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Accuracy of volume measurement by conductance catheter in isolated, ejecting canine hearts

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ABSTRACT We evaluated the accuracy of the recently reported technique of estimating intraventricular volume by measurement of intracavitary electrical conductance in six isolated, ejecting, canine left ventricles. Left ventricular volumes were measured directly by a previously validated servosystem that employed an electroconductive balloon placed in the left ventricular cavity. The volume measured continuously by the balloon method (V_{bal}) was compared with that estimated by the conductance method (V_{cath}). For this test, the hearts were made to eject and fill physiologically by the use of a previously described computer-simulated arterial loading system. Complex ejection and filling patterns were created by stimulating the atrium mechanically, which resulted in irregular arrhythmatic contractions spanning a wide range of volumes. We found that there was a highly linear relationship (r^2 = .982 ± .014) between V_{bal} and V_{cath}: V_{cath} = 0.82 (±.05) V_{bal} + 26.7 (±11.8) ml. Despite the wide variation in the offset term of this relationship among the different hearts, the offset within a given heart was predicted within 3.5 ml by a previously detailed "dilution" method that is applicable to the heart in situ within a closed thorax. Thus, since the offset term is obtainable in situ, the conductance method provides a signal that is proportional to the actual volume. To determine whether right ventricular volume influenced the accuracy of left ventricular measurement, we compared the relationship between V_{cath} and V_{bal} obtained with right ventricular volumes of 0 and 30 ml. Increasing the right ventricular volume shifted the relationship upward by less than 3 ml in the working range. Finally, with the left ventricle constrained to contract isovolumetrically, there was less than ±2 ml variation about a mean value in the conductance signal, indicating that the geometric rearrangements occurring during contraction do not significantly influence the accuracy of this method. We conclude that the conductance method of left ventricular volume measurement provides a continuous signal that is proportional to the actual chamber volume and may therefore prove to be useful in the assessment of ventricular performance in patients and in laboratory animals.
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INSTANTANEOUS ventricular pressure and volume are the fundamental variables essential for understanding and assessing ventricular contraction. Whereas semiconductor catheter–tip transducers provide high-fidelity continuous measurement of ventricular pressure, techniques for measuring instantaneous ventricular volume of the heart in vivo accurately and continuously throughout the cardiac cycle have not been available. Recently, however, a method was introduced by Baan et al.[1] whereby ventricular volume could be estimated by measurement of intraventricular conductance with a specially designed catheter. In previous studies, the accuracy of this method for determining stroke volume and cardiac output has been evaluated in dogs with an electromagnetic flow probe,[1] and in humans with the thermodilution technique.[2,3] The accuracy of absolute left ventricular volume and ejection fraction measurements obtained with this catheter was tested in vitro in isolated canine hearts,[4] in intact dogs using ferromagnetic fluid dilution,[3] and in humans by cineventriculography.[2,3] The results of all these studies have generally shown good correlations between the volume measured by the conductance technique (V_{cath}) and those by other methods, but the correlation data obtained in vivo showed significant scatter. Because each of the methods against which the conductance catheter method was compared in vivo

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has limited accuracy in measuring ventricular volume, the scatter could have been caused, at least in part, by inaccuracies in the other methods rather than those in the conductance catheter method.

The purpose of the present study, therefore, was to reevaluate the accuracy of the conductance catheter method more reliably than in previous studies by use of an isolated, beating left ventricular preparation in which left ventricular volume could be measured accurately by use of a balloon fitted to its cavity. To our knowledge, the balloon method yields the most accurate measurement of the ventricular cavity volume in isolated hearts.[5] Furthermore, in this preparation it is possible to produce physiologic changes in ventricular volume with the use of a specially designed computer-simulated arterial loading system.[6] Thus, the evaluation was made in physiologically ejecting left ventricles of isolated canine hearts.

Methods

Conductance catheter. The technique used to estimate ventricular volume by measuring electrical conductance in the cavity has been described in detail by Baan et al.[1, 3] Briefly, a catheter with eight electrodes equidistantly placed along the end of a No. 7F catheter was positioned inside the ventricular cavity (figure 1). To match the electrode spacing on the catheter to the size of the left ventricle of a 20 kg dog, we used a catheter in which the distance between the first and the last electrode was 6 cm. An alternating current, with a constant amplitude (20 kHz, 30 μA) was passed between electrodes 1 (in the apex) and 8 (at the base) to set up an electrical field inside the ventricular chamber. The five potential differences, $\Phi_i(t)$, between each successive pairs of remaining electrodes (i.e., electrode pairs 2–3, 3–4, 4–5, 5–6, and 6–7) were measured continuously. Dividing the current by each of the $\Phi_i(t)$ signals results in five conductances [$G_i(t)$; i = 1 to 5)]. Summing the $G_i(t)$s gives an overall signal, G(t), which is linearly related to ventricular volume, V(t), by the following equation[3]:

$$V(t) = (1/\alpha)\,(L^2/\sigma)\,G(t) - V_c \qquad (1)$$

where α is a dimensionless slope constant, L is the distance between adjacent electrodes, σ is the conductivity of the fluid in the cavity, and V_c is a correction term that accounts for the conductance of the tissues surrounding the cavity. V_c will be discussed in detail below. The current is delivered by a signal conditioner-processor (Leycom Model Sigma-5, The Netherlands). In addition, this signal processor is equipped with the means to measure the resistivity (rho) of the blood, which it displays on a digital readout panel. Rho is simply equal to the reciprocal of the conductivity, σ, in equation 1 (rho = $1/\sigma$). Since the device provides a direct readout of this quantity, we will report the value of rho rather than that of σ. Finally, the Leycom device measures the voltages $\Phi_i(t)$ and performs the necessary analog computations to obtain V(t) *not* accounting for the correction terms V_c and α of equation 1. The output signal of the processor [i.e., (L^2/σ) G (t)] will be referred to as the (uncorrected) catheter volume, $V_{cath}(t)$.

V_c is linearly related to the parallel conductance of the surrounding structures, G^p, by[3]

$$V_c = (1/\alpha)\,(L^2/\sigma)\,G^p \qquad (2)$$

which follows from the condition that, when cavity volume is zero [V(t) = 0 in equation 1], all current passes through the surrounding structures. In the isolated heart preparation, G^p is composed of the conductances of the balloon used to measure cavity volume (see below), the ventricular wall, and the contents of the right ventricle. Two methods have been described previously for determination of the value of αV_c for the heart in situ,[3] one of which was used in the present study.

We used the so-called dilution method to obtain αV_c, which is applicable to the heart in situ within a closed thorax. Briefly, a bolus (1 to 2 ml) of saturated saline solution (conductivity = 75 S/m in contrast to that of blood, which is approximately 0.7 S/m) is injected into the hydraulic system while end-systolic and end-diastolic volumes are held constant. As the bolus mixes with the fluid in the ventricular cavity, its conductivity (σ in equation 1) increases, causing the overall conductance signal, G(t), to increase while the parallel component, G^p, remains constant. In practice then, end-systolic overall conductance, G_{es}, is plotted as a function of end-diastolic overall conductance, G_{ed}, during the mixing of the bolus; linear regression analysis is applied to the G_{es}-G_{ed} data points, and G^p is equal to the intersection point between the regression line and the line of identity.[3] In our study (see figure 4) we plotted V_{cath} (= $[L^2/\sigma]G$) at end-systole vs end-diastole rather the G, while considering the factor L^2/σ constant and equal to its original value before the bolus injection. Thus, the value determined by the intersection of the regression line with the line of identity was equal to αV_c (= $[L^2/\sigma]G^p$). This procedure will be described in detail below.

The value for αV_c obtained by the dilution method was compared with a more direct measure of this offset volume that was determined by plotting V_{cath} against actual balloon volume

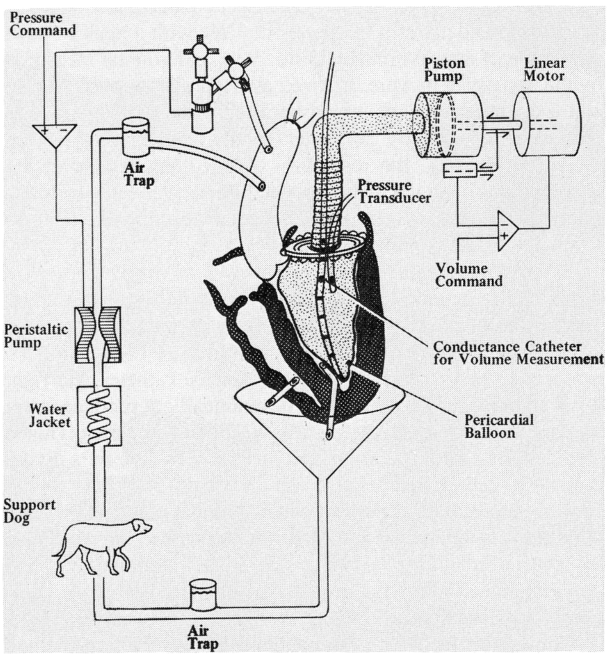

FIGURE 1. Schematic diagram of the isolated heart preparation indicating the positions of the conductance catheter and pressure sensor relative to the left ventricular chamber. Electrode 1, situated near the apex, and electrode 8, at the level of the base, are used to apply alternating current. Remaining electrodes (2 through 7) are used to measure voltage drops, which are converted to segmental volume. Note that the balloon placed inside the left ventricle was made out of pericardial tissue.

(V_{bal}) as measured directly by the servosystem (see below). Applying linear regression analysis to the data over a wide range of volumes, we obtained

$$V_{cath} = m\ V_{bal} + b \qquad (3)$$

in which, from comparison to equation 1, it is evident that the y intercept, b, provides an estimate of αV_c, while the slope, m, gives an estimate of α.

No independent experimental way to estimate the slope factor α has been devised yet, but theoretical studies[4, 7, 8] have addressed this problem by consideration of a possible relationship between α and G^p, as discussed below.

Surgical preparation. The procedures used to isolate and support the canine hearts were similar to those described by Suga and Sagawa.[5] Six pairs of mongrel dogs were anesthetized with sodium pentobarbital (30 mg/kg iv). The femoral arteries and veins of one dog of each pair (support dog) were cannulated and connected to a perfusion system (figure 1) used to supply oxygenated blood to the heart isolated from the second dog (donor dog). The chest of the donor dog was opened under artificial respiration. The left subclavian artery was cannulated with the arterial line of the perfusion system. The brachiocephalic artery was cannulated to monitor the coronary perfusion pressure. The azygos vein, superior and inferior venae cavae, descending aorta, and lung hili were ligated. The heart was then removed from the donor dog and coronary perfusion was provided by the support dog via a constant-pressure perfusion pump. The left atrium was opened and all the chordae tendineae were freed from the mitral valve leaflets. A plastic adapter that holds the isolated heart to the ventricular volume servopump system (see below) was sutured to the mitral ring. When the surgical preparation was complete, this mitral ring adaptor was connected to the pump system so that a specially made saline-filled pericardial balloon (described below) could be fitted inside the left ventricular cavity (figure 1).

The conductance catheter was positioned in the intraventricular balloon so that the most distal electrode was in the apex and the most proximal electrode would lie between 3 and 7 mm outside the balloon, the exact distance being dependent on the size of the heart studied.

In all experiments the coronary perfusion pressure was maintained between 80 and 100 mm Hg by a servocontrolled finger pump. The temperature of the perfusate was maintained between 35° and 37° C.

Ventricular volume servosystem. A servosystem, depicted in the upper right portion of figure 1, was used to control ventricular volume. Details of its design and performance have been reported by Sunagawa et al.[9] A linear motor controlled the position of the piston within a double rolling–diaphragm cylinder. A specially made pericardial balloon was secured to a tube connected to the outflow tract of the cylinder. The cylinder, connecting tube, and balloon were all filled with water made conductive by adding sodium chloride. The position of the piston was sensed by a linear displacement transducer attached to the shaft of the piston, thus producing a signal proportional to the V_{bal} and therefore ventricular cavity volume. This signal was used in a negative feedback loop for comparison with a volume command signal that represented the desired instantaneous volume. The error signal resulting from this comparison was supplied to a power amplifier (Crown DC-300), which in turn drove the linear motor.

The accuracy of ventricular volume thus measured is expected to be within less than 1 ml of the actual ventricular volume as long as the balloon is tightly fitted to the endocardial surface.[10]

Simulated arterial loading system. The volume signal for the volume servosystem was generated by the interaction between the left ventricular pressure signal, measured by a semiconductor tip transducer (Miller, model 380), and a specially designed loading system that has previously been described in detail by Sunagawa et al.[6] The afterloading circuit was the three-element modified windkessel model, which has been shown to be a reasonable respresentation of the aortic hydraulic input impedance,[11] and a diode that functioned as the aortic valve. Using this system, the isolated heart can be made to eject physiologically. The ventricle was also filled in diastole by the computer-simulated venous filling circuit, which consisted of a pressure source and a resistance to filling.

Pericardial balloon. Because the myocardium is electrically conductive (σ of approximately 0.25 S/m[12]), although less so than blood (σ of approximately 0.70 S/m), some of the excitation current delivered by the catheter passes through the ventricular wall and therefore the conductance method overestimates the volume of the ventricular lumen by an amount αV_c (equation 1), as explained above. To avoid elimination of this offset by the use of standard nonconductive rubber balloon within the isolated heart, we made balloons out of pericardial tissue, which is highly conductive (surface conductance >2 S/m²). This provided electrical continuity between the fluid inside the balloon and the myocardial tissue. In addition, the conductivity, σ, of the fluid inside the balloon was adjusted to be comparable to that of blood, i.e., approximately 0.70 S/m (resistivity, rho = $1/\sigma$, of blood approximately 140 $\Omega\cdot$cm).

Protocol and data analysis.

Pericardial balloon study. Before performing studies on the isolated heart, we evaluated the ability of the catheter to measure the volume of the balloon alone. The catheter was positioned inside a pericardial balloon, as described above. This balloon was filled with saline solution with a resistivity of 135 $\Omega\cdot$cm, which is comparable to that of canine blood. The balloon was then completely submersed in fluid contained within a Plexiglass tank, which created a parallel conductance. V_{bal} was varied sinusoidally at a frequency of 1 Hz with a peak-to-peak amplitude of approximately 35 ml. V_{cath} and volume measured by the servosystem were digitized at a sampling rate of 200 Hz and a quantitative comparison between these two signals was performed off-line by computer. After investigating a wide range of volumes, the resistivity of the fluid outside of the chamber was changed and the procedure was repeated to determine how a change in parallel conductance influences the performance of the volume catheter.

Isolated heart studies. Experiments were performed on a total of six canine hearts. Each ventricle was made to pump under various preload and afterload conditions producing ventricular volumes over a wide range from approximately 15 to 50 ml. To provide a rigorous test for the conductance catheter, the right atrial appendage was stimulated mechanically to produce irregular and complex ejection patterns. V_{cath} and V_{bal} were digitized at a sampling rate of 200 Hz and analyzed off-line by a digital computer. In each heart approximately 30 sec (6000 data points) of continuous data obtained under a wide range of loading conditions were analyzed in each run. A comparison was made by plotting the digitized data for V_{cath} as a function of V_{bal} and applying linear regression analysis to obtain the regression coefficients of equation 3.

The value of αV_c was determined by the dilution method outlined above in five of the hearts. This value was compared with the value of b determined directly by applying linear regression to the V_{cath} and V_{bal} data as outlined above.

The influence of right ventricular volume on left ventricular V_{cath} was determined in three hearts by placing a second pericardial balloon inside the right ventricle and repeating the measurements outlined above with the right ventricle filled with a constant volume of 30 ml of saline of the same conductivity as the fluid in the left ventricle.

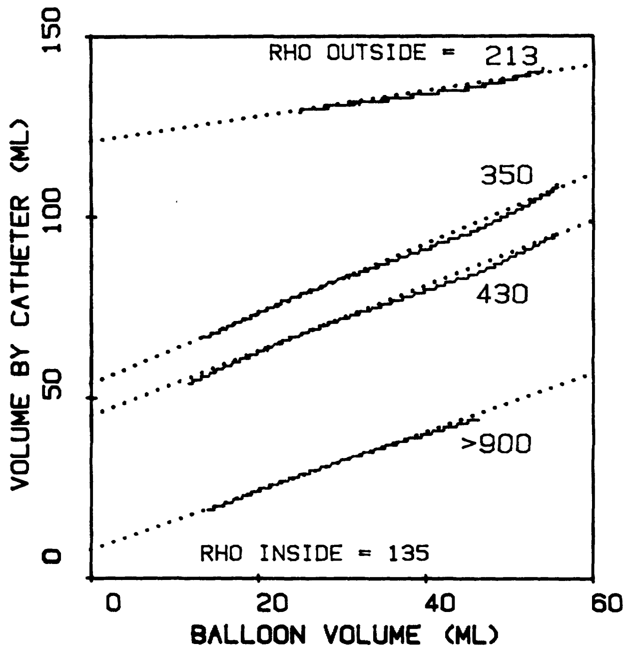

FIGURE 2. Isolated pericardial balloon study: relationship between actual V_{bal} and V_{cath} when the resistivity of the surrounding fluid is varied. See text and table 1 for details.

Finally, the influence on the conductance signal of changes in ventricular shape that occur during the cardiac cycle[13] was investigated. This was accomplished by recording the V_{cath} signal during forced isovolumetric contraction of the left ventricle at different volume settings.

Results

Pericardial balloon studies. The result of the studies with the pericardial balloon, filled with saline solution with resistivity of 135 Ω·cm and submersed in fluids with different resistivities, are presented in figure 2. The V_{cath} is plotted as a function of the actual V_{bal} imposed by the servosystem. As is evident in these graphs, the catheter provided a signal that was linearly related to the actual volume inside the balloon. The results of the quantitative analysis of these data are summarized in table 1. When the resistivity of the surrounding fluid was high (rho > 900 Ω·cm), the relationship between V_{bal} and V_{cath} had a slope of 0.80 and a y intercept of 8.4 ml, which is close to the line of identity. When the resistivity of the surrounding fluid was decreased, the y intercept increased, and at very low resistivities (rho = 213 Ω·cm) the slope decreased significantly. The linearity of the relationship, however, was not altered, as judged by the linear correlation coefficients which were always high (table 1). The situation in which the external-internal resistivity ratio was 350:135 (3 in table 1) closely mimics conditions in the left ventricle in situ.

TABLE 1
Influence of surrounding resistivity on the performance of the conductance catheter

	Surrounding resistivity (Ω·cm)	m	b (ml)	r^2
1.	>900	0.80	8.4	.998
2.	430	0.90	44.7	.999
3.	350	0.95	54.3	.997
4.	213	0.36	120.6	.981

Resistivity of fluid in balloon 135 Ohm-cm.
m = slope; b = y axis intercept.

TABLE 2
Results of linear regression analysis V_{cath} and V_{bal} data (n = 5 hearts)

Heart No.	m	b (ml)	r^2	αV_c (ml)	Error in αV_c (ml)
1	0.75	11.0	.963	7.5	−3.5
2	0.81	22.9	.972	23.1	0.2
3	0.83	25.0	.987	22.9	−2.1
4	0.89	43.3	.998	45.2	1.9
5	0.80	31.1	.992	28.7	−2.4

Abbreviations are as in table 1.
αV_c was determined by the dilution method (error in $\alpha V_c = \alpha V_c - b$).

Isolated heart studies. Simultaneous ventricular volume tracings obtained in an isolated heart by the balloon method and by the conductance catheter are presented in figure 3. The resistivity of the fluid inside the pericardial balloon was 120 Ω·cm. The right atrial appendage of the heart was stimulated mechanically to produce an irregular ejection pattern, as is depicted in the two panels at the top of the figure. As is shown, V_{cath} closely tracked the V_{bal} throughout this series, except for small deviations during isovolumetric pauses, and V_{cath} computed by conductance was linearly related to V_{bal}: in the example in figure 3, in which instantaneous V_{cath} is plotted as a function of V_{bal}, $V_{cath} = 0.76\ V_{bal} + 26.5$ ($r^2 = .987$).

In five experiments we evaluated the dilution method of determining $\alpha V_c{}^2$ (see Methods). The procedure is depicted in figure 4. First, a comparison between actual V_{bal} and V_{cath} was obtained by a method similar to that shown in figure 3. In the example of figure 4, *A*, the value of the y intercept is 31.1 and the slope is 0.8. Next, the conductivity of the fluid inside the chamber was increased by the infusion of hypertonic saline solution. As depicted in the original recordings in figure 4, *B*, the actual end-systolic and end-diastolic volumes, as recorded by the balloon method, were constant during this run, while the catheter signal increased in magnitude as the hypertonic saline mixed with the fluid in the pericardial balloon. As explained

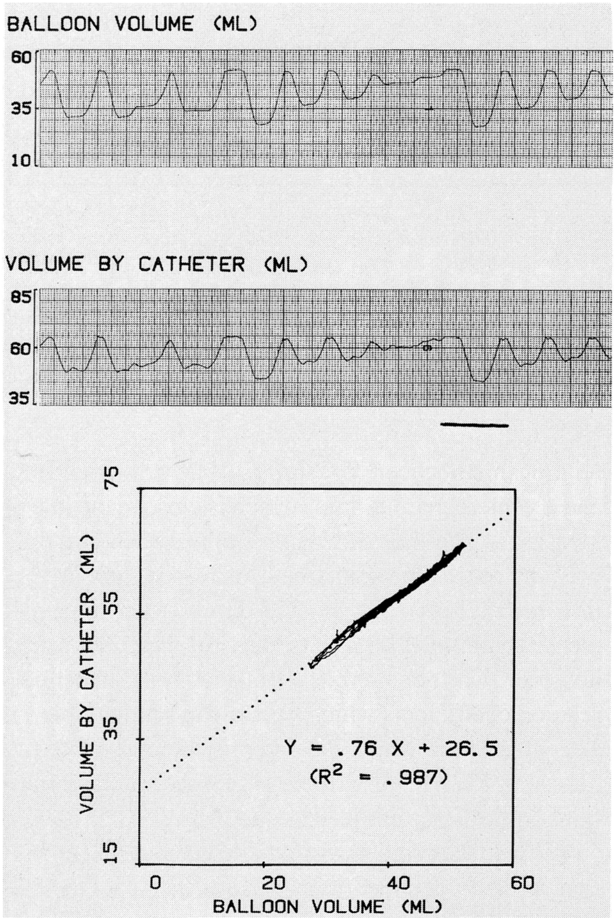

FIGURE 3. Simultaneous recordings from the conductance catheter and from the servosystem obtained from a typical isolated heart experiment while mechanically stimulating the right atrial appendage to produce a complex ejection pattern. Solid line below *middle* panel is 1 sec marker. The relationship between V_{cath} and V_{bal} is illustrated at the *bottom*. Dotted line represents the line of regression between the two.

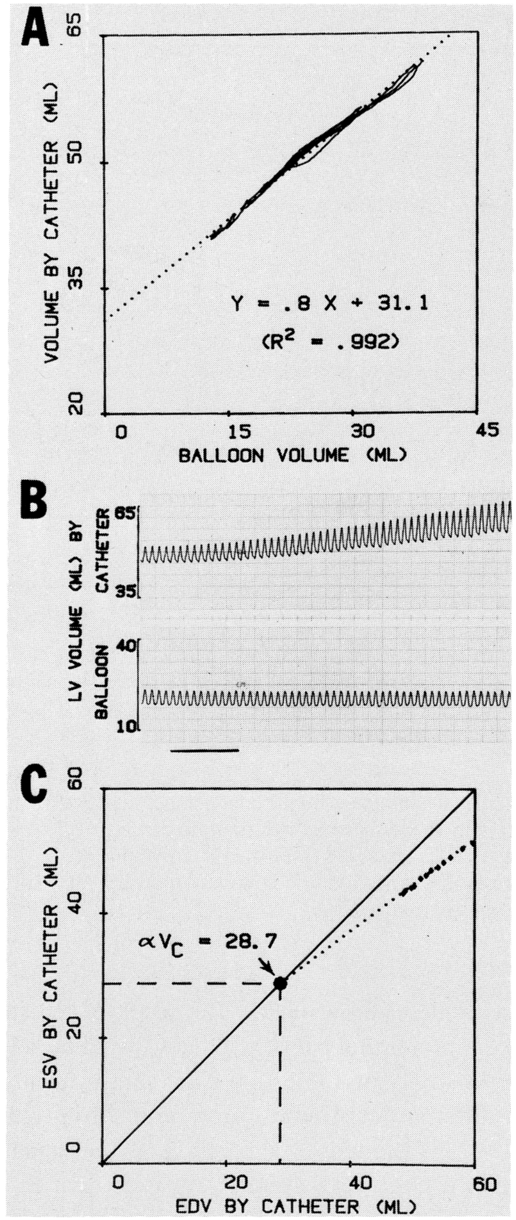

FIGURE 4. *A*, Relationship between V_{bal} and V_{cath} obtained over a wide range of volumes. By linear regression the slope, m = 0.8, estimates α while the offset, b = 31.1, estimates αV_c. *B*, While maintaining ventricular end-systolic and end-diastolic volumes constant, the resistivity of the fluid inside the balloon was decreased by infusion of hypertonic saline. V_{cath} gradually increased to a new steady level as this hypertonic fluid mixed with the fluid in the balloon. Solid line at the bottom is a 5 sec marker. *C*, End-systolic V_{cath} plotted as a function of end-diastolic V_{cath} during the transient in *B*. The intersection of the line of regression (dotted line) with the line of identity (solid line) estimated αV_c as 28.7, which is very close to that determined directly in *A*.

in Methods, end-systolic values for V_{cath} were plotted as a function of end-diastolic V_{cath} for several of the beats during the transient period, as depicted in panel *C*. The αV_c was then estimated by applying linear regression analysis to the data and determining the point of intersection of that regression line with the line of identity. A value of 28.7 ml was obtained for αV_c, which compared favorably with the 31.1 ml y intercept value determined directly (figure 4, *A*).

The results of this analysis in five isolated hearts are summarized in table 2, where the slope, intercept, and correlation coefficient of the linear regression between V_{cath} and V_{bal} are presented along with αV_c obtained by changing intracavitary conductivity. These results indicate a highly linear relationship between V_{cath} and the actual volume measured by the servosystem. The error in the dilution method–estimated αV_c is small in each experiment.

Influence of the right ventricle. The influence of right ventricular volume on the performance of the conductance catheter was assessed in three ventricles. The left ventricles filled and ejected as described above, and the volume of the right ventricular pericardial balloon was kept constant at either 0 or 30 ml. The results from the three hearts are presented in table 3. On average, increasing right ventricular volume from 0 to 30 ml did not influence the correlation coefficient significantly,

TABLE 3
Influence of right ventricular volume on left ventricular V_{cath}

	Experiment No.								
	1			2			3		
RVV	m	b (ml)	r^2	m	b (ml)	r^2	m	b (ml)	r^2
0	0.83	12.1	.984	0.77	26.0	.983	0.81	31.1	.970
30	0.82	15.0	.985	0.84	24.7	.983	0.79	32.3	.990

RVV = right ventricular volume (ml); other abbreviations are as in table 1.

while the influence on the slope, and the offset were small. Theoretically, the increase in right ventricular volume should hardly affect slope and should increase the value of the offset (see Discussion), which was indeed the case in experiments 1 and 3. The very slight changes in the slope (0.01 and 0.02, respectively) in experiments 1 and 3 are not statistically significant. The 0.07 increase in slope in experiment 2, and the accompanying slight decrease in offset, are somewhat anomalous.

Isovolumetric contractions. The influence of the geometric changes brought about by isovolumetric contractions on the conductance signal were evaluated in three ventricles. Original recordings from one typical experiment are illustrated in figure 5. The ventricle was made to contract isovolumetrically at 10, 15, 20, 25, 30, and 35 ml. Peak isovolumetric pressure increased from 40 to greater than 180 mm Hg over this range of volumes. The V_{cath} fluctuated by at most ± 2 ml around the mean level during the cardiac cycle. The amount of fluctuation in the catheter signal was a function of ventricular volume, which suggests that ventricular volume modulates the influences of contraction on chamber geometry. Minimal fluctuations (<0.5 ml) were observed at a volume of 25 ml and they were maximal at 35 ml. The results of the other experiments were essentially identical. Similar conclusions regarding the influence of volume on geometry in an ejecting ventricle may be drawn from the pressure-volume loops shown in figure 6 obtained by balloon and by conductance catheter. (The V_{cath}-V_{bal} correlation data corresponding to these tracings are presented in figure 4). The overall similarity between the two panels is striking. However, closer inspection reveals that the isovolumetric relaxation phases show some differences. Those in figure 6, *A*, obtained by balloon, display a slight but uniform skewness, while the isovolumetric relaxation parts of the conductance loops in panel *B* show a reversal in skewness for end-systolic volumes larger than 23 ml.

Discussion

The accuracy of the conductance catheter has been assessed previously by comparison of V_{cath} with volume measured by cineventriculography and with thermodilution and electromagnetic flow determinations of stroke volume. However, none of these techniques

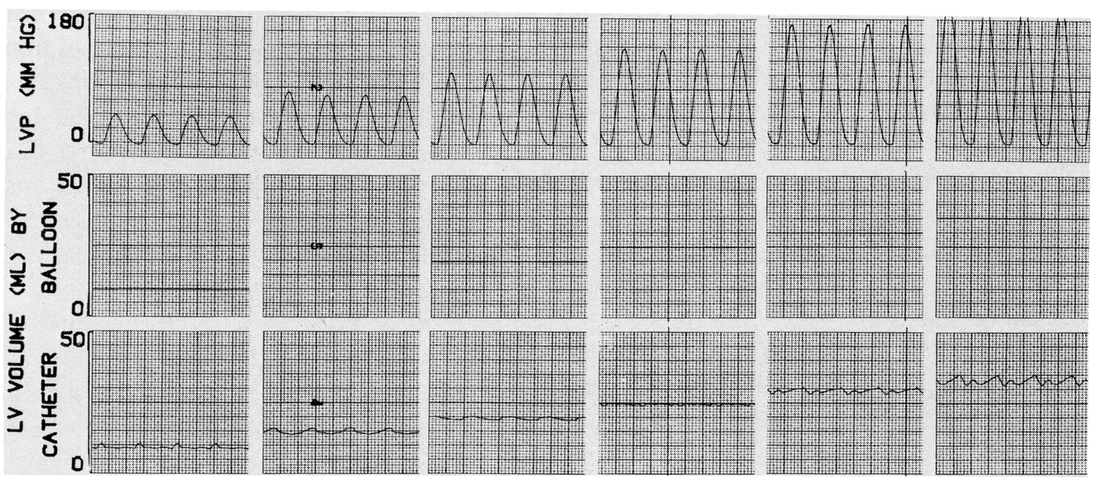

FIGURE 5. Measurement of left ventricular volume by balloon (*middle*) and by conductance catheter (*bottom*) during isovolumetric contractions at, from left to right, 10, 15, 20, 25, 30, and 35 ml. Left ventricular pressure (LVP, *top*) increased from 40 to more than 180 mm Hg. V_{cath} fluctuated by a maximum of ± 2 ml around the mean level during the cardiac cycle.

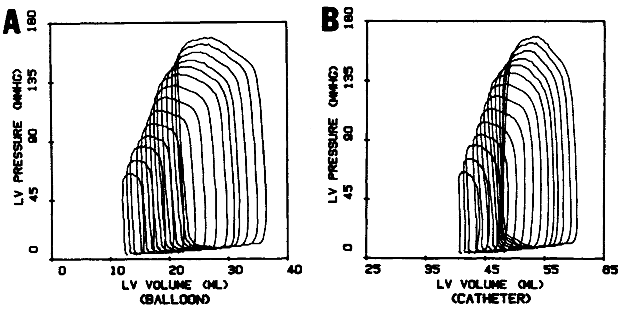

FIGURE 6. Pressure-volume loops obtained by changing preload volume in the servosystem with volume measured simultaneously by the balloon method in *A*, and by the conductance catheter in *B*. See figure 4, *A* for the relationship between V_{bal} and V_{cath}. V_{cath} as shown is directly from the Leycom signal processor, and is not corrected for the offset αV_c determined by the dilution method.

has been thoroughly validated against a truly reliable method and shown to provide precise measures of (changes in) ventricular volume throughout the cardiac cycle. In the present study the "gold standard" of ventricular volume measurement to which the conductance catheter measurements were compared was provided by the intraventricular balloon method, which has been previously validated. In this method, the volume of fluid inside the balloon is accurately measured by a carefully calibrated linear displacement transducer coupled to the shaft of a piston pump that controls the balloon value. The balloon, in principle, completely fills the ventricular lumen, thereby providing a precise measure of ventricular volume. In a previous study[10] it has been shown that this assumption is valid to within less than 1 ml, one likely source of error being that the balloon does not fill all the intertrabecular cavities in the wall. Also, in the isolated heart preparation used in this study the small amount of volume contained within the outflow tract beneath the aortic valve and above the plane of the mitral valve (where the plastic holder was sutured) is not included in the balloon measurement of ventricular volume. The extent to which this "pocket" of volume is measured by the conductance catheter depends on whether it is filled by air or by blood as provided by Thebesian vessel drainage. We were unable to determine this, but the pocket volume is probably 2 ml at most, and constant throughout the cardiac cycle.

Measurements of changes in ventricular volume by the balloon method are likely to be more precise than measurements of absolute volume since the errors discussed above are relatively constant in a given heart and independent of the ventricular volume. With knowledge of the magnitude of the potential errors in balloon method, we consider it to be the best method available at present for measuring absolute ventricular volume in an ejecting heart and therefore an appropriate gold standard for evaluation of the accuracy of the conductance catheter.

We first studied the influence of changes in the parallel conductance on the performance of the conductance catheter by changing the resistivity of the fluid surrounding the pericardial balloon without a heart. From figure 2 and table 1 it is clear that this maneuver does not influence the linearity of the measurement, but the value of the y intercept clearly increases with decreasing fluid resistivity (rho), as expected from equation 2. In fact, plotting the y intercept data against the 1/rho data in table I yielded a linear relationship ($r = .996$), which, theoretically, should be the case (see equation 2). The substantial decrease in slope when rho is lowered is also expected: in the hypothetical and extreme case in which the resistivities of the fluids inside and outside the balloon would be equal and the balloon material would have the same rho, no variation in V_{cath} (slope $= 0$) should be observed despite changes in the actual V_{bal}.

Results obtained with the isolated heart indicated a highly correlated, linear relationship between the volume measured by the servosystem and that measured by the catheter over a wide range of volumes and under different loading conditions, including arrhythmic contraction. The offset in the regression between V_{cath} and V_{bal} was predicted rather accurately (<3.5 ml error, table 2) by the dilution method, which estimates αV_c by increasing the conductivity (decreasing resistivity) of the fluid inside the cavity by infusion of hypertonic saline.

The variation in offset between different hearts is quite large, an observation that has also been made in hearts in situ.[3] Much less heart-to-heart variation is observed for the slope constant (range of from 0.75 to 0.89, which roughly covers the same range observed in situ).[3] In studies in a theoretical model,[7,8] the values for α were predicted by the (measurable) value of G^p, but the present results (table 2) do not fully support the model predictions in this respect. Therefore, more work to elucidate the factors influencing the slope is warranted.

The observed effect of right ventricular volume on V_{cath} is in accordance with the predictions of theory. An increase of right ventricular volume by a fixed quantity of well-conducting fluid increases the amount and overall conductivity of the tissue surrounding the left ventricular cavity, and thus increases G^p and, per equation 2, the y axis intercept. An increase in G^p should also result in a small decrease in slope constant.[7,8]

Generally, the observed influences on slope and offset of adding fluid to the right ventricle are quite small and are likely caused in part by statistical uncertainties.

The influence of changes in ventricular shape occurring during contraction were assessed by making conductance measurements of volume during isovolumetric ventricular contractions. In this rigorous test, only relatively small effects (less than ±2 ml from the mean) were observed.

A potential limitation in the applicability of the results of the present study to the situation in situ arises from the fact that the conductance catheter was placed through the mitral valve and not through the aortic valve as would normally be the case in patients and intact animals. First, we could not assess the possible influences of left atrial volume on catheter measurements. This is a potentially important factor since the mitral valve is very conductive and the catheter excitation current may pass into the left atrium. Second, the influence of right ventricular volume may be slightly different in situ since, when the catheter is positioned through the aortic valve, the geometric relationship between the axis of the electrical field and the right ventricular cavity would be slightly different than in the present study. These questions should be addressed in more detailed theoretical models or in postmortem studies of hearts. Preliminary studies with the latter preparation in Baan's laboratory show that the effect of left atrial volume on conductance in the left ventricle is very small.*

The advantage of the use of the conductance catheter over other methods of measurement of ventricular volume is that it provides a continuous measure of ventricular volume. It is therefore highly suitable for making on-line measurements of ventricular pressure-volume loops, such as those shown in figure 6, and thus facilitates the assessment of ventricular performance in vivo in such terms. The volume signal used in figure 6, *B* was generated in real time by the Leycom signal processor; in practice, the offset volume determined by the dilution method (28.7 ml in this case, as in figure 4, *C*) would be subtracted from this signal, resulting in a signal proportional to volume determined by the balloon method.

In summary, the conductance method of estimating continuous left ventricular volume was highly linearly correlated with volume determined by the balloon method over a wide volume range and under a large variety of loading conditions and contraction modes. The value of the offset of the regression, αV_c, was predictable with reasonable accuracy by the dilution method. The slope of the regression was constant for a given heart, and varied between 0.75 and 0.89 among hearts. The influences of right ventricular volume and geometric changes occurring during the cardiac cycle on the catheter measurements were minimal. We conclude that the intracavitary conductance method of measurement of ventricular volume provides a continuous signal throughout the cardiac cycle that is essentially proportional to actual ventricular volume. Further work is needed to determine ways of estimating the exact magnitude of the proportionality factor, α, for a given heart in situ. The conductance method of continuous volume estimation is likely to facilitate the assessment of ventricular contractile state by providing crucial information about ventricular volume.

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*Baan J, et al: Unpublished observation.

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