Mechanism of Early Systolic Closure of the Aortic Valve in Discrete Membranous Subaortic Stenosis

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SUMMARY The mechanism of the apparent early closure of the aortic valve in patients with discrete membranous subaortic stenosis was studied. Discrete membranous subaortic stenosis was simulated in vitro to assess the fluid dynamic characteristics in the region of the aortic valve that may be responsible for the early closure. In the presence of a simulated fixed membranous subaortic obstruction, early systolic closure of the aortic valve was observed on high-speed motion pictures. Opening and early closure of the valve involved only one of the three aortic leaflets. Closure of the open leaflet was associated with the development of a pronounced pressure drop across the open leaflet caused by a large decrease of pressure in the main stream of flow relative to the pressure in the sinus of Valsalva. The pressure decrease in the main stream of flow resulted from a loss of pressure energy caused by an increase in the kinetic energy of the fluid caused by turbulence. Early systolic closure of the aortic valve in discrete membranous subaortic stenosis, therefore, results from the development of a pressure drop across the open leaflet caused by fluid dynamic factors related to the development of turbulent blood flow distal to the subvalvular obstruction.

ECHOCARDIOGRAPHIC evidence of early systolic closure of the aortic valve has been described in patients with discrete membranous subaortic stenosis.1-8 The mechanism of the early systolic closure of the aortic valve is not clearly understood.8 Davis et al. suggested that the premature closure of the aortic valve might be explained by alterations of aortic flow during systole.1 The occurrence of a jet of turbulent blood flow distal to the fixed obstruction was also postulated in a nonspecific manner to affect the abnormal motion of the aortic valve in patients with discrete subvalvular stenosis.1-8.7 A direct relation, however, between the occurrence of turbulent blood flow and the early closure of the aortic valve, to our knowledge, has not been shown.

We recently postulated a mechanism by which turbulent blood flow may be directly implicated in causing the midsystolic closure of the aortic valve in patients with hypertrophic obstructive cardiomyopathy.8 The postulate was based, in part, upon the observation in patients of a midsystolic decrease in pressure in the left ventricular outflow tract distal to the obstruction and above the aortic valve.8.9 The midsystolic pressure decrease was suggested to result from a loss of pressure energy caused by an increase in kinetic energy of the fluid caused by turbulence.8 Such a mechanism might apply to discrete membranous subaortic stenosis as well. The purpose of this study was to simulate discrete membranous subaortic stenosis in vitro to assess the fluid dynamic characteristics responsible for the early systolic closure of the aortic valve.

Methods

Discrete membranous subaortic stenosis was simulated in vitro in a modified pulse-duplicating system. The basic components of the system, except for modified aortic, ventricular and mitral test sections, have been described in detail.10,11 The ventricular chamber consisted of an opaque elastic sac molded from rubber in the shape of a left ventricle and enclosed in a fluid-filled chamber. The latter was attached through a thick-walled rubber tube to a pulsatile pump. The dimensions of the ventricular sac were based on measurements of ventriculograms of patients obtained during diagnostic cardiac catheterization. Ventricular ejection was produced by a pulsatile pump, which drove an amount of fluid equivalent to the stroke volume into the fluid-filled chamber in which the ventricle was enclosed. This action resulted in the reduction of the volume of the ventricle and the opening of the aortic valve. Tests of this system in our laboratory showed that the ventricle does not collapse during ejection, but rather undergoes a symmetrical reduction of its dimensions. In this respect, the action was similar to that of the human left ventricle during ejection.

The mitral chamber consisted of a straight acrylic section with a diameter of 3.8 cm. The aortic section consisted of an acrylic mold of the aortic root of a calf, including the sinuses of Valsalva. The diameter of the aortic section was 2.9 cm. The diameter at the level of the sinuses of Valsalva was 3.8 cm. The dimensions of the mold of the aortic root were within the range measured by others in human subjects.12 The left ventricular and mitral chambers were designed to specification from clear acrylic Plexiglas (Design West). The fluid used in the system was a mixture of glycerin and saline with a viscosity of 0.04 poise at room temperature. This viscosity is equivalent to that of normal blood at 37°C.

To simulate discrete membranous subaortic stenosis, a 1.5-mm-thick rubber membrane with a centrally located 0.5-cm² orifice was positioned 8 mm
below the aortic valve. The thickness and location of the membrane below the aortic valve was within the range observed in patients with discrete membranous subaortic stenosis. A stented porcine valve with a tissue annulus diameter of 29 mm (model 242, Hancock Laboratories) was used in the aortic position. A stented porcine valve with a tissue annulus diameter of 35 mm (model 342R, Hancock Laboratories) was used in the mitral position.

Studies were performed in the presence of simulated discrete membranous subaortic stenosis and were repeated in the absence of a membrane. Aortic flow was measured with a 19-mm-diameter cannulating electromagnetic flow transducer in conjunction with a model 501 square-wave electromagnetic flowmeter (Carolina Medical Electronics). The flow transducer was located distal to the aortic root section and was operated with a 30-Hz low-pass filter.

Pressures in the aorta and left ventricle were measured with #6F catheter-tip micromanometers (Millar Instruments). The catheter-tip micromanometer used to measure left ventricular pressure was introduced retrograde across the mitral valve and was positioned in the ventricular chamber proximal to the subaortic membrane. Pressures above the aortic valve were measured at two locations. The micromanometers were introduced through precisely drilled orifices in the wall of the aortic root section. One micromanometer was positioned in one of the sinuses of Valsalva between the aortic wall and a valve leaflet during systole. The second micromanometer was positioned near the center of the aortic section in the main stream of flow just distal to the valve (fig. 1). This permitted the measurement of pressure differences across the open leaflet. Because the pressure-sensing element on the Millar catheter is built on the lateral wall of the tip of the catheter, the tip of the catheter was rotated away from the on-coming flow to ensure the measurement of static rather than dynamic pressure. All of the pressure catheters were referenced to atmospheric pressure. In addition to pressure, sound was also measured in the aortic root. The sound was derived from the pressure signal using a Millar TCB-100 control unit. The gain of the sound signals was kept constant throughout the study. The frequency responses of the micromanometers in both the pressure and audio mode have been described in detail. In this study, pressures were recorded using a 25-Hz low-pass filter. Sounds were recorded using a 250-Hz low-pass filter.

Throughout the study, the stroke rate was maintained at 80–82 strokes/min. The stroke volume was 39 ml/stroke and the systolic ejection period was 0.32–0.33 second. Systolic aortic pressure was maintained at 105–107 mm Hg and diastolic aortic pressure at 76–80 mm Hg. All pressures and sound as well as aortic flow were recorded simultaneously on a VR-12 photographic recorder (Electronics for Medicine) at a paper speed of 500 mm/sec as well as at lower speeds.

Opening and closing of the aortic valve leaflets was photographed en face using a 16-mm film at 100 frames/sec with a Fastax camera (Redlake Corp.). Timing of the frames of the film with the analog record of the aortic pressure signal was achieved by using a model 628BX timing pulse generator (Visual Instrumentation Corp.). The generator was operated at a pulse rate of 100 pulses/min, which delivered a timing mark every 0.01 second to both the 16-mm film and the photographic recorder. To achieve optimal visualization of the valve during systole, the catheter-tip micromanometer, which had been in the centerline of flow in the aorta, was withdrawn.

Frame-by-frame analysis of the aortic valve area was accomplished with the aid of an analytic projector. The area of the orifice was traced from the projected image and calculated using an electronic digitizer (Numonics Corp.) on line with a 21MX computer (Hewlett Packard) and taking into account the magnification. Graphs of the time relation between the aortic valve orifice area and the pressures near the aortic valve were constructed.

Results
In the absence of the subaortic membrane, opening of the aortic valve, as expected, involved the opening of all three leaflets. A maximal valve area of 3.4 cm² was reached within 0.10 second after the onset of ejection. The effective valve orifice area began to decrease at approximately 0.24 second after the onset of ejection. The aortic valve was completely closed 0.01 second before the apex of the incisura of the central aortic pressure. During middle ejection, a 2-mm Hg pressure difference developed across the open leaflet. Sound on both sides of the leaflet showed no murmur at the preset gain that we used.

When the subvalvular membrane was inserted in the system, the valve did not open fully. A maximal valve area of only 0.39 cm² was reached rapidly within 0.04 second of the onset of ejection. Opening of the aortic

\[ P_{o} = P + \rho \frac{u^2}{2} \]

where \( P_{o} \) is the pressure outside the turbulent zone and \( P \) is the pressure within the turbulent zone, which equals \( P_{o} - \rho \frac{u^2}{2} \). \( \rho \) is the density of fluid and \( u \) is the fluctuating velocity.

**Figure 1.** Diagram of a turbulent jet distal to a subvalvular obstruction. The locations at which pressure was measured across the open aortic leaflet are shown. The magnitude of the pressure reduction within the turbulent zone can be calculated as \( P_{o} - P = \rho \frac{u^2}{2} \).
valve involved only one of three leaflets. The remaining two leaflets showed little motion. During this brief period, there was no detectable pressure difference across the open leaflet (figs. 2 and 3). Once opening of the aortic valve was maximal, the valve area was sharply reduced by early closing motion of the open cusp (fig. 2). The effective valve area decreased sharply, reaching 0.03 cm² near middle systole, and remained small until the end of systole (fig. 2). The sharp reduction in valve area was coincident with the development of a large pressure drop across the open leaflet (figs. 2 and 3). This pressure difference, which reached a maximum of approximately 40 mm Hg, resulted from the decrease of pressure in the stream of flow relative to the pressure measured within the sinus of Valsalva (figs. 2 and 3). The pressure difference gradually decreased during late systole and was no longer present 0.08 second before the apex of the incisura of the aortic pressure (figs. 2 and 3). The decrease of pressure in the stream of flow was coincident with the development of a loud ejection murmur that persisted nearly throughout the rest of ejection; in contrast, only a low-intensity murmur was recorded in the sinus of Valsalva (fig. 3).

Discussion

Early systolic closure of the aortic valve in the presence of a subvalvular membrane was coincident with the development of a pressure drop across the open aortic valve leaflet. The pressure drop across the leaflet during ejection can be explained on the basis of fluid dynamics. The decrease of pressure in the stream of flow resulted from turbulence generated distal to the subvalvular obstruction. A pronounced ejection murmur accompanied the pressure decrease. Such a murmur is a manifestation of turbulent flow.16 17 The development of turbulence resulted in increased kinetic energy of the fluid. Because energy is conserved, the increased kinetic energy due to turbulence occurred at the expense of a reduction of pressure.

![Figure 2](http://circ.ahajournals.org/)

**Figure 2.** Relation of the aortic valve orifice area and the pressure drop across the open leaflet in the presence of a subvalvular membrane. Closed circles indicate pressure measured in the sinus of Valsalva. Open circles indicate pressure in the stream of flow. The beginning of early closure coincided with the development of a pressure drop across the open leaflet. The dotted line on the curve representing aortic valve orifice area represents uncertainty as to the exact orifice area at that time. t₁ and t₂ represent the onset and end of ejection, respectively.

![Figure 3](http://circ.ahajournals.org/)

**Figure 3.** Aortic \(A_o\) flow, sound and pressure as well as left ventricular \((L\,V)\) pressure in the pulse-duplicating system in the presence of a subaortic membrane.
energy. This was manifested as a pressure decrease. Relatively low disturbances of flow in the sinus had little effect upon pressure in this region. The resultant difference of pressure across the open leaflet caused it to close partially.

The magnitude of the pressure reduction in a turbulent zone has been calculated as \( \rho u^2 \) where \( \rho \) is the density of blood and \( u \) represents the fluctuations of velocity due to turbulence\(^a, b\) (fig. 1). The term \( \rho u^2 \), which relates to the kinetic energy of the fluid, can be represented in terms of the root-mean-square value of the pressure fluctuations inherent to turbulent flow.\(^a\) These pressure fluctuations are reflected as both the murmur as well as the fluctuations of pressure superimposed on the pressure signal.

During the simulation of discrete membranous subaortic stenosis, only one of the three leaflets of the aortic valve opened and then closed prematurely, whereas the other two leaflets remained closed. Although the orifice of the subaortic membrane was centrally located, the point of coaptation of the three leaflets in the stented porcine aortic valve was eccentric. This resulted in the jet impacting the larger of the three cusps, which caused it to open while failing to open the others adequately. Opening and closure of a single leaflet has been observed in patients.\(^7\) In these patients, it was thought that the stream originating from the subaortic membrane was directed toward that leaflet, causing it to open but failing to open the other leaflets adequately.\(^7\)

Davis et al.\(^1\) suggested that early systolic closure of the aortic valve in discrete subaortic stenosis can be explained by an alteration of aortic flow. Initial rapid flow was thought to produce some opening of the leaflets, followed by a diminution of aortic flow that results from a decrease in the size of the ventricular cavity and possibly from an increase in the actual amount of obstruction.\(^1\) The latter was postulated to result in the premature closure of the valve. In our simulation of discrete membranous subaortic stenosis, we did not observe sharp changes in the aortic flow signal. The contour of the analog signal was relatively smooth, and there was no indication of a reduction in the magnitude of flow during the early closure of the aortic leaflet.

Although the term early closure of the aortic valve is used to describe the echocardiographic appearance of the excursion of the aortic leaflet during systole in patients with subaortic stenosis, it seems that complete coaptation of the valve does not occur until just before the apex of the incisura of the central aortic pressure. The effective valve area, although markedly reduced by the premature closing action of the leaflet, was sufficient to allow continuing aortic flow through most of systole.

In conclusion, observations in this study suggest that early systolic closure of the aortic valve in discrete membranous subaortic stenosis is directly related to the development of a pressure drop across the open leaflet between the sinus of Valsalva and the stream of flow. The pressure decrease in the stream of flow appears to result from the development of turbulent blood flow generated distal to the obstruction.

References

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Circulation. 1982;65:399-402
doi: 10.1161/01.CIR.65.2.399

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1982 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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