TITLE:

Volume-Calibrated Segmental Air Plethysmography- a Comparison of Two Methods

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Data used in this study was collected in accordance with study BG91-0074 of the Clinical Research Practices Committee Institutional Review Board of the Bowman Gray School of Medicine.

Equipment used in this study was supplied by Carolina Medical, Inc., King, NC. No financial support was provided to any of the parties involved in the study.

Data gathered in this study was used to support Federal Food and Drug Administration 510(k) application number K9142000.

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ABSTRACT:

This study compares the volumetric accuracy of two methods of segmental air plethysmography. The Fixed-Volume (FVAP) method represented by the PVR Pulse Volume Recorder was tested against the Displaced-Volume (DVAP) method found in the VascuMAP Air Plethysmograph. Initial tests on a rigid cylinder showed the DVAP instrument measured a 1.0 cc change as 0.97 +/-0.06 cc and the FVAP instrument measured 119 +/-7.2 mm (1.0 +/-0.06 equivalent cc). Simultaneous volumetric tracings were then obtained from volunteers at ankle and calf sites with known volume changes introduced into the air system. At ankle sites, 1.0 cc changes were measured as 0.87 +/-0.07 cc by DVAP and 0.667 +/-0.07 equivalent cc by FVAP. At the calf, results were 0.91 +/-0.15 cc and 0.46 +/-0.11 cc, respectively, at 65 mmHg, and 0.85 +/-0.07 cc and 0.349 +/-0.135 cc, at 5 mmHg. Volumetric differences as compared to the rigid cylinder measurements were insignificant for DVAP results at the ankle ($P > 0.1$) and calf ($P > 0.50$) for 65 mmHg pressures, and borderline significant ($P < 0.05$) for calf volume testing at 5 mmHg. All three FVAP volume measurement differences were highly significant ($P < 0.001$). Testing of a clinical population showed the two systems to have a correlation coefficient of 0.80 and an average volume measurement ratio of 0.52 equivalent cc/cc, indicating that FVAP volumetric losses due to segmental tissue compliance averaged 47.9%. DVAP is superior to FVAP when true volumetric measurements are required in segmental plethysmographic examinations.

KEYWORDS:

plethysmography, segmental, air, volumetric, arterial, venous, tissue compliance

INTRODUCTION:

Segmental air plethysmography of arterial and venous changes is a valuable tool in peripheral vascular diagnosis and research. To reliably compare arterial or venous changes from one test to the next, however, it is necessary to volume-calibrate the measuring system.[1] In clinical practice, there are two basic methods to obtain volume calibrated results during air cuff plethysmography. The first method is to ensure that the air volume in the testing cuff is within narrow limits when the testing pressure is reached. Keeping the pneumatic volume fixed allows pressure changes recorded by the instrument to be volumetrically calibrated.[2,3] This method can be called Fixed-Volume Air Plethysmography (FVAP). The second method uses a standard volume displacement such as a calibrated syringe to change the volume of air in the cuff system while it is in place on the limb segment under test. The subsequent pressure change due to the known volume displacement appears on the output tracing and is used to volume-calibrate the record.[4] This method will be referred to as Displaced-Volume Air Plethysmography (DVAP).

Examination of the two methods shows that they both follow known laws of physics. One fundamental difference, however, is that DVAP calibrates volume changes in the system during the actual test, while FVAP relies on preset standards to provide volume-to-pressure calibration. Thus DVAP should automatically correct for changes such as air cuff elasticity, pneumatic volume, and the compliance of tissue enclosed by the cuff. FVAP results, on the other hand, would not be corrected.

As the use of a known air volume change provided by a syringe in a pneumatic cuff system has been shown to be equivalent to a hydraulic volume change under the test cuff and to hydroplethysmography [4], this method was chosen to test the correlation between FVAP and DVAP and to examine the influence of varying conditions on volume measurement calibration.

MATERIALS AND METHODS:

A VascuMAP Model AP-102V Medical Air Plethysmograph (Carolina Medical Inc., King, NC) was used for the DVAP instrument. This device uses a microprocessor-controlled solenoid and precision bellows to volume-calibrate its chart recorder output with a 0.50 cc volume change. A PVR-IV Pulse Volume Recorder (Life Sciences, Inc., Greenwich, CT) was used for the FVAP instrument. A standard air cuff of 12 cm width (Adult Arm Size, W.A. Baum, Co., Copiague, NY) was the testing cuff in all tests. The cuff tubing was modified to add the connections for the DVAP instrument and a 1 cc test volume syringe as shown in Figure 1. These modifications added approximately 7 cc of non-distensible volume to the air cuff system. All cuff filling and deflation was done through the FVAP device, with the DVAP instrument sensing pressures passively except during its volume-calibration cycle.

Tests using a syringe to provide standardized volume changes were performed in accordance with the cuff air volume limits and pressures specified for the FVAP device. These values are 65 to 85 cc of cuff air volume at 65 mmHg, and 5 to 15 cc at 5 mmHg. Air was pumped into the cuff using the 50 cc syringe provided in the FVAP unit. Pressure was monitored on the digital pressure readout of the DVAP instrument, as the gauge on the FVAP instrument does not monitor cuff pressure during trace recording. A section of Schedule 40 plastic pipe with a circumference of 28 cm was used for the rigid cylinder. Ankle and calf tests for this phase of the study were performed on three subjects with ankle circumferences ranging from 19 to 25.5 cm and calf circumferences ranging from 34 to 44 cm. Standard volume changes of 0.1, 0.25, 0.5 and 1.0 cc were studied. FVAP device Gain Settings of 0.25, 0.5 and 1.0 were used. 49 paired observations were made on the rigid cylinder at 65 mmHg. 25 paired observations were obtained at the ankle and 27 at the calf with a pressure of 65 mmHg. 19 paired samples were obtained for the calf at 5 mmHg.

Tests on clinical patients were performed on subjects undergoing scheduled plethysmographic examinations in the Clinical Vascular Laboratory of the Division of Surgical Services, Bowman Gray School of Medicine. The DVAP and FVAP instruments and the air cuff were the same as

used for the syringe experiments above. Pneumatic connections were the same as in Figure 1, except that the syringe was omitted. All tracings were performed by a Registered Vascular Technologist according to a written laboratory protocol, which included the FVAP cuff volume and pressure limits used in the syringe experiments. Air cuff filling was performed with the automatic inflation mechanism in the FVAP unit, and pressure was monitored using the FVAP gauge. All clinical tracings were taken at a FVAP Gain Setting of one (1). Seventy-one paired readings were obtained from the clinical subjects (39 at the ankle and 32 at the calf). Both healthy and arterially compromised limbs were tested, and no adequately paired data was excluded from analysis.

Paired tracings were mounted on data collection sheets for comparison. DVAP tracings were read using the volume scale generated by the microprocessor to compute the volume in cubic centimeters (cc's) represented in one millimeter of tracing height. The waveform height was then measured in millimeters and multiplied by this factor to arrive at the volume change in cc's. FVAP tracings were analyzed by measuring the waveform height an millimeters and then dividing this by the FVAP Gain Setting to normalize each reading to a gain factor of one (1). As each paired data set was collected simultaneously, corresponding waves could be matched exactly by observing similar features on both tracings, such as the characteristic pattern produced by the DVAP volume calibration procedure.

RESULTS:

The DVAP instrument gave a mean reading of 0.973 cc for a 1.0 cc standardized volume change when the cuff was wrapped on the rigid cylinder. The FVAP unit gave a mean reading of 119 mm for the same volume change. To compare FVAP results gathered at the various test sites and test pressures, this value of 119 mm per 1 cc was used as the conversion factor to display the FVAP measurements in "equivalent cc's". No conversion factor was used for DVAP measurements, as that instrument gives results calibrated directly in cubic centimeters.

Results obtained by FVAP measurement of standardized volume changes appears in Table 1.

The mean values and standard deviations are presented in equivalent cc's. The standard deviation is also shown in normalized form as a percentage of the mean value. Analysis of the mean differences was performed by subtracting the FVAP result in equivalent cc's from the value of the known volume change. The probability (P) that the difference of the means is NOT statistically significant is derived from these results using the method of Student. The estimating equations derived by regression analysis predict the FVAP result in estimated cc's (Y) for a known volume change in cc's (X). The lines created by plotting these estimating equations are presented in Figure 2.

Table 2 presents the same data for the DVAP instrument. In this table, all results are presented in standard cubic centimeters. Plots of the estimating equations appear in Figure 3.

A Scatter Plot of the data obtained from the clinical population is shown in Figure 4. Here the FVAP data is presented in millimeters of chart height and in equivalent cc's. Also shown on this graph is the line of the estimating equation for data obtained from both ankle and calf sites.

Table 3 displays the clinical data in tabular form for ankle, calf, and both sites combined. The slopes of the estimating equations compare FVAP readings in equivalent cc's (Y) to DVAP readings in cubic centimeters (X). The percent loss of the FVAP measurements as compared to FVAP readings taken on the rigid cylinder are derived from the magnitude of these slopes.

DISCUSSION:

A cuff wrapped on a rigid cylinder was used for volume measurement comparisons as this eliminates the effects of tissue or fluid movement losses in the volume signal. Volumetric losses (volume changes that do not cause a proportional change in cuff pressure) are thus limited to elasticity in the cuff and air bladder which can not be eliminated from the practical clinical system. Once the plethysmograph has been calibrated on such a rigid fixture, placing the cuff over a volume of tissue using the same cuff volume and pressure will indicate to what extent changing the testing substrate affects the volume measurement.

Figures 2 and 3 show how the two systems (DVAP and FVAP) react to changes in underlying tissue and cuff pressure. Readings taken with the DVAP method vary little, with measurement differences becoming statistically significant only over the calf at low cuff pressures such as those used for venous volume analysis. FVAP measurement differences, on the other hand, are all highly significant at the testing sites and pressures used. FVAP measurements also have a greater data variation than DVAP when used over tissue sites, as shown by larger standard deviations and smaller correlation coefficients than are found for DVAP measurements taken simultaneously.

Examination of the data collected from clinical patients show that the two methods of volume measurement are proportional, as indicated by the correlation coefficient of 0.80 between the instruments' readings. The line of the estimating equation comparing all the FVAP to DVAP measurements has a slope of 0.52 equivalent cc/cc. As the volumetric measurement of the DVAP instrument is not significantly different from true cubic centimeters, this slope indicates a 47.9% loss of FVAP volume measurement compared to measurements obtained on a rigid cylinder. Ankle measurements when examined separately had a slope of 0.53 equivalent cc/cc (47% loss), and calf measurements showed a slope of 0.516 equivalent cc/cc (48.4% loss).

CONCLUSIONS:

DVAP is superior to FVAP when true volumetric measurements are required in segmental plethysmographic examinations. The large variation in FVAP measurements at differing anatomic sites is explainable by variations in segmental tissue compliance - volumetric losses out of the ends of the tissue "cylinder" under the segmental air cuff. Thus tissue that is less anatomically fixed (more compliant), such as the adipose and muscle tissues which predominate in the calf, cause greater losses than the less compliant bone, ligament, and tendinous tissues found in the ankle. FVAP measurements, which are determined by preset volume-to-pressure criteria, do not correct for these losses. The DVAP method, however, corrects for tissue losses because the pressure change from the known volume change used to calibrate the system is reduced in proportion to the segmental tissue compliance.

ACKNOWLEDGMENTS:

The help of Scott Reavis RVT, and the staff of the Clinical Vascular Laboratory at The Bowman Gray School of Medicine in gathering the clinical data for this study is gratefully acknowledged.

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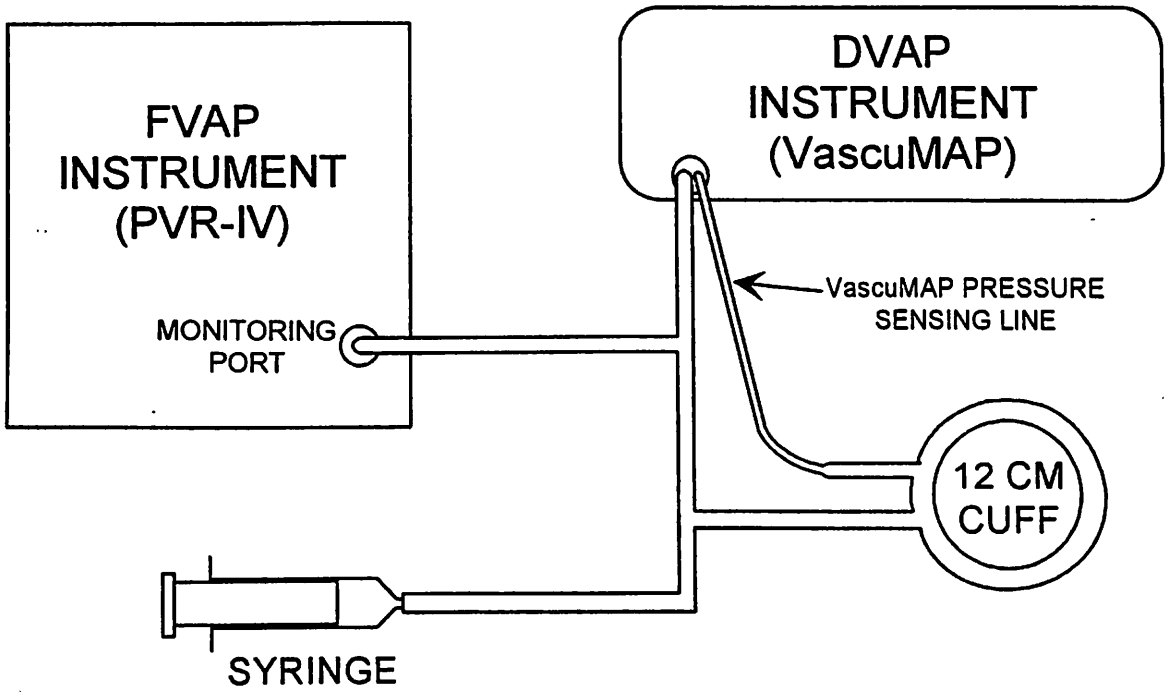

FIG 1. Pneumatic connections for testing FVAP and DVAP responses to known volume changes introduced by a syringe.

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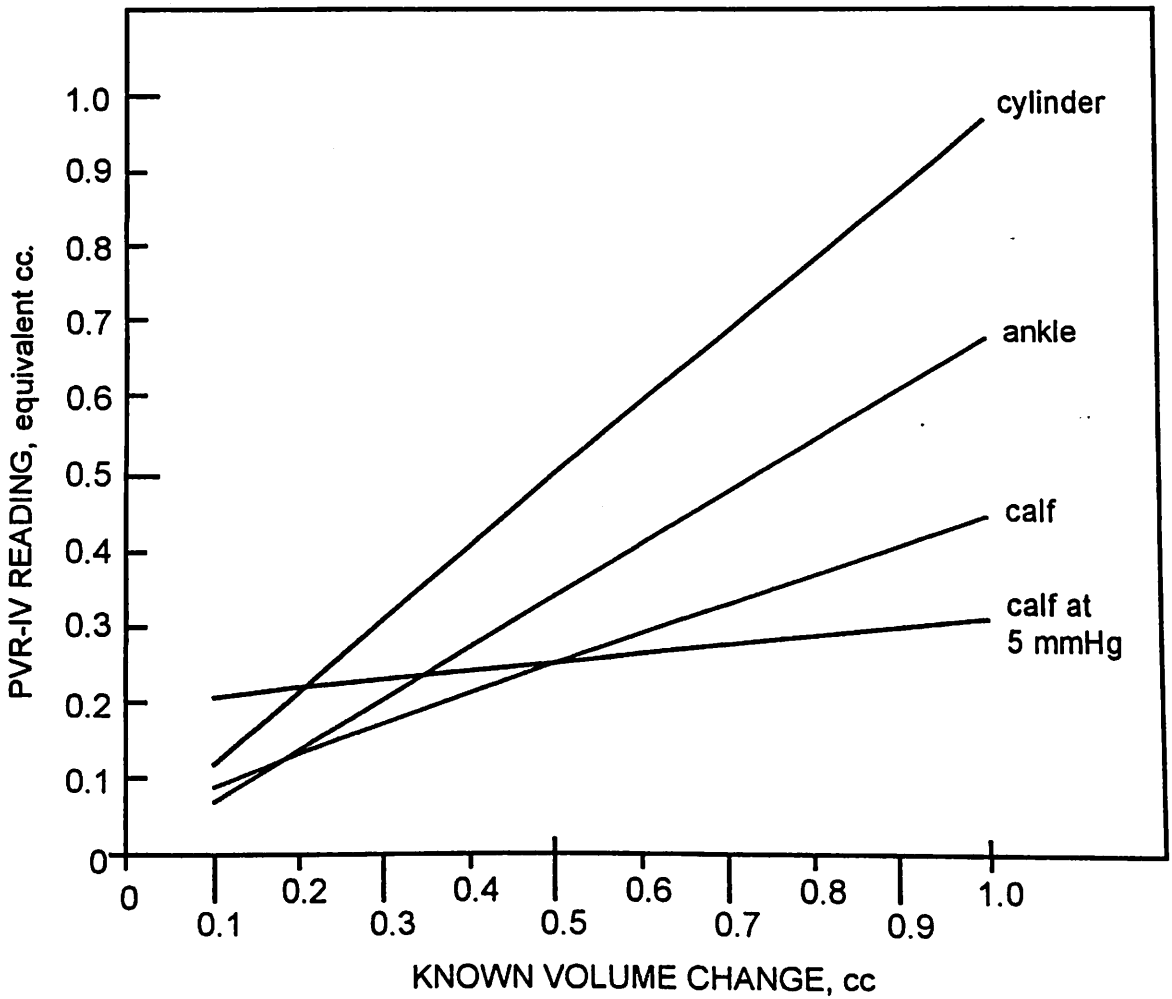

FIGURE 2: Plot of the Estimating Equation lines for FVAP measurements of known volume changes at different test sites and pressures. 1 equivalent cc equals 119 mm of PVR chart height at a gain of one (1).

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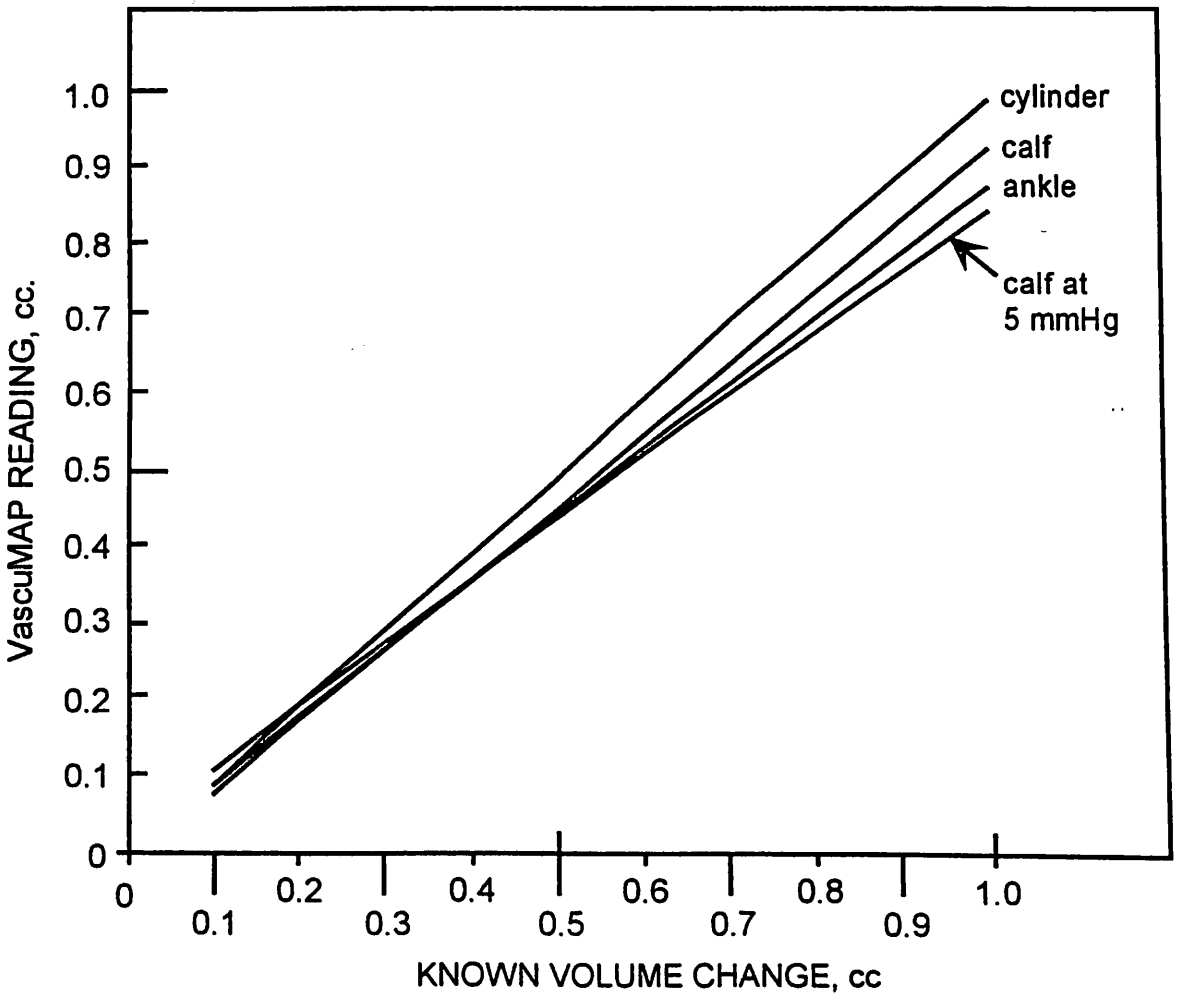

FIGURE 3: Plot of the Estimating Equation lines for DVAP measurements of known volume changes at different test sites and pressures.

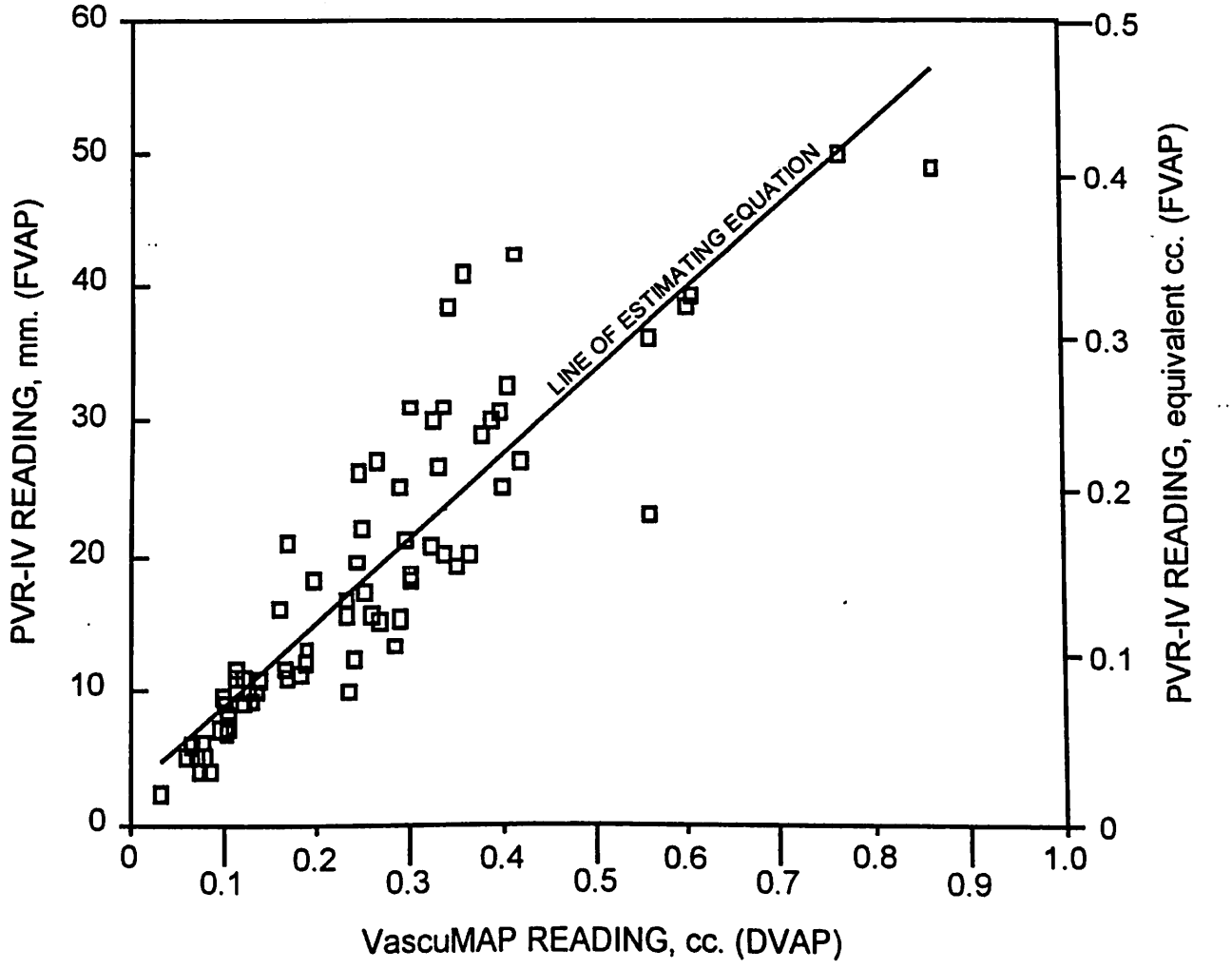

FIGURE 4: Scatter plot of FVAP versus DVAP data from ankle and calf sites in clinical patients.

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TEST SITE	RIGID CYLINDER @65 mmHg	ANKLE @ 65 mmHg	CALF @ 65 mmHg	CALF @ 5 mmHg
MEAN READING	1.0 cc (BY DEFINITION)	0.667 cc	0.460 cc	0.349 cc
STANDARD DEVIATION	0.06 cc	0.07 cc	0.11 cc	0.135 cc
% STANDARD DEVIATION	6%	10.7%	24.2%	38.8%
CORRELATION COEFFICIENT	0.99	0.96	0.75	0.21
ESTIMATING EQUATION	Y=0.941X+ 0.025	Y=0.67X+ 0.003	Y=0.385X+ 0.053	Y=0.112X+ 0.196
MEAN DIFFERENCE FROM 1 cc STANDARD	-0.0033 cc	+0.32 cc	+0.54 cc	+0.65 cc
STD DEVIATION OF DIFFERENCES	0.033 cc	0.073 cc	0.11 cc	0.135 cc
PROBABILITY (P)	>0.45	<0.001	<0.001	<0.001

TABLE 1: Fixed-Volume Air Plethysmography (FVAP) results when measuring known volume changes. FVAP volume measurements are in equivalent cc's, where 1 equivalent cc equals 119 mm of PVR chart height (see text).

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TEST SITE	RIGID CYLINDER @65 mmHg	ANKLE @ 65 mmHg	CALF @ 65 mmHg	CALF @ 5 mmHg
MEAN READING	0.973 cc	0.877 cc	0.909 cc	0.845 cc
STANDARD DEVIATION	0.058 cc	0.074 cc	0.154 cc	0.070 cc
% STANDARD DEVIATION	5.9%	8.4%	16.9%	8.2%
CORRELATION COEFFICIENT	0.99	0.98	0.89	0.93
ESTIMATING EQUATION	Y=0.998X - 0.012	Y=0.865X+ 0.005	Y=0.938X - 0.02	Y=0.81X+ 0.029
MEAN DIFFERENCE FROM 1 cc STANDARD	-0.013 cc	+0.12 cc	+0.09 cc	+0.16 cc
STD DEVIATION OF DIFFERENCES	0.028 cc	0.074 cc	0.154 cc	0.070 cc
PROBABILITY (P)	>0.30	>0.1	>0.5	<0.05

TABLE 2: Displaced-Volume Air Plethysmography (DVAP) results when measuring known volume changes. DVAP volume measurements are in true cubic centimeters.

TEST SITE	ALL SITES (ANKLE & CALF) @65 mmHg	ANKLE @ 65 mmHg	CALF @ 65 mmHg
NUMBER IN SAMPLE	71	39	32
CORRELATION COEFFICIENT	0.80	0.69	0.69
ESTIMATING EQUATION	Y= 0.52X+ 0.024	Y=0.53X+ 0.022	Y=0.516X+ 0.025
SLOPE OF ESTIMATING EQUATION	0.52 equiv cc/cc (119 mm)	0.53 equiv cc/cc 63 mm/cc	0.516 equiv cc/cc
PERCENT LOSS OF FVAP MEASUREMENT	47.9%	47.0%	48.4%

TABLE 3: Results of pulse volume data in clinical patients gathered simultaneously by FVAP (Y) and DVAP (X). FVAP results are expressed in equivalent cc's.

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