Q = \dot{v} \times a \times LVET$

Q = Stroke Volume
v = Mean aortic flow velocity
a = Cross-sectional area of aorta
LVET = Left Ventricular ejection time

Figure 2 Simultaneous tracings of E.C.G., Aortic Root & Mitral Leaflet Echo to show measurement of Parameters needed for calculation of Cardiac Output by Proposed Echo Method

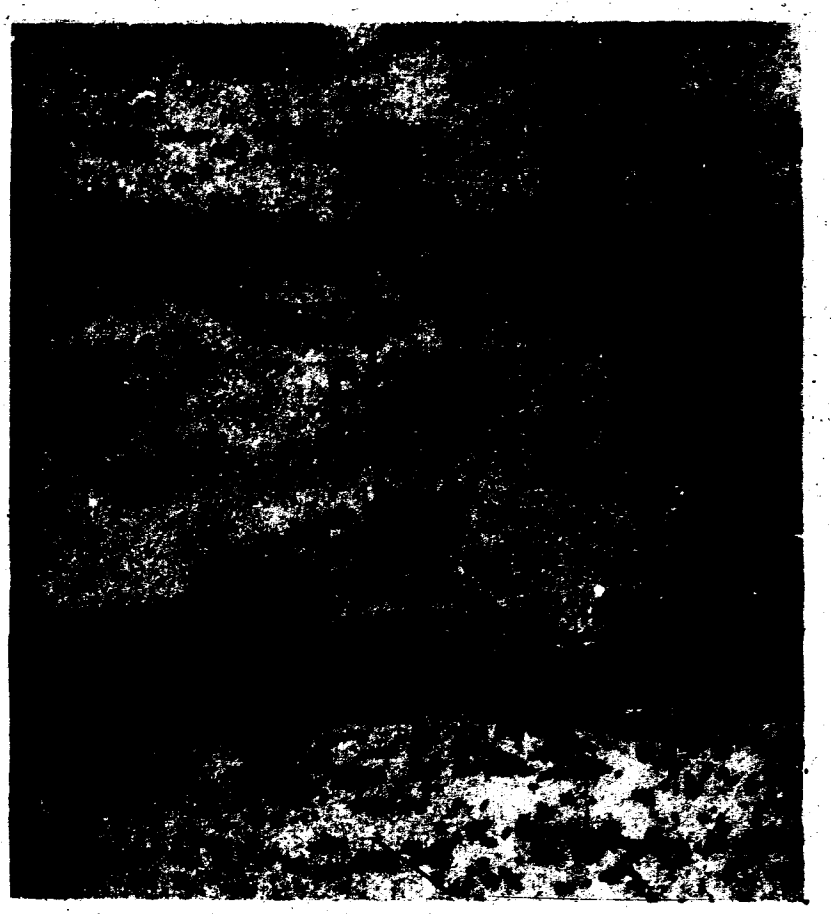



Abbreviations: E.C.G. = Electrocardiogram; L.V.E.T.= Left Ventricular Ejection Time; D = Internal Aortic Diameter

Figure 3 Representative sample of Echocardiographic Recordings from Aortic Root and Mitral Valve and Leaflets


Abbreviations: As for Fig. 2. SMCS = Systolic Mitral Closure Slope; AR = Aortic Root; AML = Anterior Mitral Leaflet; PML = Posterior Mitral Leaflet.

Figure 4 Representative sample of Echocardiographic Recording from Left Ventricular Cavity, showing Interventricular Septum and the Posterior Left Ventricular Wall



Abbreviations: E.D.D. = End-diastolic diameter; E.S.D. = End-systolic Diameter.

Figure 5 Comparison of Aortic Diameter Measurement by Echo and results obtained by direct measurement at Surgery

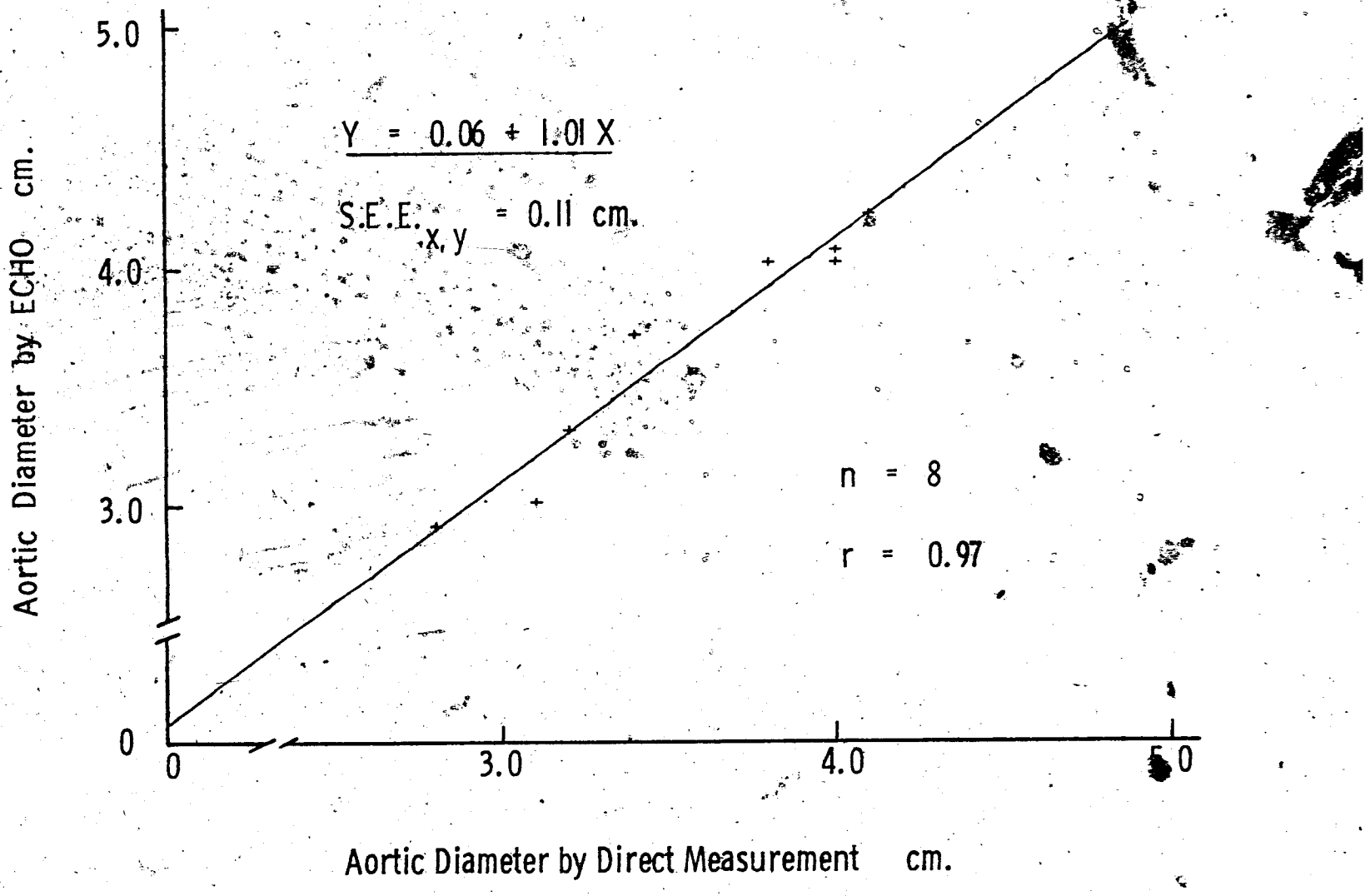


Figure 6 Comparison of Left Ventricular Ejection Time (L.V.E.T.) by Echo and from Aortic Pressure Tracings

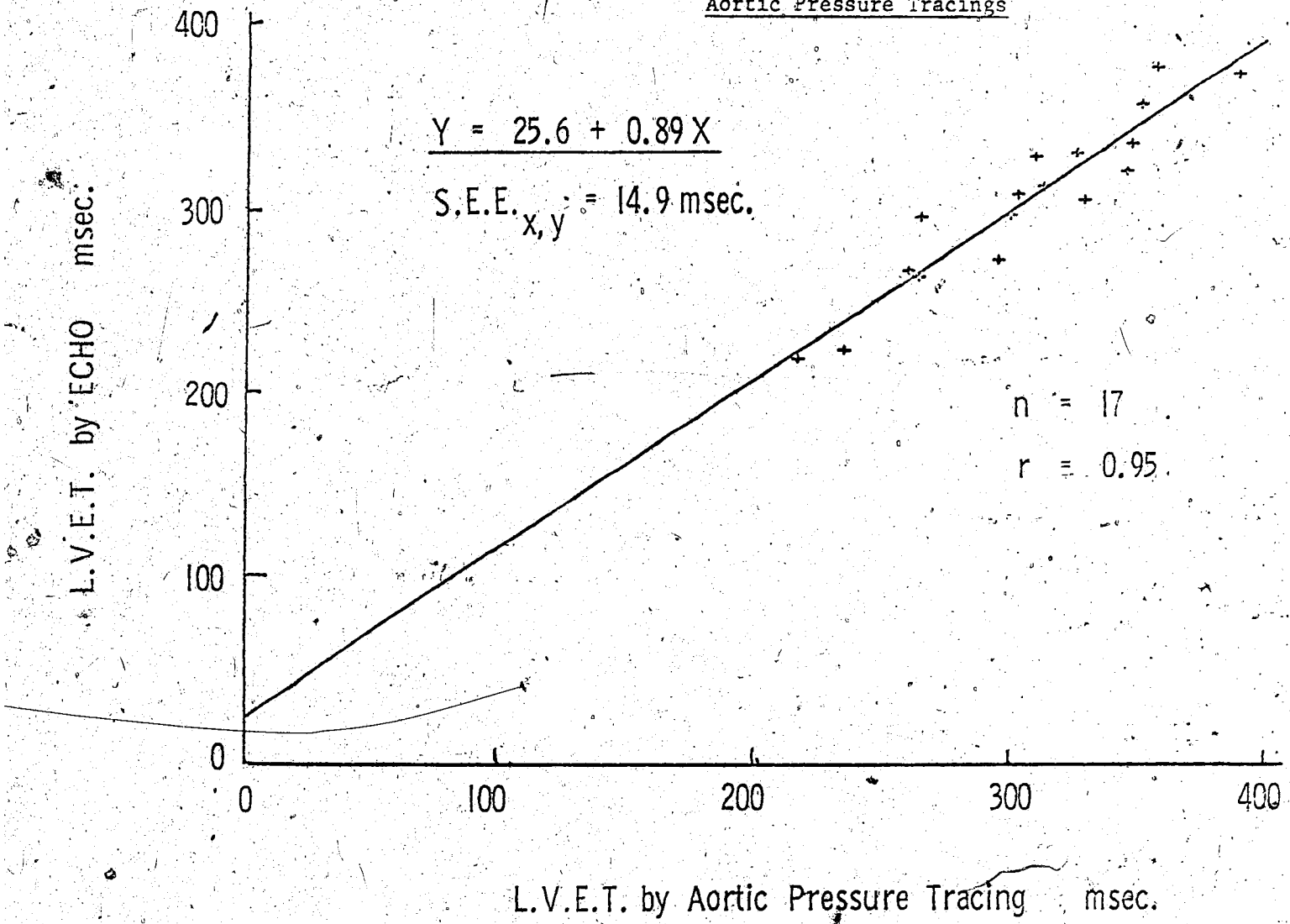


Figure 7 Comparison of Cardiac Output (C.O.) by Proposed Echo Method and the Fick Method (32 subjects)

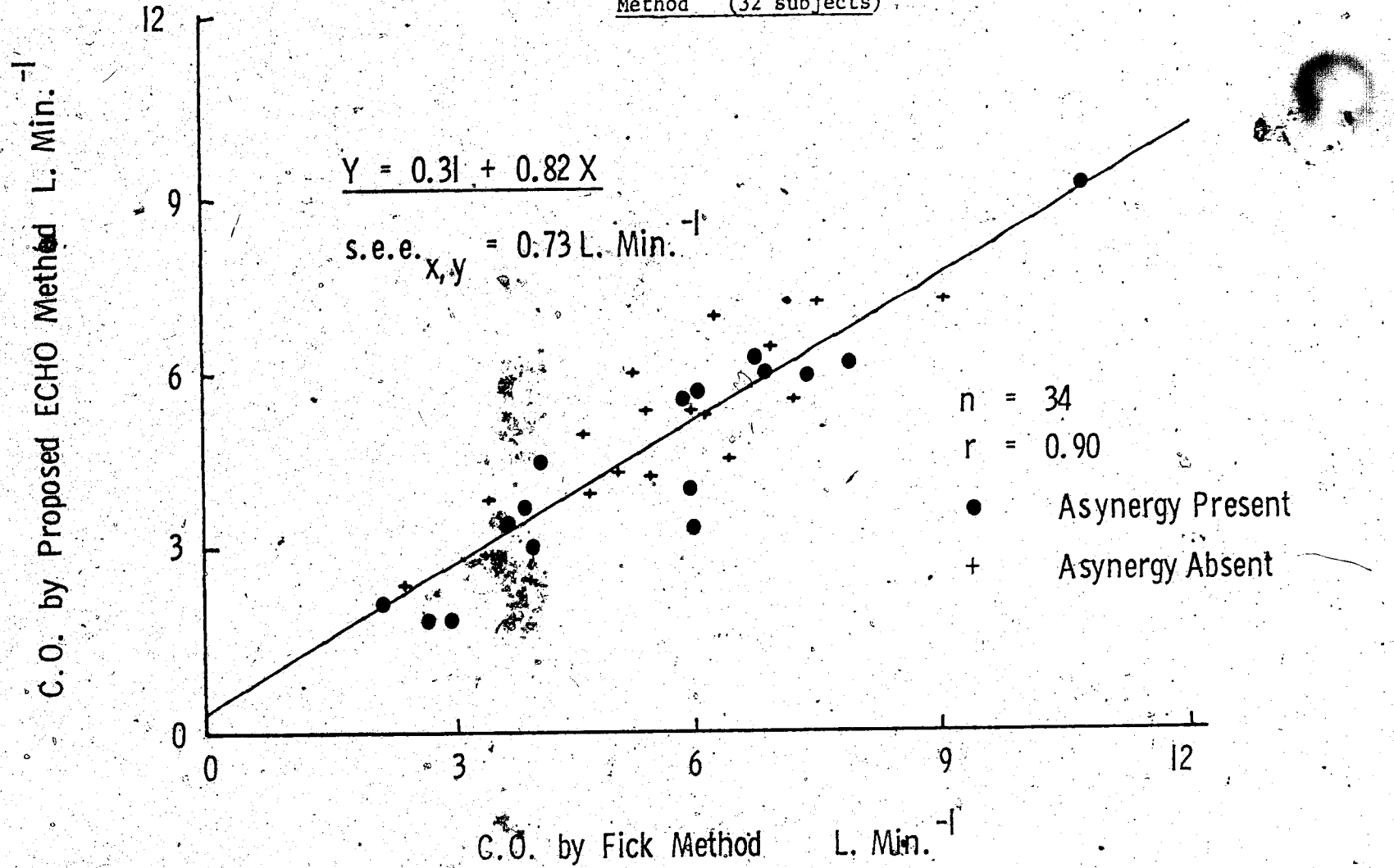


Figure 8 Comparison of Cardiac Output (C.O.) by Conventional Echo Method and the Fick Method

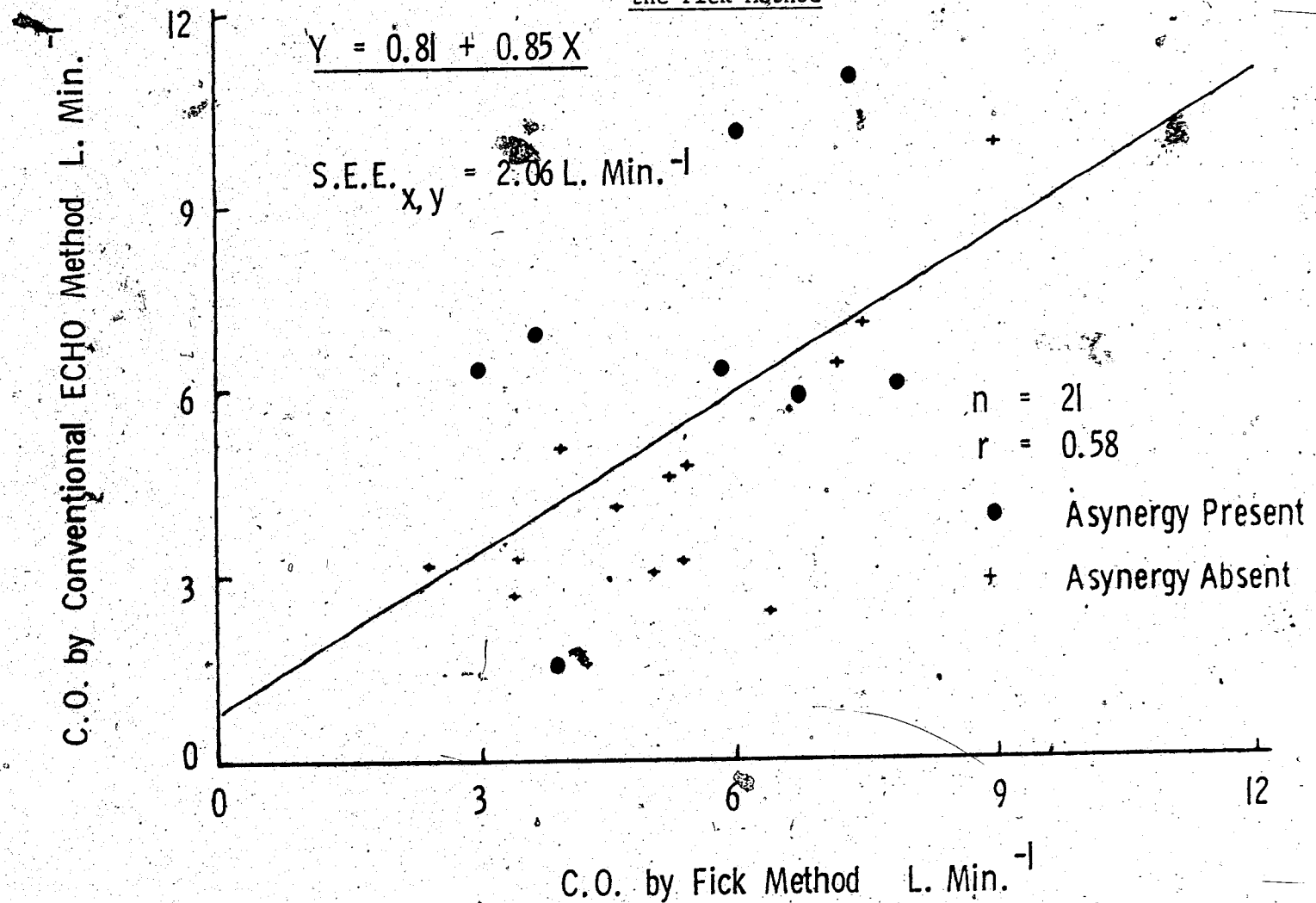


Figure 9 Comparison of Cardiac Output (C.O.) by Proposed Echo Method and the Fick Method (21 subjects)

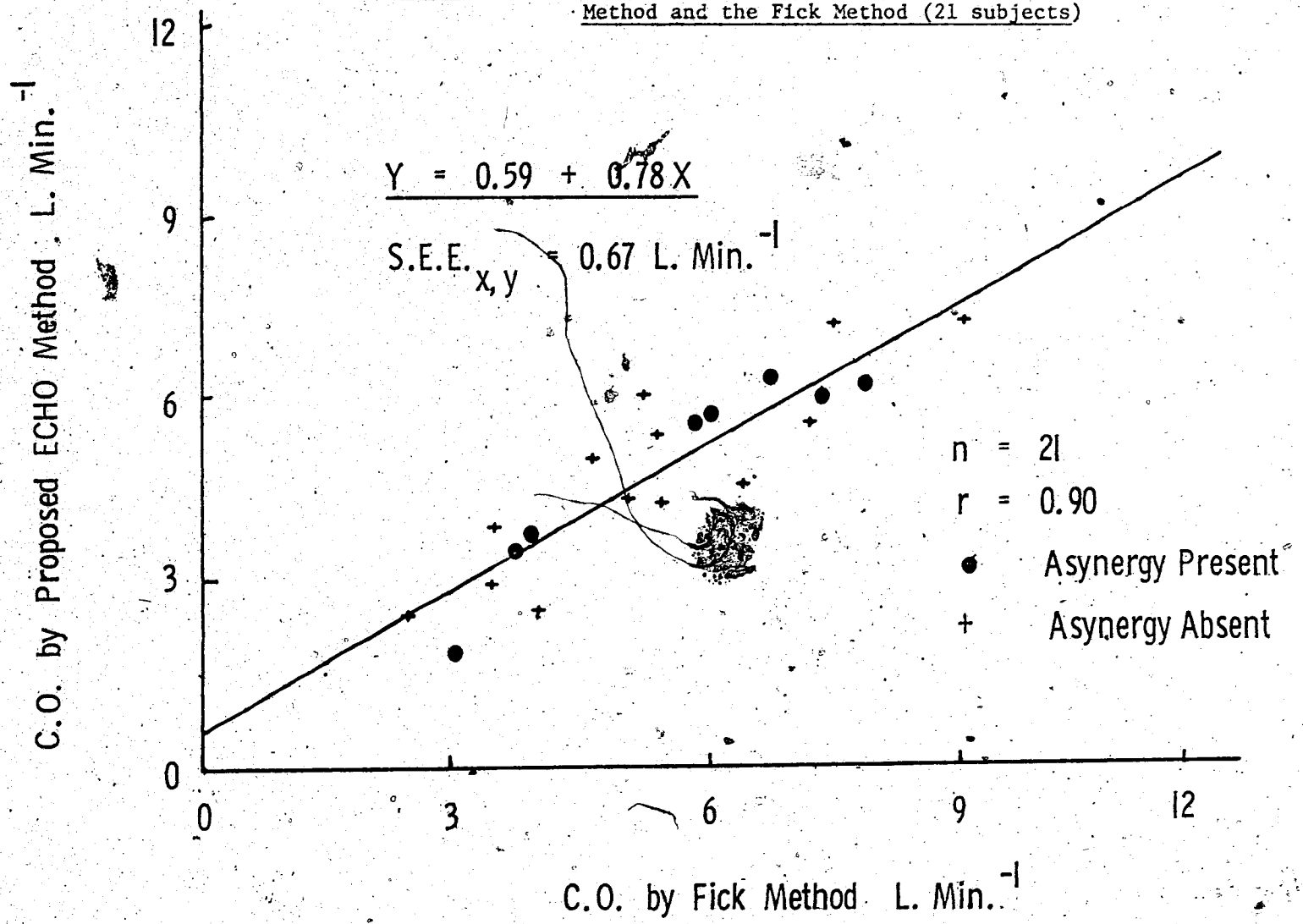


Figure 10 Representative sample of Recordings from Dogs to show Comparison of Mitral Closure Slope with Aortic Velocity and Electrocardiogram

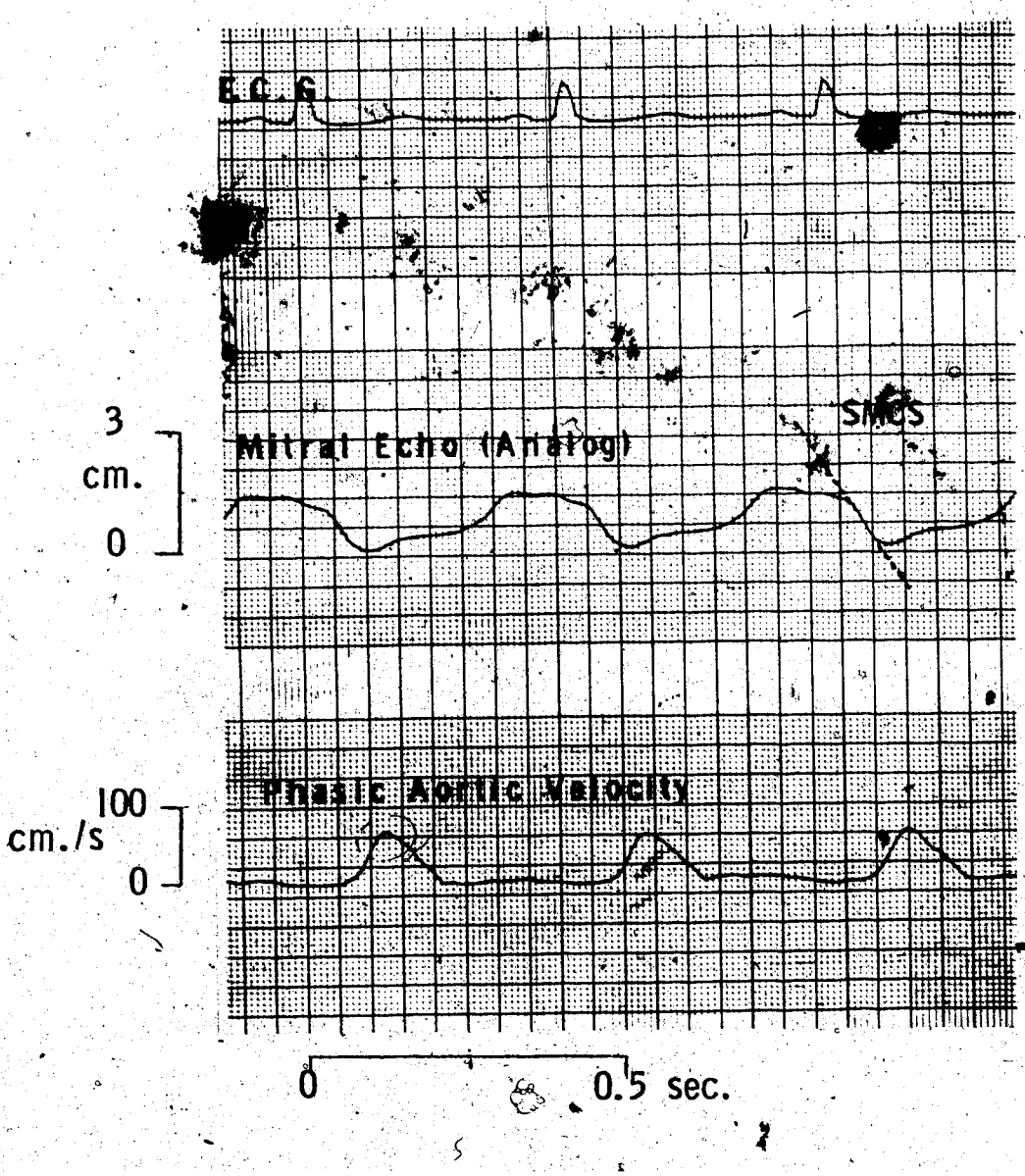


Figure 11 Comparison of Mitral Closure Slope and Mean Aortic Velocity

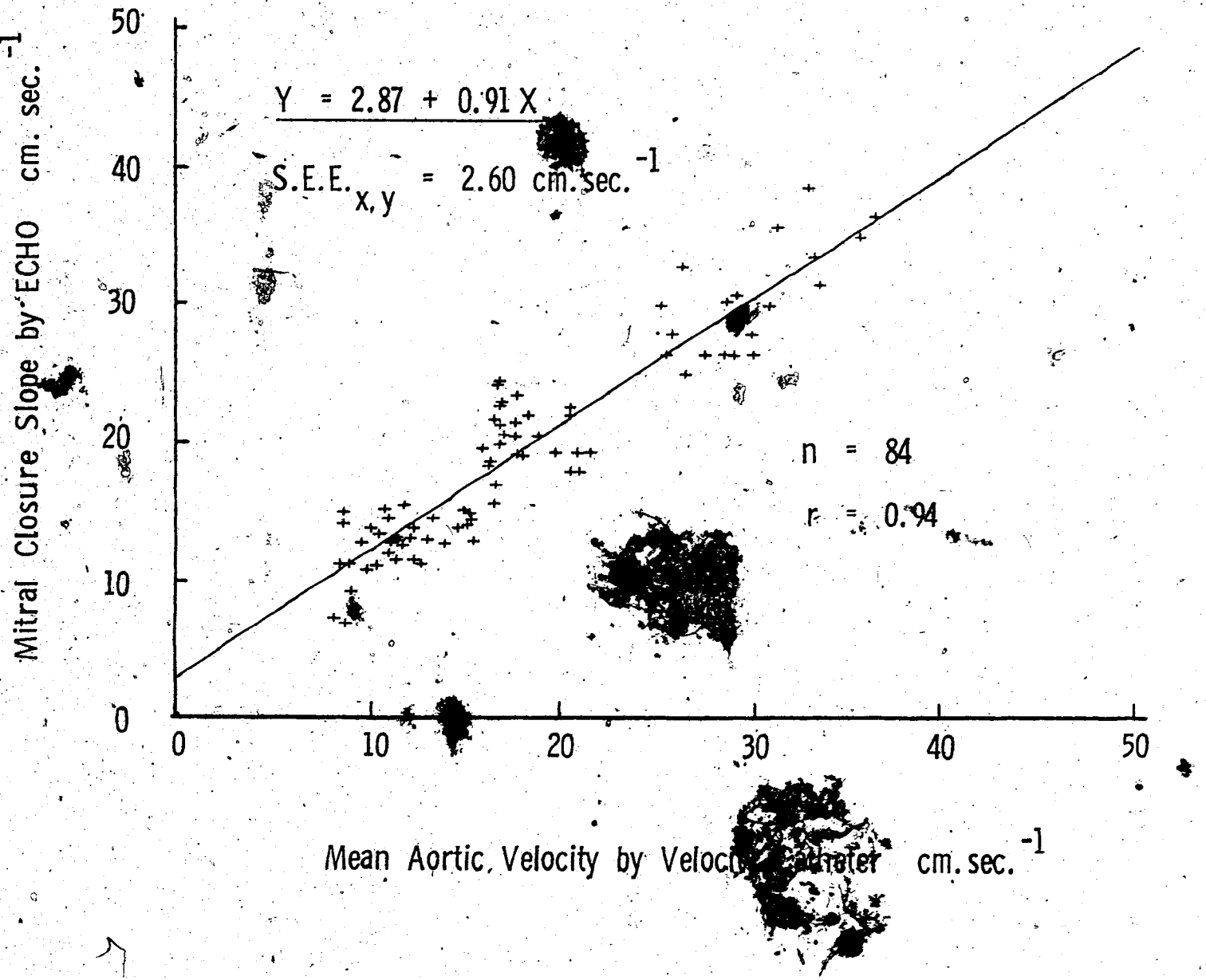


Figure 12

Representative sample of Recordings obtained from Dogs showing from top to bottom, Aortic Velocity, Mitral Valve Echo signal, and Mitral Valve Closing Velocity and Acceleration i.e. First and Second Derivatives

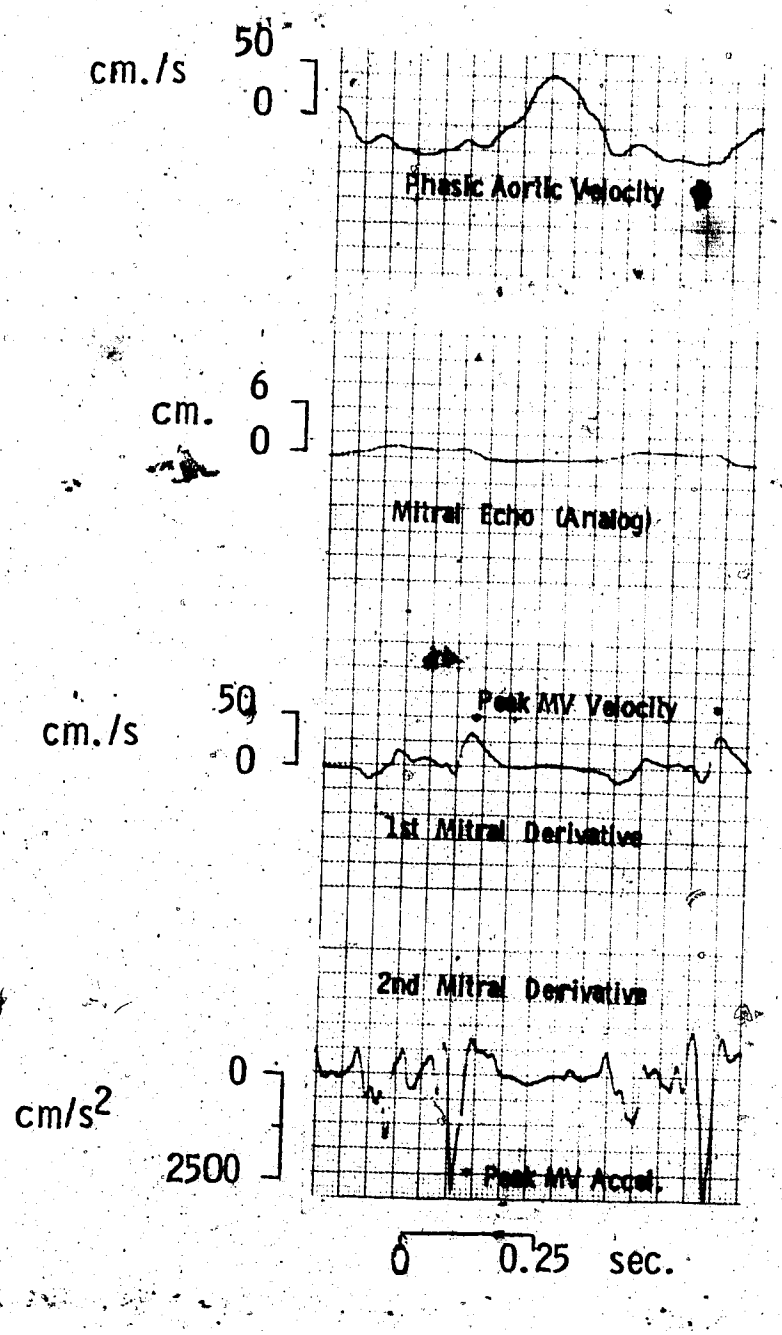


Figure 13

Representative sample of Recording from Dogs showing, from top to bottom, Electrocardiogram, Mitral Valve Echogram, Aortic Flow Velocity and it First Derivative, Aortic Acceleration.

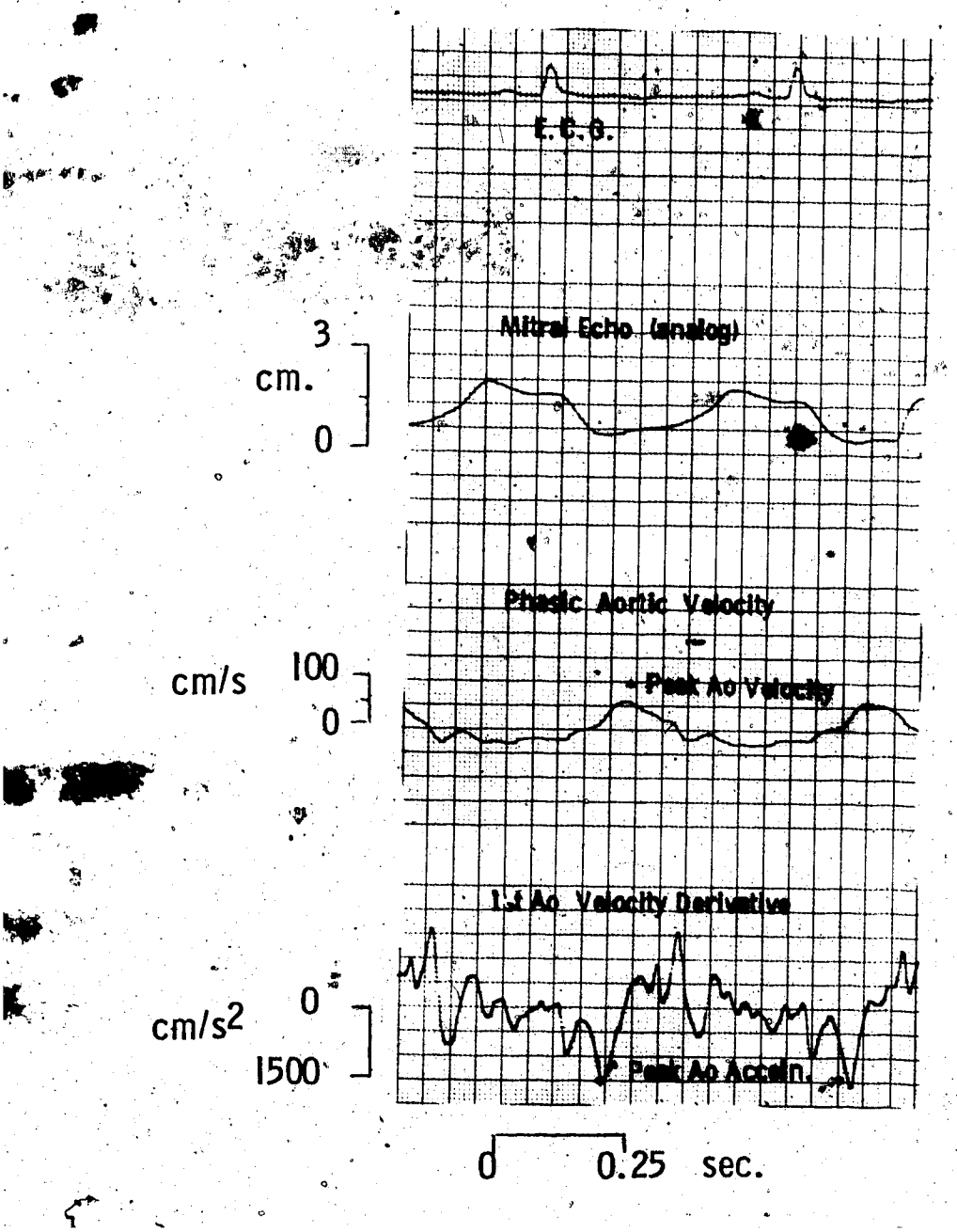


Figure 14 Comparison of Manually-drawn Mitral Closure Slope and Peak Mitral Closing Velocity - First Derivative of Slope

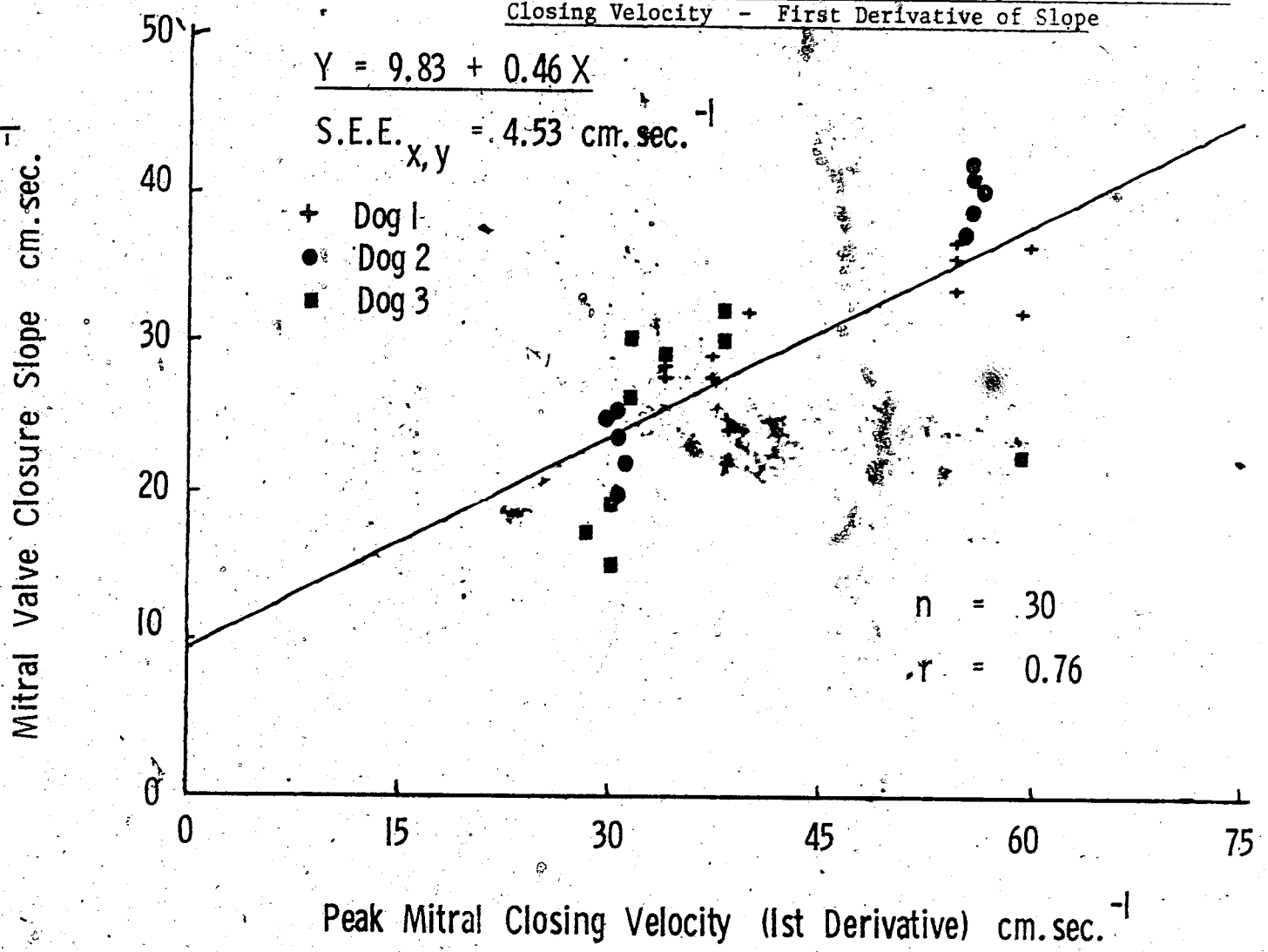


Figure 15 Comparison of Peak Mitral Acceleration (2nd Derivative) and Peak Mitral Closing Velocity (1st Derivative)

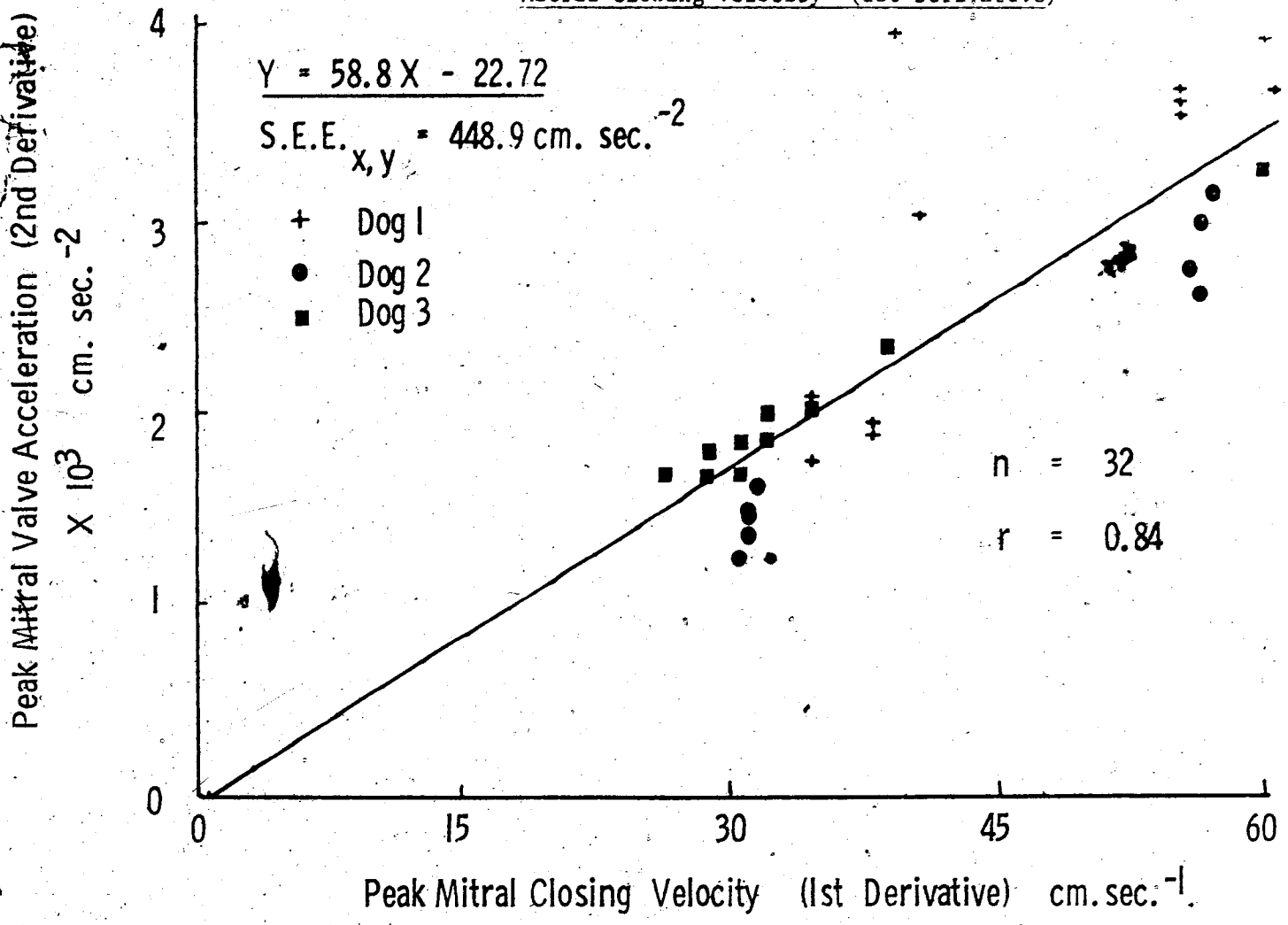


Figure 16 Comparison of Peak Mitral Closing Velocity by Echo and Peak Aortic Velocity by Velocity Catheter

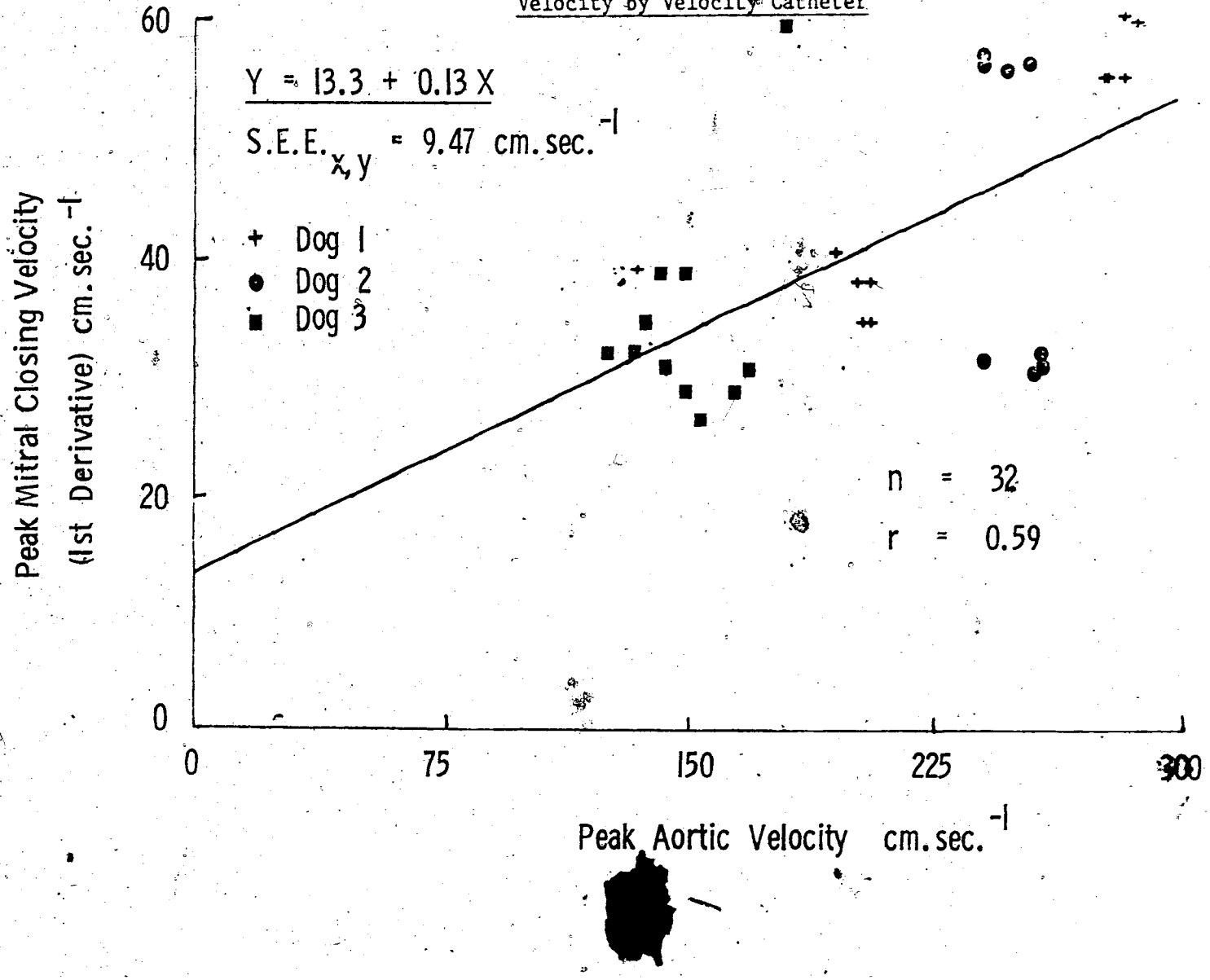


Figure 17 Comparison of Peak Mitral Closing Velocity & Peak Aortic Acceleration

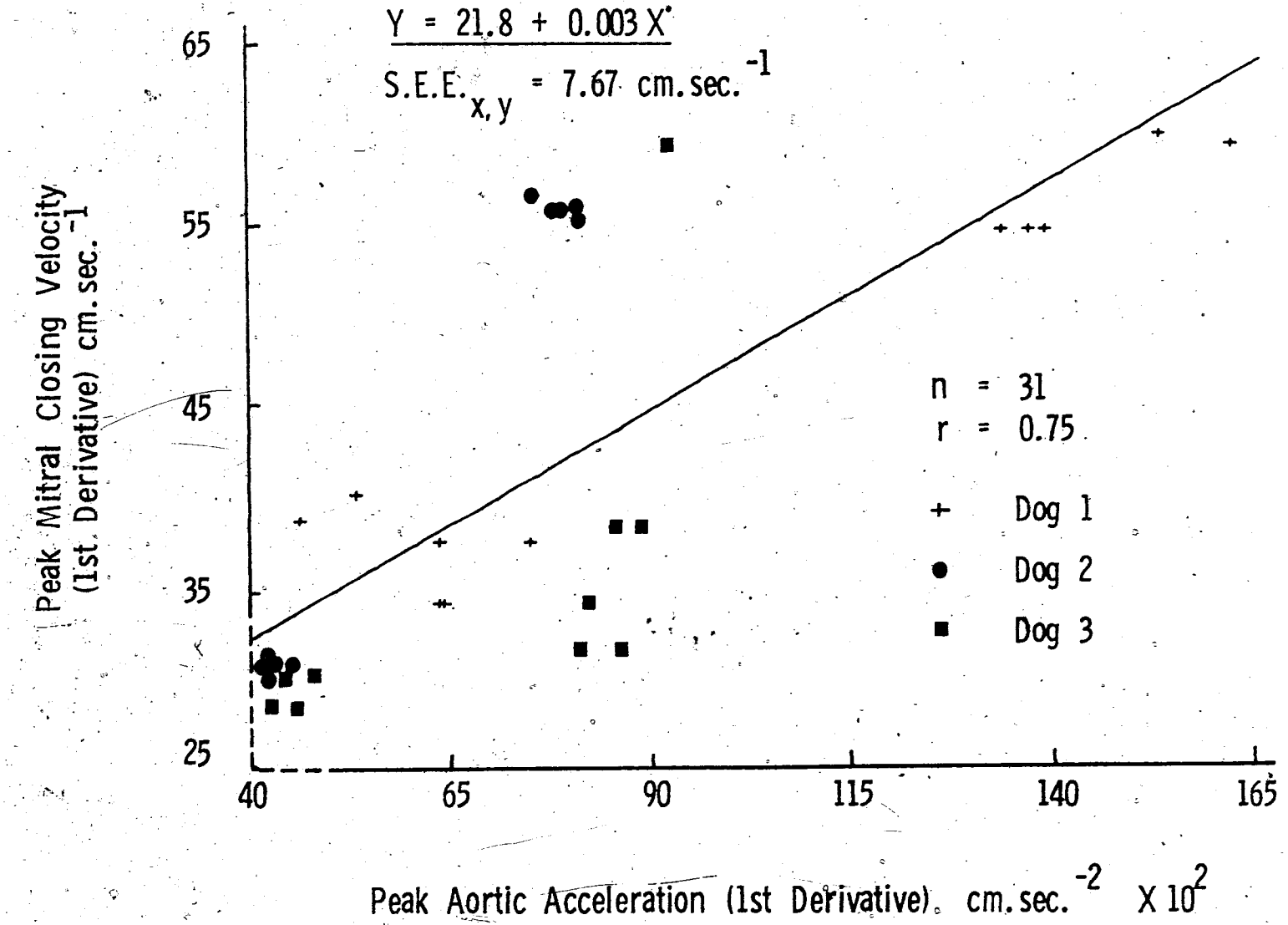
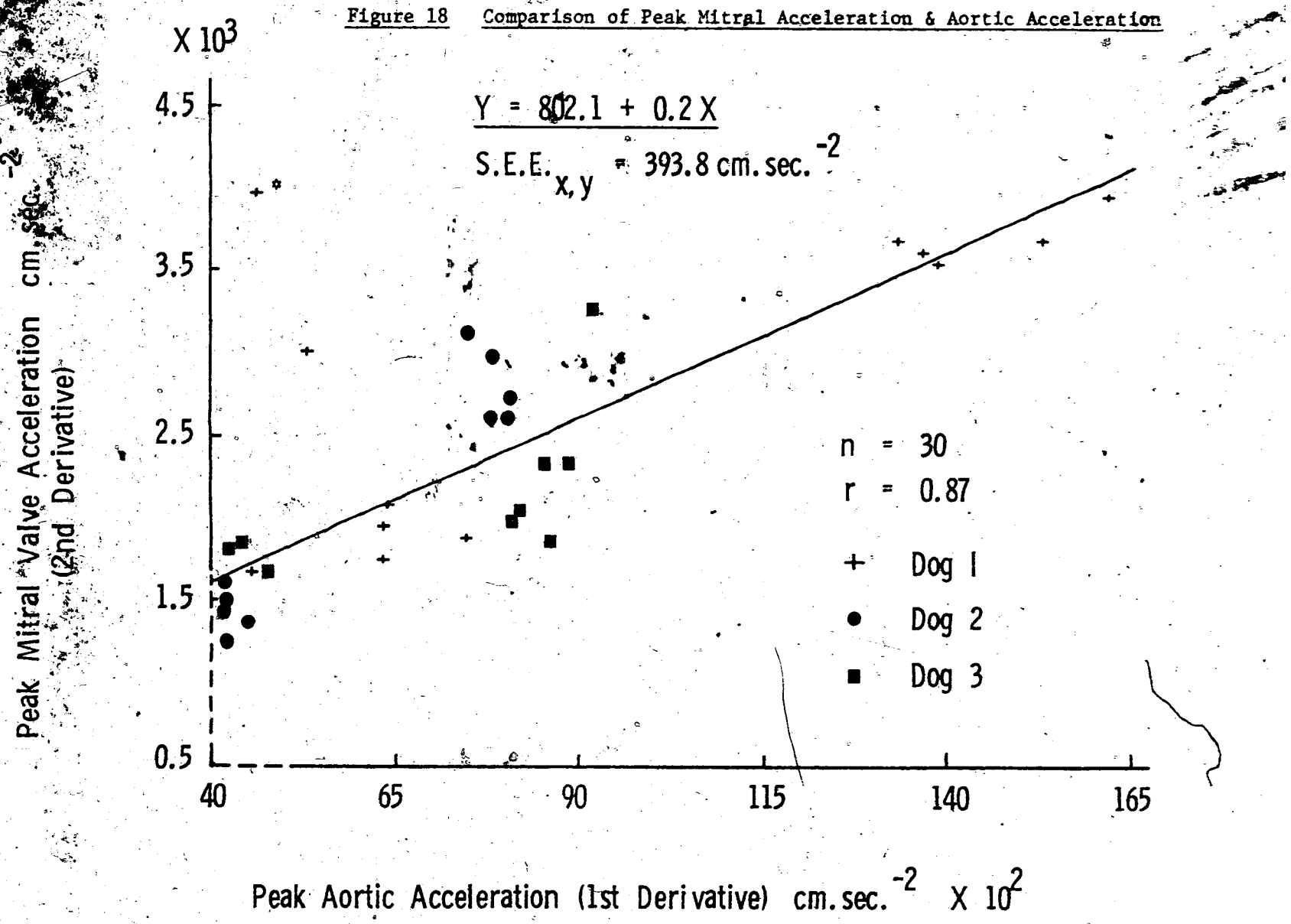


Figure 18 Comparison of Peak Mitral Acceleration & Aortic Acceleration



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