Identification of Coronary Artery Stenoses and Poststenotic Blood Flow Patterns Using a Miniature High-Frequency Epicardial Transducer

Antoinette Kenny, MRCP; Leonard M. Shapiro, MD, FACC

Background  Intraoperative epicardial coronary Doppler ultrasound has the potential to provide anatomic and functional information. This technique has been hindered by the large size of standard transducers, but a miniature transducer is available that may fulfill the potential of coronary ultrasound.

Methods and Results  Twenty consecutive patients who were undergoing coronary artery bypass grafting were studied and compared with 9 control patients with normal coronary arteries who were undergoing routine mitral valve surgery. A miniature 6.5-MHz transducer was used to image coronary arteries and measure coronary blood flow velocities. Seventeen proximal left anterior descending and 3 right coronary artery stenoses were studied. As defined by coronary angiography (1 to 34 days before surgery), there were 13 severe stenoses (>70%), 4 moderate stenoses (40% to 70%), 2 minor stenoses (<40%), and 1 subtotal occlusion. Stenoses were readily identified by ultrasound. Color flow mapping demonstrated laminar flow in normal arteries and nonlaminar flow across moderate and severe stenoses. In the control patients with unobstructed arteries, peak and mean diastolic velocities were 35±2.1 and 26±1.9 cm/s with peak and mean systolic velocities of 16±1.4 and 11±0.8 cm/s, respectively. Prestenotic flow velocities were not significantly different from normal control values, but a wide range of poststenotic flow disturbances were detected. Analysis of the 20 study patients did not reveal significant differences in poststenotic compared with prestenotic flow. A subgroup analysis of 12 patients with severe left anterior descending coronary artery stenoses was performed, and reversed poststenotic systolic flow was seen in 9. Prestenotic peak and mean systolic velocities were 16.5±1.7 and 11.9±1.1 cm/s, respectively, and were significantly altered downstream of the stenoses at -22.7±17.2 and -15.9±10.9 cm/s (P<.05 and P<.01, respectively). Reversed systolic flow was seen only distal to severe left anterior descending coronary artery stenoses and did not correlate with retrograde collateral filling as determined by preoperative coronary angiography. Moderate stenoses appeared to increase both systolic and diastolic components of poststenotic flow.

Conclusions  Epicardial Doppler ultrasound with a miniature transducer identifies coronary stenoses and associated blood flow disturbances. Compared with moderate lesions, severe stenoses demonstrated different poststenotic flow patterns. Intraoperative use of this technique may determine the hemodynamic significance of coronary stenoses. (Circulation. 1994;89:731-739.)

Key Words  • echocardiography, Doppler • flow • stenoses

Coronary angiography is the standard method of evaluating coronary artery disease, but it does not provide information on coronary blood flow, which may predict the physiological significance of a stenosis better than anatomic measurement. High-frequency ultrasound and Doppler techniques provide accurate and reliable morphological and physiological information in carotid and femoral arteries. Extension of these techniques to the study of coronary arteries using epicardial ultrasound may provide information on the hemodynamic significance of stenoses, especially angiographic lesions of intermediate severity.

The accuracy of high-frequency epicardial ultrasound in detecting atherosclerosis and measuring coronary artery luminal diameter and wall dimensions has been validated in vitro and in animal models. The use of high-frequency epicardial ultrasound in open-chest patients undergoing coronary artery bypass grafting has demonstrated diffuse coronary artery atherosclerosis unsuspected by angiography. Development of this technique to provide physiological in addition to morphological information during cardiac surgery has been limited by the large size of standard transducers. A new miniature high-frequency epicardial transducer is available that overcomes the problems of restricted access and should allow combined coronary imaging and blood flow measurement. In the present study, we use this technique to identify coronary artery stenoses and characterize poststenotic blood flow patterns in open-chest patients undergoing coronary artery bypass grafting.

Methods

Patients

Medical ethical committee approval was obtained, and patients gave written informed consent. Twenty consecutive patients undergoing routine coronary artery bypass grafting who had a proximal left anterior descending (LAD) or right (RCA) coronary artery stenosis were studied. All patients had coronary angiography performed 1 to 34 days (mean, 19 days) before surgery. A control group of 9 patients was also studied; these patients were undergoing routine mitral valve surgery.

Coronary Angiography

Coronary angiography was performed by standard Judkins technique using a single-plane imaging system (Siemens).
Images were recorded onto 35-mm cinefilm at a frame rate of 25 frames per minute and were analyzed by an expert observer. The presence or absence of coronary calcification and collateral circulation at angiography was specifically reported. Coronary artery stenoses were classified according to visually determined percent narrowing as occlusion (100%), severe (>70%), moderate (40% to 70%), or mild (<40%).

Equipment

A Vingmed CFM 750 ultrasound unit and miniature 6.5-
MHz annular array transducer with imaging, Doppler, and color flow mapping capabilities were used to obtain images of the coronary arteries. The transducer is 4 cm long and 1 cm in diameter with a footprint of 1 cm² and a focal length of 25 mm. The lateral and axial resolutions are 0.6 to 1.0 mm and <0.6 mm, respectively, operating at nominal frequency. It is a broad-bandwidth transducer enabling operation at a frequency of 7.5 MHz in the present study. Doppler frequencies of 4 to 6 MHz are available with this transducer, and in the present study, a Doppler frequency of 4 MHz was used because it was more sensitive in detecting coronary blood flow and enabled a higher Nyquist limit of 0.9 m/s at the imaging depths that were used. A specially designed holding device allowed the operator to maneuver it with ease over the coronary arteries (Fig 1).

For cross-sectional arterial imaging, a depth setting of 4 cm was used, and the reject levels were reduced to the minimum setting. Gains and contrast levels were adjusted to provide the optimal images. Blood flow velocity recordings were obtained using a pulsed Doppler sample volume size of 2 mm and a low velocity reject setting of 5 cm/s.

Intraoperative Protocol

A time limit of 10 minutes was set in accordance with the medical ethical committee recommendations for acquisition of images and Doppler data. High-frequency epicardial ultrasound was performed before initiation of cardiopulmonary bypass and after cannulation in case of transducer-induced arrhythmias. The patients were hemodynamically stable, and mean arterial pressures were 60 to 80 mm Hg during the ultrasound study.

Ultrasonic gel was applied to the imaging surface of the transducer to improve acoustic coupling. The transducer, holding device, and cable were then placed inside a sterile sleeve that measured 120 cm. A 1- to 2-cm ultrasonic standoff medium (Kitecho, 3M) was used in apposition between the transducer and sterile sleeve to improve visualization of the epicardial coronary arteries. The epicardium was moistened with sterile saline to ensure an adequate acoustic interface, and the transducer then was moved over the course of the artery being imaged.

It was elected to image an isolated proximal stenosis, demonstrated by preoperative coronary angiography, in either the LAD (before the first diagonal) or RCA (the proximal third before the right ventricular branch) in each patient. All patients had a single stenosis in these segments of the coronary arteries, ensuring that the stenosis evaluated by Doppler ultrasound corresponded with the lesion identified at angiography. In the control subjects with normal coronary arteries, the proximal LAD or RCA was studied in a similar manner. A segment of approximately 4 cm was studied. When a stenosis was located by ultrasound, color flow mapping was performed at this site. Coronary blood flow velocities were then measured by placing a pulsed Doppler sample volume in the lumen of the coronary artery immediately proximal to and just downstream from the stenosis, beyond the site of nonlaminar flow on the color map. Care was taken to record good-quality narrow spectral traces with clean envelopes and a pure audio sound. High pulse repetition frequency Doppler was used downstream from the stenoses to record peak velocities. All studies were recorded on videotape for subsequent analysis.

Velocity measurements were made using the internal measurement analysis package of the ultrasound unit. Peak and mean systolic and diastolic velocities were obtained by manual tracing around the spectral envelope.

Statistical Analysis

Differences between the control and study groups and between prestenotic and poststenotic blood flow velocities were assessed by Wilcoxon signed-rank paired test. Values are given as mean±SEM.

Results

Epicardial ultrasound did not produce cardiac arrhythmias or cause hemodynamic instability in any patient (13 men and 7 women; age range, 38 to 72 years; mean age, 61 years). Patient characteristics, site and severity of stenosis, and hemodynamic results are summarized in Table 1. The control group comprised 6 men and 3 women (age range, 44 to 68 years; mean age, 57 years).
Table 1. Patient Characteristics and Hemodynamics of Coronary Stenoses

<table>
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<tr>
<th>Sex</th>
<th>Age, y</th>
<th>Heart Rate, bpm</th>
<th>Artery</th>
<th>Stenosis</th>
<th>Collaterals</th>
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<td>DVM, cm/s</td>
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DVP indicates peak diastolic velocity; DVM, mean diastolic velocity; SVP, peak systolic velocity; SVM, mean systolic velocity; bpm, beats per minute; LAD, left anterior descending coronary artery; RCA, right coronary artery; and STO, subtotal occlusion.

Imaging Data

Normal Arteries

A 4-cm segment was studied of the LAD in five patients and the RCA in four patients. In these arterial sections, which did not have identifiable stenoses at preoperative angiography, the lumen-wall interface was clear and without encroachment of echogenic material.

Stenoses

Stenoses identified as proximal at preoperative coronary angiography were located in the same segment by high-frequency ultrasound (17 LAD and 3 RCA) and were seen as bright, dense echogenic deposits encroaching into the arterial lumen (Fig 2) or as calcific lesions casting acoustic shadows (Fig 3). A long tubular nar-

![Fig 2. Echocardiogram of stenosis (white arrow) in the left anterior descending coronary artery (LAD) and a subtotal occlusion further downstream (black arrow).](image-url)
row (Fig 4) was demonstrated, and one patient had a large proximal LAD aneurysm easily recognized by ultrasound (Fig 5) in addition to a severe LAD stenosis. Ten of the stenoses were shown to be calcific at ultrasound, and all except one of these had calcification identified at coronary angiography. The presence of a large acoustic shadow associated with calcific lesions precluded accurate measurement of the degree of luminal narrowing because the posterior coronary arterial wall was obscured. Grading of stenosis severity in this study was therefore assessed on the preoperative coronary angiogram.

**LAD Stenoses**

Twelve patients had severe, three had moderate, and one had a minor stenosis. In one patient, there was a subtotal occlusion (Fig 2), and pulsed Doppler interrogation was performed just downstream of the occlusion. In the patients with the minor proximal stenoses, the LAD was occluded further downstream (Fig 6). The patent vessel distal to the occlusion was visualized (Fig 6).

**RCA Stenoses**

Three patients with RCA stenoses were examined: one stenosis was minor, one was moderate, and one was severe.

**Color Flow Data**

Normal laminar flow on color mapping was demonstrated across normal vessels, one minor LAD stenosis, and the minor and moderate RCA stenoses. Nonlaminar flow seen as a multicolor mosaic was visualized across moderate and severe stenoses (Fig 7).

**Doppler Data**

**Normal Arteries**

In the nine control patients, coronary flow profiles were predominantly biphasic and diastolic with forward flow throughout systole and diastole. Peak and mean diastolic velocities were $35 \pm 2.1$ and $26 \pm 1.9$ cm/s with peak and mean systolic velocities of $16 \pm 1.4$ and $11 \pm 0.8$ cm/s, respectively.

**Stenoses**

In the time allocated, it was not possible to obtain flow velocities proximal to the stenoses in two patients. Coronary blood flow velocity profiles were obtained downstream from the stenoses in all patients.

Prestenotic coronary flow was characterized by biphasic and predominantly diastolic forward flow profiles, similar to that demonstrated in the control population. Peak and mean diastolic velocities proximal to the stenoses were $37.5 \pm 3.1$ and $27.3 \pm 2.2$ cm/s, respectively, and were not significantly different from control values. Prestenotic peak and mean systolic velocities were $15.7 \pm 1.6$ and $11.8 \pm 1.1$ cm/s, respectively, and also were not significantly different from control measurements.

There was a wide range of Doppler-detected disturbances in poststenotic coronary artery blood flow (Table 1). From an analysis of the coronary artery disease group as a whole, peak and mean diastolic velocities proximal to the stenoses were not significantly changed downstream of the stenoses (before: $37.5 \pm 3.1$ and
27.3±2.2 cm/s; after: 47.1±7.5 and 32.1±4.6 cm/s, respectively; P>.05). Prestenotic peak and mean systolic velocities were 15.7±1.6 and 11.8±1.1 cm/s, respectively, with poststenotic values of −0.25±13.3 and 0.1±8.1 cm/s. The differences in poststenotic systolic velocities largely reflect the contribution of reversed systolic flow signals demonstrated downstream of significant LAD stenoses but in the group as a whole did not achieve statistical significance.

**Severe LAD Stenoses**

Subgroup analysis was performed of the 12 patients with severe proximal LAD stenoses. The principal finding in this group was the presence of a large reversed poststenotic systolic flow signal in nine patients (Figs 8 and 9). Prestenotic peak and mean systolic velocities were 16.5±1.7 and 11.9±1.1 cm/s, respectively, and were significantly altered downstream of the stenoses at −22.7±17.2 and −15.9±10.9 cm/s (P<.05 and P<.01, respectively; Table 2). Reversed systolic flow was seen only distal to severe LAD stenoses. There was no correlation between retrograde collateral filling by preoperative coronary angiography and the presence of reversed poststenotic flow (Table 1). Prestenotic peak and mean diastolic velocities were 40.5±4.3 and 29.7±2.9 cm/s, respectively, with poststenotic values of 35.9±6.6 and 25.7±4.9 cm/s (P>.05).

**Moderate and Minor Stenoses**

The number of studied patients with moderate stenoses is too small to allow separate analyses, but both diastolic and systolic poststenotic velocities appeared to be increased (Table 1). Only two minor stenoses were studied, and these did not alter flow.

**Discussion**

Coronary angiography, the gold standard for examination of coronary artery anatomy, has limitations. Pathological and physiological studies suggest that coronary angiography underestimates the extent and severity of coronary artery disease. Visually estimated percent diameter narrowing on coronary angiography as a measure of stenosis severity is not universally accepted, especially in lesions of intermediate severity. Perhaps most important, coronary angiography yields no information on blood flow, which may better predict

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2. Figure 5. Left, Echocardiogram of aneurysmal dilatation of the proximal left anterior descending coronary artery. Right, Corresponding left coronary artery angiogram in the right anterior oblique projection. A indicates aneurysm.

3. Figure 6. Echocardiogram of occlusion (O) in left anterior descending coronary artery (LAD) with patent vessel distal to occlusion (arrow).
the hemodynamic significance of a coronary stenosis. In view of these limitations, techniques of coronary ultrasound and Doppler have received much interest recently.

In open-chest patients undergoing coronary artery bypass grafting, the combination of high-frequency epicardial ultrasound and Doppler has the potential to directly image coronary stenoses and provide hemodynamic information. Although high-frequency epicardial coronary ultrasound provides accurate morphological information,\(^\text{6,11}\) the large size of transducers relative to the thoracotomy has prevented application of this technique to the study of coronary blood flow. Miniaturization of ultrasound technology may realize the full potential of epicardial coronary ultrasound.

A miniature 5-MHz transducer has been reported that is easily maneuvered, allowing a new combination of epicardial scanning planes without compromise of image quality.\(^\text{6}\) Higher-frequency transducers, however, are necessary to provide high-quality images of coronary arteries. In vitro validation of the accuracy of a 7.5-MHz transducer in measuring coronary artery diameter and identifying atherosclerosis by comparison with histopathology has been performed.\(^\text{4}\) We used a prototype 6.5-MHz miniature transducer (operating at a total frequency of 7.5 MHz) that is otherwise identical to the 5-MHz miniature transducer to image and measure blood flow across coronary artery stenoses. This is the first study combining high-frequency epicardial coronary ultrasound and Doppler to provide both hemodynamic and anatomic information.

In normal coronary arteries, most blood flow occurs in diastole as myocardial compression during systole increases distal vascular resistance, reducing the pressure difference between the aorta and coronary arteries. Coronary artery blood flow in the control group and in prestenotic regions demonstrated this characteristic bi-phasic, predominantly diastolic, pattern. This is in accordance with that reported in other studies of prestenotic coronary flow in humans.\(^\text{12,13}\)

The principal finding in this study was a large reversed poststenotic systolic flow signal downstream of severe LAD stenoses (Figs 8 and 9), which was not explained by angiographic retrograde collateral filling. Only one severe RCA stenosis was studied; therefore, it is not possible to comment on the hemodynamic effects of severe RCA stenoses. Studies of phasic poststenotic coronary flow patterns in animals have revealed changes in the normal predominant diastolic pattern to a pattern less predominantly diastolic with a greater systolic flow contribution, occurring with increasing severity of epicardial coronary artery stenosis.\(^\text{14-17}\) There have been only two previous studies examining blood flow disturbances downstream from coronary artery stenoses in humans.\(^\text{13,18}\) Kajiya et al.\(^\text{18}\) used an epicardial pulsed Doppler velocimeter during coronary artery bypass surgery of nine patients with significant (75% to 99%) proximal LAD stenoses and revealed poststenotic increased systolic flow components and reduced diastolic flow components. Poststenotic blood flow patterns were sampled at several locations distal to the stenosis. Immediately distal to the stenosis, the ratio of diastolic to systolic flow was reduced, and reversed flow velocities were frequently observed near the vessel wall, indicating the existence of flow separation and recirculation in these regions. At a site 4 cm distal to the stenosis, Kajiya et al failed to detect reversed flow, but the ratio of diastolic to systolic flow remained low.\(^\text{18}\) Other studies have confirmed significant flow separation with turbulence in the coronary region immediately beyond a significant stenosis.\(^\text{19,20}\) After bypass grafting, the velocity patterns distal to the graft insertion site returned to the normal predominant diastolic pattern.

A newly designed Doppler coronary artery flow guide wire has been used to measure coronary artery blood flow velocities proximal and distal to coronary artery stenoses before and after percutaneous coronary angioplasty.\(^\text{13}\) Before angioplasty, coronary blood flow velocities distal to a significant (>70%) stenosis revealed decreased ratios of diastolic to systolic flow compared with normal vessels. After angioplasty, distal abnormal
Phasic velocity patterns generally returned to normal. The poststenotic flow disturbances described using the Doppler guide wire technique were sampled from the distal vessel, considerably downstream from the stenotic site. In the more distal coronary artery, flow is expected to become laminar again, and no reversed flow velocities were detected in this study. In addition, flow in distal and proximal segments of coronary arteries may differ, making comparison of that study and the present study difficult.\textsuperscript{21,22}

In the present study, poststenotic pulsed Doppler sampling was performed downstream of the area of nonlaminar flow on the color flow map, and therefore the reversed systolic flow detected is unlikely to reflect areas of flow separation. The intramyocardial "pump" model provides an alternative explanation for the reversed systolic flow signal.\textsuperscript{23} This model suggests that epicardial resistance will become the limiting factor for antegrade coronary flow during periods of no-reverse intramyocardial flow and low distal arterial and venous

\begin{figure}
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\includegraphics[width=\textwidth]{fig8.png}
\caption{Top, Doppler spectral tracing of left anterior descending coronary artery blood flow velocity proximal to severe stenosis demonstrating biphasic and predominant diastolic flow. Bottom, Doppler spectral tracing of left anterior descending coronary artery blood flow velocity distal to the same stenosis, demonstrating reversed systolic flow.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig9.png}
\caption{Doppler spectral tracing of left anterior descending coronary artery blood flow distal to a severe stenosis, demonstrating reversed systolic flow (arrow). In this patient, the direction of blood flow was away from the transducer; therefore, antegrade diastolic flow is depicted below the line, and reversed systolic flow is depicted above the line.}
\end{figure}
resistances (diastole). During systole, reverse coronary flow from the intramyocardial pump “charges” the underfilled epicardial coronary capacitance artery. The presence of reversed systolic flow precluded measurement of poststenotic ratios of diastolic to systolic flow. Three patients with severe LAD stenoses did not demonstrate reversed poststenotic systolic flow. These patients, however, demonstrated poststenotic increased systolic flow components similar to those noted in the study of Kajiya et al.16 It has been postulated that this increase in systolic flow in the presence of a severe proximal stenosis may be the result of reduction in myocardial contractility consequent to localized ischemia, which reduces compression of the peripheral bed and lowers distal vascular resistance during systole.18

A trend toward decreased poststenotic diastolic velocities was seen in the present study, but this did not achieve statistical significance. The decrease in poststenotic diastolic components of flow with increasing degree of epicardial stenosis may be explained by the increased influence of an epicardial stenosis on flow during periods of low distal vascular resistance (diastole) compared with that during periods of high distal vascular resistance (systole).24

Moderate LAD stenoses appeared to increase both diastolic and systolic velocities, although the numbers in this group were small. This is in accordance with the flow pattern detected at the stenotic site of moderate coronary artery stenoses examined in a study using a Doppler flow catheter.12 This may be because of a pressure gradient across the stenosis leading to increased flow velocities without achieving the level of epicardial resistance seen with severe stenoses, which reduces flow during diastole. As expected, minor stenoses had no effect on coronary flow.

**Study Limitations**

There are some study limitations. Examination of coronary flow velocities is time consuming, and within the time allowed, only an incomplete examination was possible in some patients. The technique is safe, however, and it would appear reasonable in a clinical setting to extend the duration of the Doppler study to provide complete hemodynamic data. Measurement of a stenosis by ultrasound is limited if calcification is present because a large acoustic shadow obscures the posterior coronary artery wall. It may also be technically difficult in some cases to get in line with coronary blood flow and obtain adequate Doppler traces. In the present study, all stenoses studied were proximally and anteriorly situated. Further studies are required to assess the ability of this transducer to image posterior and more distal segments of the coronary arterial tree.

Other ultrasound methods and newly devised Doppler techniques of assessing the hemodynamic effects of coronary artery stenoses are also subject to limitations. High-frequency ultrasound transducers have been mounted on coronary catheters to allow intravascular examination of proximal coronary arterial wall anatomy but have no facility for flow measurement.25,26 Transesophageal Doppler evaluation of coronary blood flow velocity has been performed but is limited to the very proximal coronary arteries.27-29 Coronary artery Doppler catheters have been used to measure coronary velocities in the prestenotic and stenotic segments to permit assessment of percent stenosis by the continuity equation.12,30 It was impossible, however, to measure flow velocities at severe stenoses because aliasing occurred. It was also difficult to position the sample volume in the center of the coronary lumen, especially in curved vessels. In addition, intravascular Doppler catheters, even the newer 3F (1 mm diameter) catheters, significantly affect blood flow.31

The newly developed Doppler guide wire consists of a 12-MHz piezoelectric transducer integrated onto the tip of a 0.018-in. flexible, steerable angioplasty guide wire.32 It causes less disruption of flow velocity profiles and is less obstructive in small arteries, reducing the area of a 1.2-mm circular lumen by approximately 15%.32 The main limitations of this technique relate to positioning and manipulation of the guide wire. In large vessels, the Doppler beam may not intercept the true peak flow because of an inability to direct the wire tip far enough away from the wall to sample the central portion of the stream.32 The wire tip may also be unstable under high-flow conditions. In tortuous coronary segments, the wire tip may “hug” the wall, and considerable manipulation is necessary to point the transducer away from the wall and into the flow stream. Occasionally, vessel wall artifact cannot be avoided, and the wire must be repositioned. Small changes in wire position, especially in a tortuous vessel, may produce significant differences in the measured coronary velocity.

**Conclusions**

The present study demonstrates that the combination of high-frequency epicardial ultrasound and Doppler with a miniature transducer allows identification of coronary artery stenoses and associated blood flow disturbances. The technique was safe and did not cause complications, which is in accordance with other studies of epicardial ultrasound techniques. Severe stenoses demonstrated different poststenotic flow patterns compared with moderate lesions. In particular, a large reversed poststenotic systolic flow signal was associated with the presence of a significant proximal LAD stenosis. It may therefore provide a method of determining the functional significance of a stenosis, especially angiographic lesions of intermediate severity. Larger numbers of stenoses with different degrees of severity and morphology need to be examined with this technique to allow correlation of flow disturbance with degree and type of stenosis. Coronary atherosclerosis may advance rapidly, and this technique may play a future role in assessing coronary anatomy and blood flow in patients.
in whom coronary angiography has been performed some months before surgery. With further developments in ultrasound technology, epicardial ultrasound and Doppler techniques should play a role in the diagnosis and management of coronary artery disease.

Acknowledgments

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References


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