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New Mathematical Models to Estimate Aortic Valve Area by Echocardiography

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AORT KAPAK ALANININ EKOKARDİYOGRAFİ İLE ÖLÇÜMÜ İÇİN YENİ MATEMATİK MODELLER

ÖZET

Amaç: Aort stenozunun değerlendirilmesinde, invazif olmayan yöntemlerden ekokardiyografi ile ilgili bir çok parametre kullanılması önerilmiştir. Bu prospektif çalışmanın amacı, Gorlin formülü yardımı ile kalp kateterizasyonu sırasında ölçülen aort kapak alanını (AVA), Doppler hız indeksi (DVI), fraksiyonel kısalma hız oranı (FSVR) ve sol ventrikül ejeksiyon zaman farkı (LVETD) adlı parametreleri kullanarak belirlemeye çalışmaktır.

Metod ve Bulgular: Yukardaki parametrelerin hesaplanmadığı veya kalp kateterizasyonu sırasında aort kapağın geçilemediği hastalar çalışmadan çıkarılmıştır. Aort stenozu şüphesi ile hastaneye yatırılan kırküç hasta (8 kadın ortalama yaş 63±13 sene) çalışmaya alınmıştır. Tüm hastalardaki parametreler, kateterizasyon sonuçlarından haberi olmayan tek bir ekokardiyograf tarafından hesaplanmıştır. Her parametre için, lineer veya mültipl lineer regresyon analizleri yapılmıştır:

AVA= 1.81 [DVI] + 0.06 (PDVI < 0.00001); 0.45 [FSVR] + 0.19 (PFSVR < 0.00001); 0.81 [LVETD] + 0.46 (PLEVTD = 0.02); 0.84 [DVI] + 0.30 [FSVR] + 0.098 (PVDI = 0.08; PFSVR = 0.009); 1.67 [DVI] - 0.33 [LVETD] + 0.10 (PDVI = 0.001; PLVETD = 0.28); 0.42 [FSVR] - 0.47 [LVETD] + 0.23 (PFSVR < 0.00001; PLVETD = 0.08); 0.65 [DVI] + 0.31 [FSVR] - 0.37 [LVETD] + 0.15 (PDVI = 0.19; PFSVR = 0.007; PLVETD = 0.19).

Sonuç: Bu çalışma, Gorlin formülü yardımı ile kalp kateterizasyonu sırasında ölçülen aort kapak alanını hesaplamada, Doppler hız indeksi (DVI) ve/veya fraksiyonel kısalma hız oranını (FSVR) tek başlarına, veya sol ventrikül ejeksiyon zaman farkı (LVETD) ile kombine olarak, çok iyi derecede bir korelasyona sahip olduklarını göstermiştir.

Anahtar kelimeler: *Aort stenozu, Doppler hız indeksi, fraksiyonel kısalma hız oranı, sol ventrikül ejeksiyon zaman farkı, ekokardiyografi.*

Significant advances have been made in echocardiography in the past decades. In most patients with aortic stenosis, the degree of obstruction to outflow can be reliably determined by Doppler echocardiography. Thus echocardiography has become a powerful noninvasive method with the ability to provide both anatomic and hemodynamic information in aortic stenosis (1). Doppler echocardiographic methods based on the continuity equation can accurately determine aortic valve area (AVA) in patients with clinically significant aortic stenosis (2-4). Despite the current widespread acceptance of this equation, this method has some limitations in the calculation of AVA. Several previous studies have suggested that simpler descriptors of aortic stenosis severity - including Doppler velocity index (DVI) (5-7), fractional shortening-velocity ratio (FSVR) (8-10), left ventricle ejection time difference (LVETD) (11, 12) - may be as useful in clinical decision-making as continuity equation derived valve areas.

The aim of this prospective study was, using the above-mentioned parameters, to predict the aortic valve area values estimated by the Gorlin formula from the hemodynamic data obtained during cardiac catheterization.

PATIENTS and METHODS

Patient population

Forty-nine consecutive patients who underwent cardiac catheterization and Doppler echocardiographic studies for suspected aortic stenosis were analyzed. Six patients were excluded: two because the aortic valve could not be passed through during cardiac catheterization, and four because of failure in obtaining echocardiographic and Doppler measurements. Of the remaining 43 patients, 8 were women and 35 were men, with a mean age of 63 ± 13 years. 36 patients were in sinus rhythm and 7 patients in atrial fibrillation.

Cardiac catheterization

Cardiac catheterization was performed via femoral access, and the aortic valve was crossed with a soft guide wire. The cardiac output was estimated by means of the thermo-

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dilution method. Simultaneous left ventricular and femoral artery pressures were registred, and the slow pull-back from the left ventricle to the ascending aorta was performed at the end of the procedure. The aortic valve area was calculated automatically by means of the Gorlin formula that is incorporated in the software of the Micor (Siemens-Elema, Solna, Sweden) hemodynamics system.

Echocardiography

All patients were examined with echocardiography within 2 days of the catheterization.

M-mode and two-dimensional echocardiographic measurements

Two-dimensional echocardiographic studies were performed in the left lateral decubitus position using a Hewlett-Packard Sonos 1000 (Hewlett-Packard, Andover, MA) equipped with 2.5- or 3.5-MHz probes for imaging, a 2.5-MHz probe for pulsed Doppler echocardiography, and a 1.9-MHz stand-alone probe for continuous wave Doppler echocardiography. Studies were recorded on 0.5-inch videotape (Panasonic 750 D) for storage and review.

All M-mode studies were performed according to the American Society of Echocardiography guidelines [13].

The aortic annular diameter was measured in the parasternal long-axis view as previously described [14], using the intercostal space from which the clearest image of these structures was obtained. Measurements were repeated three times for each patient, and an average value was obtained.

Doppler measurements

Pulsed Doppler studies were performed using the same above-mentioned imaging systems, which are equipped with movable cursors and adjustable sample volume sizes. Blood flow velocity in the left ventricular outflow tract (LVOT) was recorded from the apical window: the sample volume was placed into the aortic valve, and gradually moved apically (approximately 0.5-1 cm upstream from the valve) until a clear spectral display was obtained (15, 16). All velocities were recorded at 100 mm/s, and the area under the velocity curve or time velocity integral was derived by digitizing the external contour of the darkest portion of the curves. These curves were used to derive LVOT time-velocity integral and maximal flow velocity (V_{LVOT}) (m/s)

Continuous wave Doppler recordings of the jet velocity through the aortic valve were made using a 1.9-MHz non-imaging transducer equipped with audio and spectral displays. In each patient, recording of the jet velocity was attempted from multiple windows, including the apical, right parasternal, suprasternal, and subcostal windows. Cardiac cycles with the highest peak velocities were selected for calculations. The spectral display was digitized along its outer border from which the following measures were obtained: maximal aortic jet velocity (V_{AS}) (m/sec), maximal gradient (G max.) (mmHg) derived using the simplified Bernoulli equation as $4(V^2_{AS} - V^2_{LVOT})$ [17], mean gradient (G mean) (mmHg), and velocity-time integral (cm).

An average of three cardiac cycles was used for patients in sinus rhythm, whereas an average of six cardiac cycles was used for patients in atrial fibrillation for the measurements of all parameters. All echocardiographic and Doppler measurements were performed by the same physician, without knowledge of the results of cardiac catheterization data.

Doppler velocity index (DVI)

Rearranging the continuity equation and applying the simplified peak velocity method [15, 17], the Doppler velocity index (DVI) was obtained by dividing the maximal left ventricular outflow tract velocity (V_{LVOT}) by the maximal aortic jet velocity (V_{AS}):

$$DVI = V_{LVOT} / VAS$$

Fractional shortening-velocity ratio (FSVR)

Fractional shortening-velocity ratio was obtained by dividing the extent of left ventricular fractional shortening (%FS, calculated as the difference between end-diastolic and end-systolic dimensions, divided by end-diastolic dimension of left ventricle at the midventricular level) by the Doppler derived pressure gradient accross the valve ($4V^2$, where V is the peak instantenous Doppler-derived flow velocity across the aortic valve):

$$FSVR = \%FS / 4V^2$$

Left ventricle ejection time difference (LVETD)

Left ventricular ejection time was measured from the onset to the end of systolic flow by pulsed Doppler (from the apical window corresponding to the sample volume position at the aortic annulus). With the use of an equation previously derived by Harley et al. [18], a left ventricular ejection time (ET in seconds) was predicted from the Doppler-determined stroke volume (SV in milliliters) as: ET predicted = 0.002SV + 0.106.

The magnitude of prolongation of ET in relation to SV, called the "left ventricle ejection time difference (LVETD)", was defined as Doppler-measured ET (Dop. LVET) minus the predicted ET (pre. LVET):

$$LVETD = Dop.\ LVET - pre.\ LVET$$

Statistical methods

Simple and multiple linear regression analyses were used to predict the mathematical equations fitting the data obtained by cardiac catheterization and by echocardiography [19]. P-values less than 0.05 were considered significant.

RESULTS

Echocardiographic Doppler and cardiac catheterization data

In order to predict the aortic valve area (AVA) values estimated by cardiac catheterization, linear (simple or multiple) regression analysis was used for each parameter separetely, or combined (two or three). Using DVI alone (Fig. 1), we obtain AVA = 1.81[DVI] + 0.06; pDVI < 0.00001; and using FSVR alone (Fig. 2), we obtain AVA = 0.45[FSVR] + 0.19; pFSVR < 0.00001. When using LVETD alone (Fig. 3), we obtain AVA = 0.81[LVETD] + 0.46; pLVETD = 0.02. These results show that DVI or FSVR alone appears to be very significant factors predicting the AVA.

When using DVI and FSVR together (Fig. 4), we obtain AVA = 0.84[DVI] + 0.30[FSVR] + 0.098; pDVI = 0.08; pFSVR = 0.009; p whole-model < 0.00001) Despite the significance of each of these parameters in univariate analyses, FSVR alone remained significant in multivariate approach but not DVI.

However, when using DVI and LVETD together (Fig. 5), DVI appears to be significant (AVA = 1.67[DVI] - 0.33[LVETD] + 0.10; pDVI = 0.001; pLVETD = 0.28; p whole-model < 0.00001). FSVR

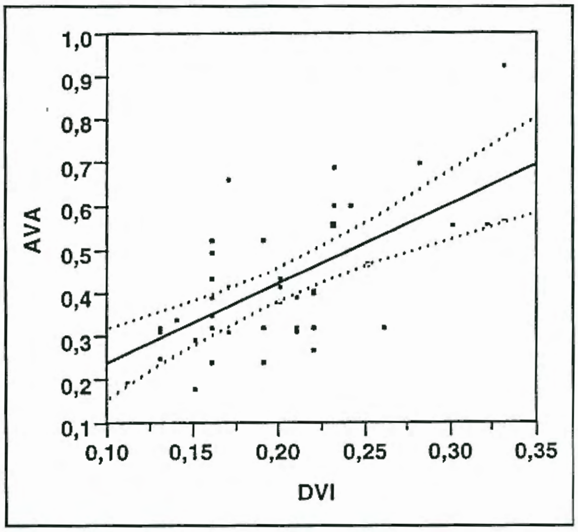

Figure 1. Correlation (r^2=0.40; p < 0.00001) between AVA index (aortic valve area, calculated by cardiac catheterization, cm^2/m^2) and DVI (Doppler velocity index). (straight line represents the "correlation", dashed line the "standard error")

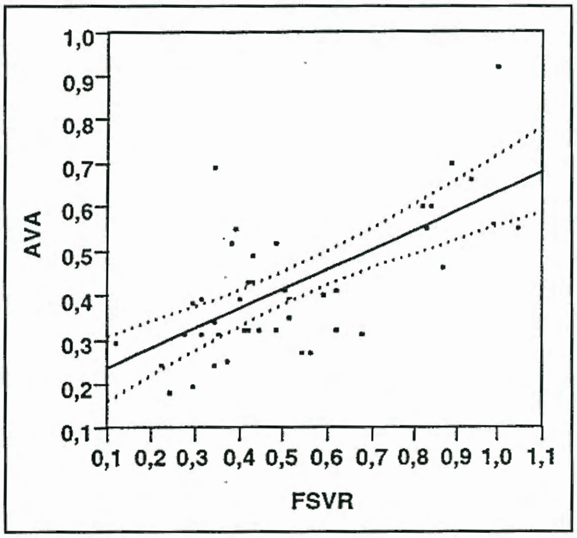

Figure 2. Correlation (r^2=0.46; p < 0.00001) between AVA index (aortic valve area, calculated by cardiac catheterization, cm^2/m^2) and FSVR (fractional shortening-velocity ratio). (straight line represents the "correlation", dashed line the "standard error")

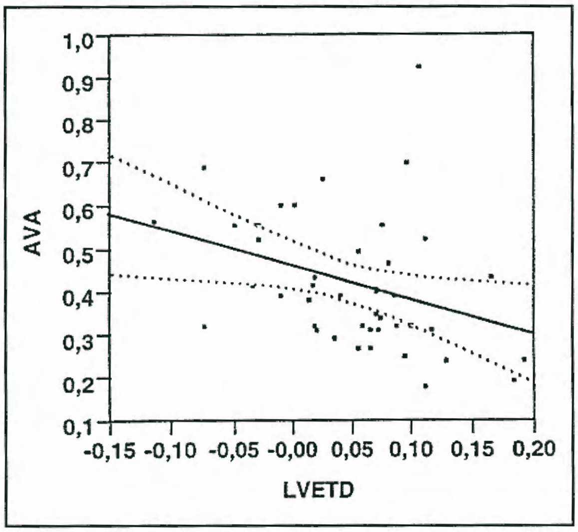

Figure 3. Correlation (r^2=0.12; p = 0.02) between AVA index (aortic valve area, calculated by cardiac catheterization, cm^2/m^2) and LVETD (left ventricular ejection time difference). (straight line represents the "correlation", dashed line the "standard error")

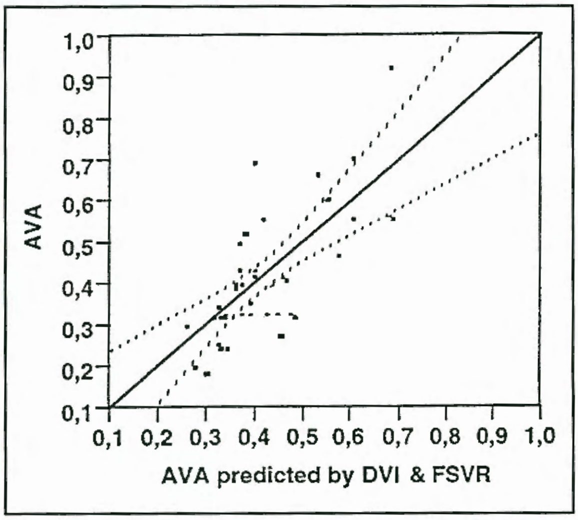

Figure 4. Correlation (r^2=0.50; p_{DVI} = 0.08; p_{FSVR} = 0.009; p whole-model < 0.00001) between AVA index (aortic valve area, calculated by cardiac catheterization, cm^2/m^2) and the predicted AVA by multiple linear regression analysis done using DVI (Doppler velocity index) and FSVR (fractional shortening-velocity ratio). (straight line represents the "correlation", dashed line the "standard error")

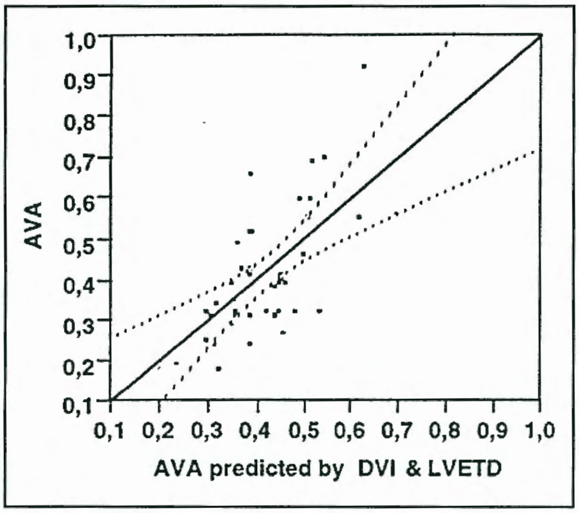

Figure 5. Correlation (r^2=0.42; p_{DVI} = 0.001; p_{LVETD} = 0.28; p whole-model < 0.00001) between AVA index (aortic valve area, calculated by cardiac catheterization, cm^2/m^2) and the predicted AVA by multiple linear regression analysis done using DVI (Doppler velocity index) and LVETD (left ventricular ejection time difference). (straight line represents the "correlation", dashed line the "standard error")

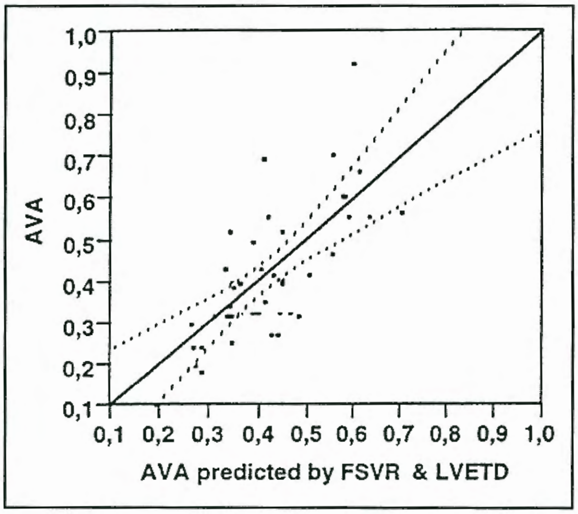

Figure 6. Correlation (r^2=0.50; p_{FSVR} < 0.00001; p_{LVETD} = 0.08; p whole-model < 0.00001) between AVA index (aortic valve area, calculated by cardiac catheterization, cm^2/m^2) and the predicted AVA by multiple linear regression analysis done using FSVR (fractional shortening-velocity ratio) and LVETD (left ventricular ejection time difference). (straight line represents the "correlation", dashed line the "standard error")

predicts again significantly the AVA when FSVR and LVETD values used together (Fig. 6): AVA = 0.42[FSVR] - 0.47 [LVETD] + 0.23; pFSVR < 0.00001; pLVETD = 0.08; p whole-model < 0.00001

Finally, when combining DVI, FSVR, and LVETD together (Fig. 7), we obtain AVA = 0.65[DVI] + 0.31[FSVR] - 0.37[LVETD] + 0.15; pDVI = 0.19; pFSVR = 0.007; pLVETD = 0.19; p whole-model < 0.00001; in this case, FSVR remains again significant.

For all the analyses done, except for LVETD (r^2=0.12), there was a strong correlation between the predicted AVA (DVI, r^2=0.40; FSVR, r^2=0.46; DVI&FSVR, r^2=0.50; DVI&LVETD, r^2=0.42; FSVR& LVETD, r^2=0.50) and AVA, calculated by cardiac catheterization. The best correlation (r^2=0.52) was obtained between the AVA predicted using three values together (DVI, FSVR, LVETD) and AVA calculated by cardiac catheterization.

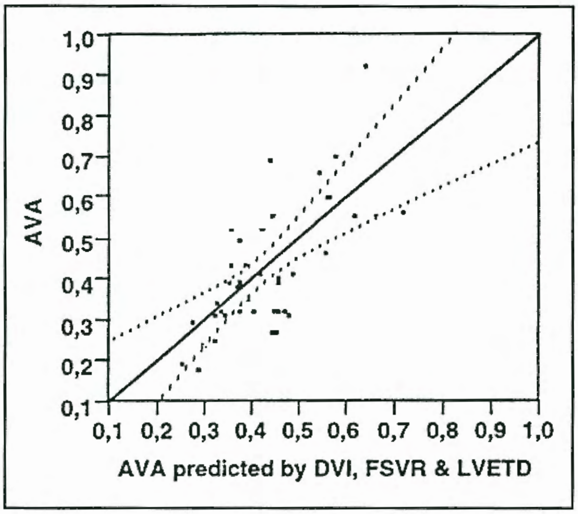

Figure 7. Correlation (r^2=0.52; p_{DVI} = 0.19; p_{FSVR} = 0.007; pLVETD = 0.19; p whole-model < 0.00001) between AVA index (aortic valve area, calculated by cardiac catheterization, cm^2/m^2) and the predicted AVA by multiple linear regression analysis done using DVI (Doppler velocity index), FSVR (fractional shortening-velocity ratio) and LVETD (left ventricular ejection time difference). (straight line represents the "correlation", dashed line the "standard error"

DISCUSSION

The diagnosis of hemodynamically significant aortic stenosis remains an important clinical problem. Doppler echocardiographic techniques now are accepted clinical methods for evaluation of aortic stenosis severity. The valve areas, determined by the continuity equation, have been well validated compared with the valve areas, obtained by the Gorlin formula, in patients with a wide range of stenosis severity [20-22]. Several previous studies have suggested that simpler descriptors of aortic stenosis severity may be as useful in clinical decision-making as continuity equation valve areas [5-12].

In this study, we tested several ultrasound methods for predicting the aortic valve area values obtained during cardiac catheterization using the Gorlin formula. To our knowledge, there are no similar studies trying to predict the AVA with nonivasive echographic parameters, i.e., DVI, FSVR, and LVETD.

Doppler velocity index (DVI)

The outflow tract diameter, necessary for calculation of aortic valve area by the continuity equation, is the most difficult variable to measure especially in patients in whom the parasternal image is suboptimal [15,23]. In this circumstance, DVI should be applied: changes in hemodynamic status affect velocities across the left ventricular outflow tract and the aortic valve proportionately, so that their velocity ratio remains essentially unchanged. In fact, this ratio alone appears to be a very sensitive and specific index in the detection of significant aortic stenosis [5,7]. The results of the present study shows that this index may be helpful in predicting the aortic valve area. The prediction of AVA using DVI alone as well as combined to other parameters appears to be very significant.

Fractional shortening-velocity ratio (FSVR)

The FSVR was derived empirically [24]. It incorporates an index of systolic left ventricle function in the numerator and an index of the transvalvular pressure gradient in the denominator. Therefore, this ratio should compensate for patients in whom pathologic flow states might result in "misleading" transvalvular pressure gradients [8]. The previous studies showed that FSVR is a sensitive and accurate index for identifying patients with clinically significant aortic stenosis [8-10]. In our study, like DVI, this index predicts AVA efficiently alone or combined to the other used parameters.

Left ventricle ejection time difference (LVETD)

A significant correlation between aortic valve area by the Gorlin formula and the magnitude of ejection time prolongation in relation to stroke volume was demonstrated by Bache et al. using cardiac catheterization [25]. In their study, using Doppler echocardiography, Zoghbi et al. confirm that the high impedance to ejection imposed by a stenotic aortic valve area produces a prolongation of ejection time relative to stroke volume and distorts the normal relation between these two parameters [11]. The major advantage of this parameter is that it does not require measurement of the stenotic jet velocity. For this reason, this index is particularly valuable in instances where interrogation of the stenotic jet by continuous wave Doppler is not feasible or in cases where the adequacy of recording of aortic jet velocity is in doubt. The previous studies showed that LVETD is a sensitive index for detection of critical aortic stenosis [11, 12]. In the present study, the value of this index alone to predict the aortic valve area did not appear to be powerful.

Ideally, to estimate the AVA, it is recommended to use the three echocardiographic parameters all together, i.e., DVI, FSVR and LVETD. However, in daily practice when all of the parameters together are not feasible, DVI or FSVR alone will also predicts efficiently the AVA.

Conclusion

This prospective study concludes that the Doppler velocity index (DVI) and/or the fractional shortening velocity ratio (FSVR), is strongly correlated with the aortic valve area estimated during cardiac catheterization using the Gorlin formula.

In cases where the continuity equation cannot be used, the above-mentioned parameters would be suitable to predict the aortic valve area (AVA). A larger scale studies are needed to confirm these results.

REFERENCES

1. **Nishimura RA, Tajik J:** Quantitative hemodynamics by Doppler echocardiography: a noninvasive alternative to cardiac catheterization. Prog Cardiovasc Dis 1994; 4: 309-42

2. **Zhang Y, Myhre E, Nitter-Hauge S:** Noninvasive quantification of the aortic valve area in aortic stenosis by Doppler echocardiography. Eur Heart J 1985, 6: 992-8

3. **Richards KL, Cannon SR, Miller JF, Crawford MH:** Calculation of aortic valve area by Doppler echocardiography: a direct application of the continuity equation. Circulation 1986, 73: 964-9

4. **Carabello BA, Crawford FA:** Valvular heart disease. N Engl J Med 1997, 1: 32-41

5. Otto CM, Pearlman AS, Comess KA, Reamer R, Janko C: Determination of the stenotic aortic valve area in adults using Doppler echocardiography. J Am Coll Cardiol 1986; 7: 509-17

6. Oh JK, Taliercio CP, Holmes DR et al: Prediction of the severity of aortic stenosis by Doppler aortic valve area determination: prospective Doppler catheterization correlation in 100 patients. J Am Coll Cardiol 1988; 11: 1227-34

7. Karpuz H, Aebischer N, Jeanrenaud X, Eeckhout E, Debbas N, Goy JJ, Kappenberger L: Doppler velocity index as a marker of aortic stenosis severity: a prospective evaluation. Eur Heart J 1995; 16 (Abstract Suppl): 173

8. Mann DL, Usher BW, Hammerman S, Bell A, Gillam LD: The fractional shortening-velocity ratio: validation of a new echocardiographic Doppler method for identifying patients with significant aortic stenosis. J Am Coll Cardiol 1990; 15: 1578-84

9. Otto CM, Nishimura RA, Davis KB et al: Doppler echocardiographic findings in adults with severe symptomatic valvular aortic stenosis. Am J Cardiol 1991; 68: 1447-84

10. Karpuz H, Aebischer N, Jeanrenaud X, Debbas N, Eeckhout E, Goy JJ, Kappenberger L: Fractional shortening-velocity ratio as a marker of aortic stenosis severity: a prospective evaluation. Eur Heart J 1995; 16 (Abstract Suppl): 239

11. Zoghbi WA, Galan A, Quinones MA: Accurate assessment of aortic stenosis severity by Doppler echocardiography independent of aortic jet velocity. Am Heart J 1988; 3: 855-63

12. Karpuz H, Jeanrenaud X, Aebischer N, Debbas N, Goy JJ, Kappenberger L: Can "left ventricular ejection time" still be used as a marker of critical aortic stenosis? J Am Coll Cardiol 1997; 29 (Abstract Suppl): 518A

13. Gardin JM, Henry WL, Savage DD, Ware JH, Burn C, Borer JS: Echocardiographic measurements in normal subjects: evaluation of an adult population without clinically apparent heart disease. J Clin Ultrasound 1979; 7: 439-45

14. Lewis JF, Kuo LC, Nelson JG, Limacher MC, Quinones MA: Pulsed Doppler echocardiographic determination of stroke volume and cardiac output: clinical validation of two news methods using the apical window. Circulation 1984; 70: 425

15. Zoghbi WA, Farmer KL, Soto JG, Nelson JG, Quinones MA: Accurate noninvasive quantification of stenotic aortic valve area by Doppler echocardiography. Circulation 1986; 73: 452-92

16. Skjaerbe T, Hegranes L, Hatle L: Noninvasive estimation of valve area in patients with aortic stenosis by Doppler ultrasound and two dimensional echocardiography. Circulation 1985; 72: 810-8

17. Otto CM, Pearlman AS: Doppler echocardiography in adults with symptomatic aortic stenosis. Arch Intern Med 1988; 148: 2553-60

18. Harley A, Starmer CF, Greenfield JC Jr: Pressure-flow studies in man: an evaluation of the duration of the phases of systole. J Clin Invest 1969; 48: 895-905

19. Simple regression and curve fitting. In: JMP Statistics and Graphics Guide. SAS Institute Inc., Cary, NC, USA, 1995. pp 43-64

20. Hatle L, Angelsen BA, Tromsdal A: Non-invasive assessment of aortic stenosis by Doppler ultrasound. Br Heart J 1980; 43: 284-92

21. Currie PJ, Seward JB, Reeder GS et al: Continuous-wave Doppler echocardiographic assessment of severity of calcific aortic stenosis: a simultaneous Doppler-catheter correlative study in 100 adult patients. Circulation 1985, 71:1162-9

22. Teirstein P, Yeager M, Yock PG, Popp RL: Doppler echocardiographic measurement of aortic valve area in aortic stenosis: a noninvasive application of the Gorlin formula. J Am Coll Cardiol 1986; 5: 1059-65

23. Otto CM, Pearlman AS, Gardner CL: Hemodynamic progression of aortic stenosis in adults assessed by Doppler echocardiography. J Am Coll Cardiol 1989, 13:545-50

24. Gorlin R, Gorlin SG: Hydraulic formula for calculation of the area of the stenotic mitral valve, other cardiac valves, and central circulatory shunts. Am Heart J 1951; 41-29

25. Bache RJ, Wang Y, Greenfield JC Jr: Left ventricular ejection time in valvular aortic stenosis. Circulation 1973; 47:52-63