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Is Peripheral Arterial Pressure a Satisfactory Substitute for Ascending Aortic Pressure When Measuring Aortic Valve Gradients?

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Substitution of peripheral arterial pressure for ascending aortic pressure is a common but poorly validated practice in the assessment of aortic valve gradients by catheterization. The accuracy of this practice was assessed by comparing the left ventricular-ascending aortic mean gradient in 26 cases of aortic stenosis with the left ventricular-femoral artery gradient, both with and without compensation for temporal delay in femoral artery pressure. Aligned left ventricular-femoral artery gradients (matching upstrokes to compensate for peripheral time delay) underestimated the left ventricular-ascending aortic gradient by 10 mm Hg (range 0 to −17). Unaltered simultaneous left ventricular-femoral artery gradients overestimated the left ventricular-ascending aortic gradient by an average of 9 mm Hg (range +1 to +18). For both peripheral techniques, the error was relatively constant throughout the range of aortic valve gradients. The most accurate estimate of both aortic valve gradient and area was obtained by averaging the gradients and areas derived from aligned and unaltered left ventricular-peripheral arterial simultaneous tracings.

Although only occasionally critical for clinical decision-making, these errors may be overwhelming in certain types of research applications, such as comparisons of valve prosthesis gradients and serial evaluations of aortic stenosis. An additional source of error is a coexistent peripheral arterial gradient that was present in 21% of otherwise technically suitable patients in the screened study group.

The transvalvular pressure gradient in patients with aortic stenosis is ideally measured by simultaneous recording of phasic pressure on both sides of the diseased valve. This requires a retrograde arterial catheter in the ascending aorta and a catheter placed in the left ventricle by means of transseptal catheterization or direct left ventricular puncture, or retrograde passage of the aortic valve with a second arterial catheter or a single double lumen catheter. Because many cardiologists do not perform transseptal or left ventricular puncture procedures, the retrograde technique is most commonly employed. To spare patients the added discomfort and risk of a second aortic catheterization, a peripheral arterial pressure reading is often substituted for determination of ascending aortic pressure; this is especially common because the recent use of sidearm sheaths has made it possible to record femoral or brachial artery pressure simultaneously with left ventricular pressure without a second arterial puncture (1,2).

The validity of this approach assumes that the pressure pulse in a peripheral artery resembles that in the ascending aorta. In fact, this assumption is only approximately true. Although the decrease in mean pressure is trivial, the timing, contour and peak systolic pressure of the phasic pressure pulse are substantially altered by wave mechanics as the pulse travels from the ascending aorta to a peripheral site (Fig. 1 and 2). Although this has long been recognized (3,4), current textbooks on cardiac catheterization (5–9) do not specify the extent to which mean aortic valve gradients so measured might be altered by this effect. Furthermore, three textbooks (6,8,9) recommend the widespread practice of aligning the peripheral arterial pressure pulse with the left ventricular pressure curve so that their upstrokes coincide. We have been unable to locate references proving whether this yields a more accurate estimation of the true aortic valve gradient.

This study analyzes the accuracy of mean aortic valve gradients obtained from peripheral pressure tracings as compared with gradients obtained from simultaneous ascending aortic tracings. Furthermore, it addresses the question of whether temporal alignment of peripheral arterial and left ventricular pressure tracings improves the accuracy of the method.

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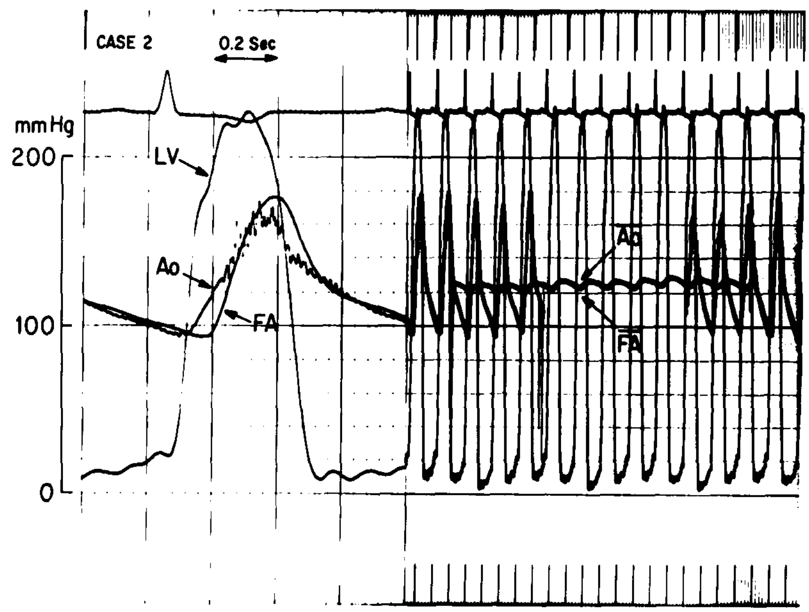


Figure 1. Case 2. Simultaneous recording of left ventricular (LV), ascending aortic (Ao) and femoral artery (FA) pressures. These pressures were measured using a transseptal 8 French Brockenbrough catheter, 7 French pigtail catheter and the side arm of an 8 French percutaneous femoral artery sheath, respectively. Six patients were studied in this manner. Despite the temporal delay and altered waveform of the phasic femoral artery pressure, the mean femoral artery ($\overline{FA}$) and mean ascending aortic pressures ($\overline{Ao}$) are identical (**right panel**).

Methods

Study patients. This study is based on analysis of catheterization data of 26 patients from a consecutive series of 73 studies demonstrating any degree of aortic stenosis with or without associated aortic regurgitation. Fifty patients were identified prospectively and 23 retrospectively. Criteria for inclusion focused on the quality of catheterization data. Ascending aortic and femoral artery pressures must have been simultaneously recorded at a paper speed of 100 mm/s and a gain setting of 20 mm Hg/cm. In addition, left ventricular pressure must have been recorded using the same technique, either simultaneously with ascending aortic and femoral artery pressure or sequentially with those pressures, provided that there was no change in heart rate between the two sequential recordings. Patients were excluded if there was an imprecise balance between ascending aortic and femoral artery pressure channels (see following) or if there was evidence of an abnormally high peripheral gradient as indicated by the absence of typical augmentation of systolic peripheral pressure. In Kroeker and Wood's series (3) of healthy subjects, peak systolic pressure in the femoral artery always exceeded the peak central aortic pressure. On this basis, we excluded all patients whose peak femoral pressure was not at least equal to the ascending aortic pressure in order to avoid compounding errors of valve gradient estimation.

Forty patients were excluded for technical reasons (no simultaneous aortic-peripheral arterial recording in 23 pa-

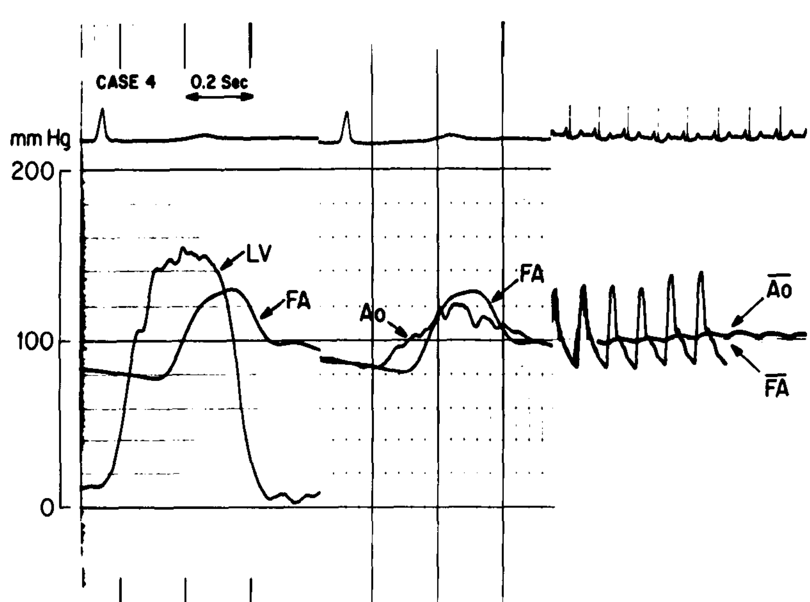


Figure 2. Case 4. Sequential recording of left ventricular (LV) pressure and simultaneous ascending aortic (Ao) (**left panel**) and femoral artery (FA) pressures (**middle panel**). Left ventricular and ascending aortic pressures were measured from the same 7 French pigtail catheter before and after, respectively, pullback across the aortic valve. Femoral artery pressure was recorded simultaneously using the side arm of an 8 French sheath. Twenty patients were studied in this manner. Mean femoral artery ($\overline{FA}$) and mean ascending aortic ($\overline{Ao}$) pressures are identical (**right panel**).

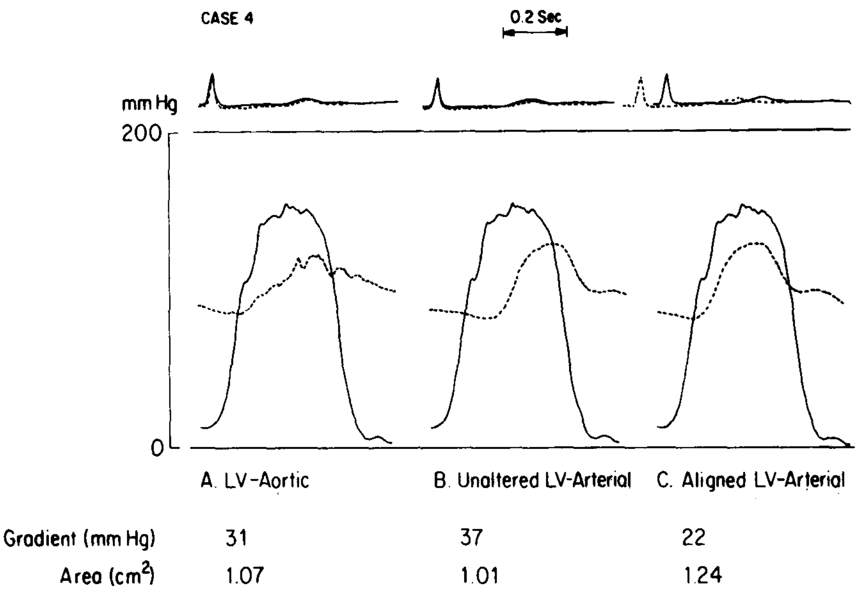


Figure 3. Case 4. The three gradients analyzed in this study. **A**, LV-aortic is the "true" aortic valve gradient measured either by simultaneous left ventricular and ascending aortic recordings (Fig. 1) or by sequential left ventricular and ascending aortic recordings (Fig. 2) superimposed by lining up the electrocardiographic R waves. **B**, Unaltered LV-arterial is the left ventricular-femoral artery gradient obtained from simultaneous or sequential tracings synchronized on the R wave. **C**, Aligned LV-arterial is the left ventricular-femoral artery gradient obtained by temporally advancing the femoral artery tracing so that its upstroke matches that of the left ventricle. Although displayed here separately, ascending aortic and femoral artery pressures were always measured simultaneously. To demonstrate methods of alignment, these pressures, along with their simultaneous electrocardiograms, are illustrated by the **dashed lines**.

tients, simultaneous aortic-peripheral arterial recording not at a paper speed of 100 mm/s in 7 patients, left ventricle not entered in 3 patients and imprecise transducer balance in 7 patients). Of the remaining 33 technically suitable studies, 7 were excluded because of evidence of abnormal peripheral arterial gradients.

Table 1. Gradients and Valve Areas in 26 Patients With Aortic Stenosis

		Gradient				Valve Area			
Case	Technique	A LV-Ao	B Unaltered LV-Art	C Aligned LV-Art	D Average B and C	E LV-Ao	F Unaltered LV-Art	G Aligned LV-Art	H Average F and G
1	Retro	84	93	69	81	0.40	0.39	0.43	0.41
2	TS	58	65	44	55	0.84	0.85	0.95	0.90
3	Retro	56	62	41	52	0.85	0.81	0.95	0.88
4	Retro	31	37	22	30	1.07	1.01	1.24	1.13
5	Retro	47	65	39	52	1.07	0.98	1.14	1.06
6	Retro	33	48	25	37	0.91	0.95	1.02	0.99
7	Retro	28	33	13	23	1.15	1.22	1.45	1.34
8	Retro	55	60	43	52	0.79	0.78	0.88	0.83
9	Retro	21	29	17	23	1.27	1.13	1.36	1.25
10	TS	38	47	31	39	0.86	0.79	0.92	0.75
11	TS	23	30	14	22	1.55	1.36	1.75	1.56
12	TS	77	86	74	80	0.54	0.53	0.55	0.54
13	TS	49	50	36	43	0.22	0.22	0.25	0.24
14	Retro	44	54	32	43	1.08	1.07	1.24	1.16
15	Retro	24	34	18	26	1.91	1.90	2.16	2.03
16	Retro	20	33	16	25	2.13	1.89	2.49	2.19
17	Retro	32	42	29	36	1.22	1.08	1.25	1.17
18	Retro	23	30	18	24	1.27	1.24	1.41	1.33
19	Retro	69	74	54	64	0.78	0.76	0.82	0.79
20	Retro	55	68	43	56	1.16	1.23	1.33	1.28
21	Retro	56	65	39	53	0.65	0.62	0.72	0.66
22	Retro	43	51	33	41	1.00	1.00	1.10	1.06
23	TS	59	62	49	56	0.68	0.68	0.71	0.70
24	Retro	64	79	58	69	0.57	0.59	0.63	0.61
25	Retro	17	31	9	20	1.17	1.03	1.60	1.32
26	Retro	55	71	55	63	0.62	0.60	0.61	0.60
Mean	—	44.7	53.8	35.4	44.8	0.99	0.95	1.11	1.03

Peripheral artery is femoral in all cases. All ascending aortic (Ao) pressures and peripheral arterial (Art) pressures are simultaneous. LV = left ventricular; Retro = retrograde sequential left ventricular pressure; TS = transseptal simultaneous left ventricular pressure.

Catheterization technique. In six patients, all three pressures were recorded simultaneously (Fig. 1): the left ventricle using an 8 French Teflon Brockenbrough transseptal catheter, the ascending aorta using a 7 French polyurethane pigtail catheter and the femoral artery using the side arm of the 8 French sheath (Cordis, Inc.) through which the pigtail was passed. In the remaining 20 patients, left ventricular pressure was recorded using a 7 French pigtail catheter, either immediately after or before the recording of simultaneous ascending aortic pressure via the same pigtail catheter and femoral artery pressure via the side arm of an 8 French sheath through which the pigtail catheter was passed. For gradient analysis, the simultaneous ascending aortic and femoral artery tracings were superimposed on left ventricular pressure recordings by lining up respective QRS complexes (Fig. 3).

All pressures were measured using fluid-filled systems and Statham P23-ID pressure transducers that were balanced against a mercury standard weekly. All air bubbles were carefully purged from the system to produce optimal frequency response and damping characteristics. Pressure signals were amplified and recorded by an Electronics for Medicine model VR 12 physiologic recorder. The mean natural frequency of damped spontaneous oscillations in the left ventricular tracings of 23 patients in whom this measurement was possible was 34 hertz (range 14 to 50). The frequency response of the sheath was more difficult to estimate because of the absence of spontaneous oscillations. However, in two patients tested specifically for this, the mean natural frequency of damped oscillations from the sheath was 20 hertz. More important, the pressure tracings from the pigtail catheter were virtually superimposed on those of the sheath when the pigtail tip was pulled back to the level of the femoral artery.

If simultaneously displayed electronic mean pressures from the ascending aorta and femoral artery were not identical (superimposed tracings on monitor screen, Fig. 1 and 2), the two channels were electronically recalibrated. If a discrepancy still existed, the transducers were reversed. If reversing transducers also reversed the pressure difference or if femoral artery mean pressure was greater than ascending aortic mean pressure, balance was considered inexact and the patient was excluded. If the direction and magnitude of the gradient remained the same after reversing transducers, balance was considered exact and the difference was attributed to a true ascending aortic-femoral artery gradient.

Data analysis. Mean gradients were measured by hand planimetry technique (7). Oscillating catheter artifacts were tracked by the planimeter as a means of geometric smoothing. The following measurements were made for each patient: "true" left ventricular-ascending aortic mean gradient from simultaneous or QRS-synchronized tracings (Fig. 3A), "unaltered" left ventricular-femoral artery gradient from simultaneous or QRS-synchronized tracings (Fig. 3B) and "aligned" left ventricular-femoral artery gradient from tracings in which the peripheral arterial pressure was advanced in time so that its upstroke corresponded with that of the left ventricular tracing (Fig. 3C). Finally, aortic valve areas were calculated from each of the three tracings by substituting the appropriate gradients, systolic ejection periods,

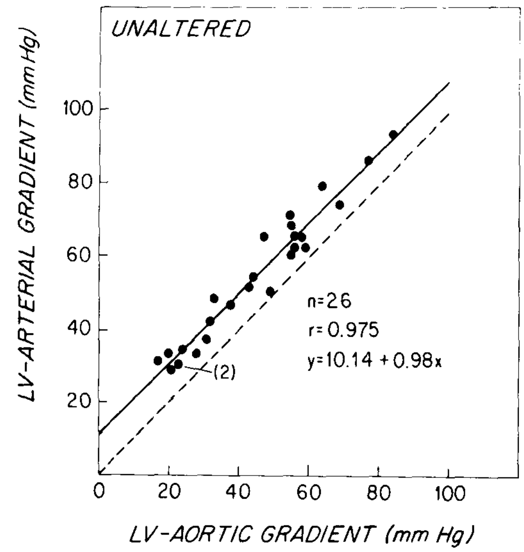
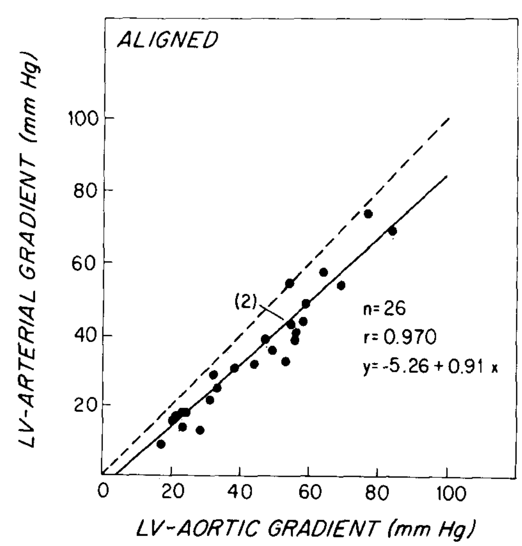


Figure 4. Comparison of mean gradients from left ventricular (LV)-ascending aortic and unaltered left ventricular-femoral artery pressures in 26 patients. Unaltered left ventricular-arterial gradients overestimate the true mean left ventricular-aortic gradient by 9 mm Hg (range +1 to +18).

Figure 5. Comparison of mean gradients from left ventricular (LV)-ascending aortic and aligned left ventricular-femoral artery pressures in 26 patients. Aligned left ventricular-arterial gradients underestimate the true mean left ventricular-aortic gradient by 10 mm Hg (range 0 to −17).



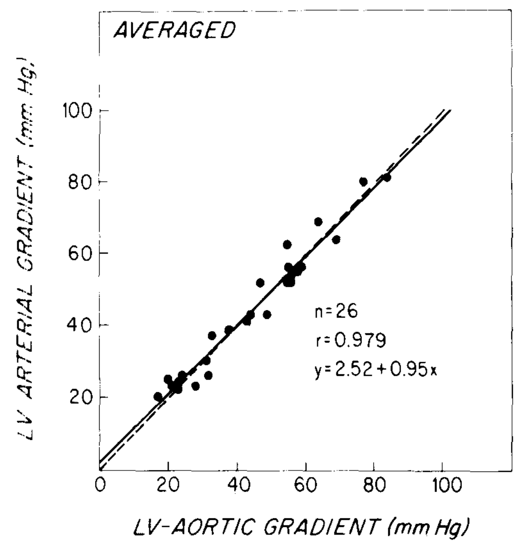


Figure 6. Comparison of mean gradients from left ventricular (LV)-ascending aortic and averaged unaltered and aligned left ventricular-femoral artery pressures in 26 patients. This method provides the most accurate estimation of true aortic valve gradient using the femoral artery pressure. The mean error is +0.1 mm Hg (range +8 to −6).

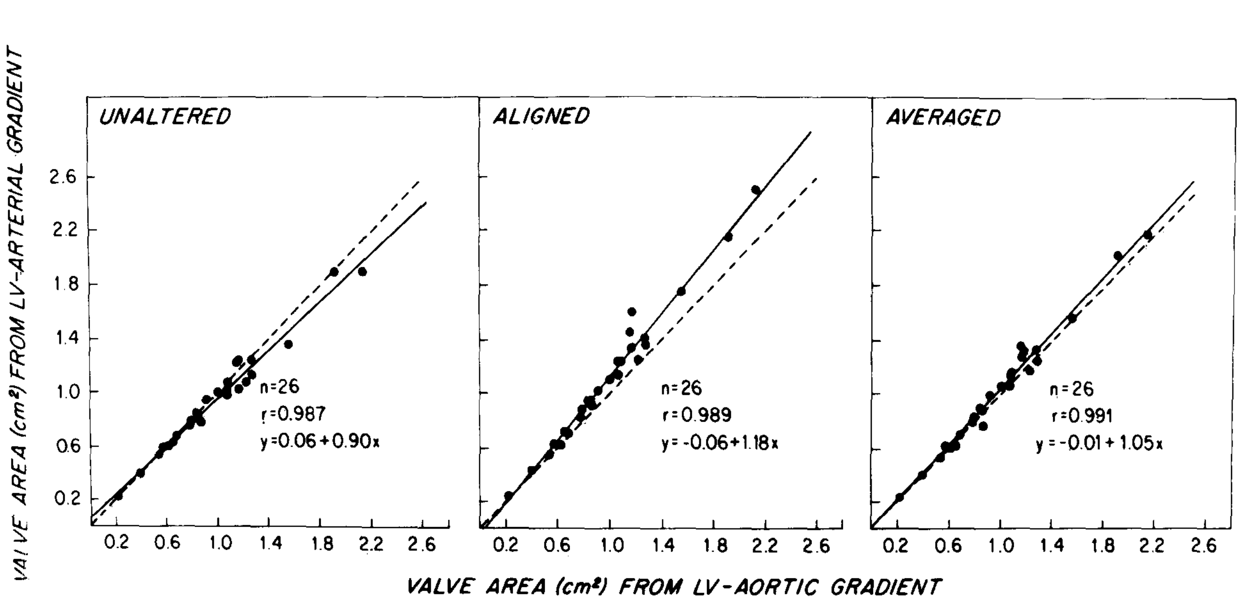
heart rates and cardiac outputs into the Gorlin aortic valve area formula (10). Fick or green dye output determinations were used in patients with isolated aortic stenosis and angiographic cardiac output determinations (11) were used when there was coexistant aortic regurgitation.

Results

Mean aortic valve gradients. Gradients and associated valve areas calculated by the three different methods are displayed in Table 1. Unaltered left ventricular-femoral artery gradients are plotted against corresponding true gradients in Figure 4, and aligned left ventricular femoral artery gradients are plotted against corresponding true gradients in Figure 5. In every patient, the gradient derived from unaltered left ventricular-femoral artery tracings *overestimated* the true left ventricular-ascending aorta gradient. The mean overestimation was 9 mm Hg (range +1 to +18). In every patient but one, the gradient derived from aligned left ventricular-femoral artery tracings *underestimated* the true left ventricular-ascending aortic gradient. The mean underesstimation was 10 mm Hg (range 0 to −17). The degree of error for both peripheral techniques was relatively constant throughout the range of absolute gradients (Fig. 4 and 5). Although the average true gradient (44.7 mm Hg) in all patients was closely approximated by averaging all unaltered and aligned gradients (44.8 mm Hg), the average of unaltered and aligned gradients in any one patient did not always agree exactly with the true gradient (Fig. 6). The variation ranged from +8 to −6 mm Hg.

Aortic valve areas (Fig. 7). As expected, calculated aortic valve area was underestimated using unaltered gradients and overestimated using aligned gradients. The degree of area error is relatively less than gradient error because the gradient error is reduced by a square root factor in the Gorlin formula. Surprisingly, the "true" aortic valve area was more closely approximated using the unaltered peripheral gradients (0.04 cm^2 underestimation) than the

Figure 7. Comparison of aortic valve areas calculated from left ventricular (LV)-ascending aortic gradients with areas calculated from unaltered left ventricular-femoral artery gradients (**left panel**), areas calculated from aligned left ventricular-femoral artery gradients (**middle panel**) and the average of unaltered and aligned areas (**right panel**). The average of unaltered and aligned areas approximates the true area most closely. Although the aligned method is probably most widely practiced, it is least accurate in predicting the true valve area. Regardless of which method is used, most of the error occurs in valve areas greater than 1.0 cm^2.



aligned gradients (0.12 cm^2 overestimation). The average of unaltered and aligned areas (0.04 cm^2 overestimation) predicted the true area better than the aligned technique, but did not improve the accuracy obtained by use of the unaltered technique alone.

Peripheral arterial gradients. The high prevalance of peripheral atherosclerosis in male veterans is demonstrated by the fact that 7 (21%) of 33 patients who were otherwise technically suitable for this study were excluded on the basis of peripheral obstruction as indicated by a peak femoral artery pressure less than peak ascending aortic pressure. Among excluded patients, the average mean ascending aorta to femoral artery gradient was 6.8 mm Hg (range 3.4 to 14). The mean aortic-femoral artery gradient among the 26 patients included in this study was 0.9 mm Hg.

Discussion

Left ventricular-ascending aorta versus left ventricular-femoral artery gradient. This study demonstrates the systematic error of estimating mean left ventricular-ascending aortic pressure gradients from recordings of simultaneous left ventricular-femoral artery pressures. A similar degree of error in opposite directions occurs when these pressures are analyzed with or without compensation for temporal delay by alignment. The most accurate estimate of true left ventricular-ascending aortic gradient and its calculated valve area is obtained by averaging the gradients and areas obtained from unaltered and aligned simultaneous left ventricular-femoral artery pressure tracings.

The effect of this error on calculated valve area is relatively small whether the gradients are measured from unaltered or aligned pressure recordings. This error is especially small in the range of surgically significant aortic stenosis (valve area <0.8 cm^2). Interestingly, the least accurate method for estimating valve area (from aligned tracings) is also probably the most widely practiced.

Although we analyzed only data from patients in whom peripheral pressure was recorded from the femoral artery, there is ample evidence that the same kind of error influences tracings from the brachial artery. One patient excluded from our series because of a large femoral artery gradient was studied from the brachial route. The unaltered tracings overestimated and the aligned tracings underestimated the true aortic valve gradient. The work of Kroeker and Wood (3) suggests that the degree of error from the brachial site might be less than that from the femoral site because the degree of pulse distortion is less in the brachial artery. Pulse distortion (upstroke delay, systolic amplification and ejection time prolongation) increases in proportion to the distance from the ascending aorta (3,4).

Practical implications. In most instances, these errors are not large enough to affect clinical decision-making; however, they are potentially critical in research studies that require a high degree of accuracy. An important example is the postoperative evaluation of prosthetic aortic valves in which the degree of potential error in some patients might actually exceed the true gradient of the prosthesis. Other examples include serial studies assessing the progression of aortic stenosis and validation studies of noninvasive techniques in which cardiac catheterization is the reference standard. Our findings emphasize the importance of using simultaneous left ventricular-ascending aortic pressures whenever a high degree of accuracy is required. If the peripheral technique is employed, the calculated mean gradient should be an average of the unaltered and aligned left ventricular peripheral arterial gradients. Likewise, the aortic valve area should be an average of the areas calculated from unaltered and aligned tracings.

In addition, simultaneous ascending aortic and peripheral arterial pressures must always be recorded in such studies to avoid additional error from an abnormal peripheral arterial gradient, which was present in 21% of the technically suitable patients screened for this study. When such gradients are encountered (that is, when peak aortic pressure exceeds peak peripheral pressure), we recommend that pressure be recorded from another peripheral arterial site, from an ascending aortic catheter or after pullback across the aortic valve.

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References

1. Barry WH, Levin DC, Green LH, Bettman MA, Mudge GM Jr, Phillips D. Left heart catheterization and angiography via the percutaneous femoral approach using an arterial sheath. Cathet Cardiovasc Diagn 1979;5:401–9.
2. Folland ED, Kemper AJ, Bloomfield P, Parisi AF. Brachial artery catheterization employing a side arm sheath. Cathet Cardiovasc Diagn 1984;10:55–61.
3. Kroeker EJ, Wood EH. Comparison of simultaneously recorded central and peripheral arterial pressure pulses during rest, exercise and tilted position in man. Circ Res 1955;3:623–32.
4. Remington JW, Wood EH. Formation of peripheral pulse contour in man. J Appl Physiol 1956;9:433–42.
5. Grossman W. Pressure measurement. In: Grossman W, ed. Cardiac Catheterization and Angiography. 2nd ed. Philadelphia: Lea & Febiger, 1980:111–2.
6. Yang SS, Bentivoglio LG, Maranhao V, Goldberg H. From Cardiac Catheterization Data to Hemodynamic Parameters. 2nd ed. Philadelphia: FA Davis, 1978;45–8.
7. Verel D, Grainger RG. Methods of measuring pressure. In: Verel D, Grainger RG, eds. Cardiac Catheterization and Angiography. 3rd ed. New York: Churchill Livingstone, 1978:12–3.
8. Saksena FB. Aortic stenosis. In: Saksena FB, ed. Hemodynamics in Cardiology. New York: Praeger, 1983:269–70.
9. Murray JA, ed. Handbook of Cardiac Catheterization. 3rd ed. Seattle: University of Washington Affiliated Hospitals, 1973;21-1.
10. Gorlin R, Gorlin G. Hydraulic formula for calculation of area of stenotic mitral valve, other cardiac valves and central circulatory shunts. Am Heart J 1951;41:1–29.
11. Sandler H, Dodge HT, May RE, Rackley CE. Quantitation of valvular insufficiency in man by angiography. Am Heart J 1963;65:501–13.