# Clinical Significance of the Acoustic Detection of Coronary Artery Stenosis

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**Abstract**

*Objectives*. The clinical usefulness was investigated of phonocardiography of coronary artery disease based on stenosis sounds.

*Methods*. Heart sounds were recorded in 128 patients undergoing coronary angiography and 40 normal young men. Acoustic recordings were made with the patient supine using five sensors affixed to the skin on the left sternal border at the second L2 , third L3 and fourth L4 intercostal spaces, and the right sternal border at the second R2 and third R3 intercostal spaces. Approximately 400 msec of waveforms immediately following the second heart sound were passed through a band pass filter 400  1,500 Hz and subjected to frequency analysis using the maximum entropy method. The ratio of heart sound amplitudes within the 400  700 Hz band to those within the 400  1,500 Hz band was designated as the power ratio.

*Results*. The relationship between the degree of stenosis and the stenosis sounds suggested that the power ratio was greater in mild or moderate 50  75% stenosis. The patients were divided into the stenosis  American Heart Association AHA 50  75% , severe stenosis AHA 90  100% , and normal groups. The power ratio was significantly greater $p$   0.005  in the stenosis group than in the normal and severe stenosis groups for patients with stenosis of the left anterior descending artery or the left main trunk  single-vessel disease . Using a cut-off level of 45%, the sensitivity was 71%, specificity was 65%, and accuracy was 66%. The greatest power ratio difference was recorded at L4, and represented noninvasive detection of mild to moderate stenosis in the left anterior descending artery or left main trunk. No other site showed any statistically significant difference. Detection was impossible in multivessel disease or in cases complicated with valvular disease.

*Conclusions*. Phonocardiography may allow reliable detection of coronary artery stenosis with mild  AHA 50  75%  stenosis.

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**Key Words**

Coronary artery disease        Phonocardiography        Spectrum analysis

## INTRODUCTION

Prevention of cardiac incidents in patients with coronary artery disease requires early detection of stenotic lesions in the coronary arteries. Currently available noninvasive techniques for detection of coronary artery disease include electrocardiography, ultrasonography and scintigraphy, but none of these methods can detect mild or moderate coronary artery stenosis. In addition, only a limited number of institutions are equipped for clinical application of these methods, as with standard computed tomography and magnetic resonance angiography imaging of the coronary arteries, and so screening of large numbers of patients for coronary artery disease is not possible. Therefore, a new, simple and widely available system is needed for the detection of coronary artery stenosis.

Previously, we attempted to detect the characteristics of stenosis by phonocardiography[1] . Here we describe our clinical study of a considerable number of patients to assess the clinical usefulness of

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**Table 1   Subjects in the study**

| Type | No. of cases | Men  % | Age  yr, mean± SD |
|------|-------------|--------|-------------------|
| Stenosis  AHA 50  75% | 33 | 28  85 | 61± 10 |
|     LMT/LAD | 17 | | |
|     LCX | 4 | | |
|     RCA | 1 | | |
|     Multivessel | 11 | | |
| Severe stenosis  AHA 90% or more | 33 | 29  88 | 62± 10 |
| No stenosis  AHA 0  25% | 34 | 32  94 | 58± 8 |
| Complex lesion | 18 | 14  78 | 62± 9 |
| Valvular heart disease | 10 | 9  90 | 57± 18 |
| Normal young man | 40 | 40  100 | 23± 1 |
| Total | 168 | | |

AHA  American Heart Association ; LMT   left main trunk ; LAD   left anterior descending artery ; LCX   left circumflex artery ; RCA   right coronary artery.

this new method.

## SUBJECTS AND METHODS

### 1. Subjects

This study included 128 patients admitted to Jikei University Hospital in Tokyo with suspected coronary artery disease who had undergone coronary arteriography, and 40 young men in good health Table 1 . The young healthy men did not undergo coronary arteriography. Nine of the patients with significant valvular disease had aortic valve incompetence five in category  , three in  and one in   of the Sellers classification , and one had severe pulmonary valve incompetence. Phonocardiography examinations were performed only after the patients had been given an oral outline of the study, and had granted informed consent. The administration of current oral medication was not discontinued.

### 2. Coronary artery stenosis sound detection system

The equipment for the detection of coronary artery stenosis sounds and the analysis method are described below.

#### 1   Recording of coronary artery stenosis sounds

Testing was performed in an examination room after normal hospital hours to avoid interference by external vibrations as far as possible. The patient lay supine during recording. Five high sensitivity sensors PBC336, Piezotronics Inc. were affixed to the skin on the left border of the sternum at the second L2 , third L3 and fourth L4 intercostal spaces, and on the right border at the second R2 and third R3 intercostal spaces. Electrocardiography was performed simultaneously with the sound recording. To prevent any interference from respiratory sounds, the patient was instructed to hold the breath for between 10 and 15 sec for each recording. A total of 30 sec of recording of the heart sounds was made at each intercostal space.

#### 2   Acquisition of diastolic heart sound data

All phonocardiographic data obtained from each site was fed through a band-pass filter 400  1,500 Hz ; Fukuda Electronics , and recorded on a data recorder  sampling frequency 24 kHz ; PC208A data recorder, Sony Corp. for offline processing.

The sounds of coronary artery stenosis occur early in diastole, when the coronary blood flow reaches its maximum, so waveform processing was performed after the second heart sound between 400 and 1,500 Hz was passed through the band-pass filter. Waveforms were transferred to a personal computer  using a PCIF 260 interface, Sony Corp., and a PC 208A, Sony Corp. together with the electrocardiogram, and the mean of the heart sounds for approximately 400 msec from the second sound was calculated  the diastolic sounds were analyzed by selecting fifteen 50 msec segments just after the second heart sound and by averaging the data for each  .

#### 3   Spectrum analysis of diastolic heart sounds

The autoregressive moving average method has been used for detection of coronary stenosis sounds[2] . However, since a high degree of frequency resolution is necessary for measuring coronary

artery stenosis sounds, frequency analysis was carried out using the maximum entropy method MemCalc; Suwa Trust Co. [3] .

### 4 Quantitative assessment of coronary artery stenosis sounds

In early testing, the peak amplitudes or power of the stenosis sounds were found to be within the 400 700 Hz range[1,4] . The ratio was calculated between the area under the curve AUC of the power ratios for the 400 700 Hz range and the AUC for the 400 1,500 Hz range. This ratio was designated the power ratio and used to quantitatively assess differences in the spectrum pattern between patients.

Power ratio power of 400 700 Hz band / power of 400 1,500 Hz band

### 3. Clinical testing
### 1 Severity of coronary artery lesions and stenosis sounds

The changes due to stenosis in the diastolic heart sounds were studied in single-vessel disease in the left anterior descending artery LAD or the left main trunk LMT of the coronary artery. The patients were grouped according to the categories for coronary artery lesions established by the American Heart Association AHA [5] as follows: normal group 29 patients , 50% stenosis group mild stenosis, 5 patients , 75% stenosis group moderate stenosis, 9 patients , 90% stenosis group 3 patients , 99% stenosis group 7 patients , and 100% stenosis group 2 patients . The relationship between the degree of stenosis and the power ratio was investigated. The normal group contained fewer than 25% of patients with uneven internal surfaces on the vascular wall.

### 2 Clinical data

Analysis of the diastolic heart sounds was performed in all 168 subjects. Patients were divided into single-vessel and multivessel disease to investigate whether the presence of stenosis sounds could be used as an indication for the diagnosis of stenosis. The effects of the site of recording and the concurrent presence of a severe lesion were also examined.

### RESULTS

### 1. Changes in diastolic heart sounds associated with coronary artery stenosis

**Fig. 1** shows the phonocardiograms of a patient with 50% stenosis and a normal subject and **Fig. 2**

shows the power spectra of the diastolic heart sounds in patients with 50% stenosis and complete occlusion, and in a normal subject. Stenosis was associated with a peak at a frequency of approximately 700 Hz with power ratios greater than seen in normal or severe stenosis cases. **Fig. 3** presents the power ratio for each degree of stenosis. The heart sound power ratios between 400 and 700 Hz in cases of 50% and 75% stenosis were significantly greater than those in normal subjects $p$ 0.05 , but there was no significant difference between cases of severe 90% or more stenosis and normal subjects. This suggests that the present method is suitable for the detection of cases of stenosis between 50% and 75%. The acoustic clinical data were then classified into a stenosis group AHA 50 75% and a severe stenosis group AHA 90 100% , in addition to the normal subjects.

### 2. Clinical data for the diagnosis of coronary artery stenosis
### 1 Effect of site of recording

The results of the analysis of the diastolic heart sounds of 168 patients are shown in **Table 2**, and **Fig. 4** shows the findings for each recording site, obtained on the basis of these results.

Single-vessel disease: The severe stenosis group showed higher heart sound power ratios than the stenosis group in the LMT or the LAD **Fig. 4 upper** . This difference in power ratios was significant in the results obtained at L4, but no statistically significant difference was seen in the recordings made at any other site. There were only a few cases of lesions of the circumflex coronary branch and of the right coronary artery, and so their data were eliminated from the study.

Multivessel disease: The results of the analysis when severe lesions were concurrently present in other branches complex cases , or when there was stenosis in two or more branches, are shown in **Figs. 4 middle** and **lower**, respectively. Higher power ratios were seen when a severe lesion was present together with a mild or moderate lesion in another branch. Recordings made at L2 or L4 showed statistically significant differences in the power ratios. However, when the lesions were spread over multiple branches, increased power ratios were difficult to detect[4] .

### 2 Effects of aortic and pulmonic valve incompetence
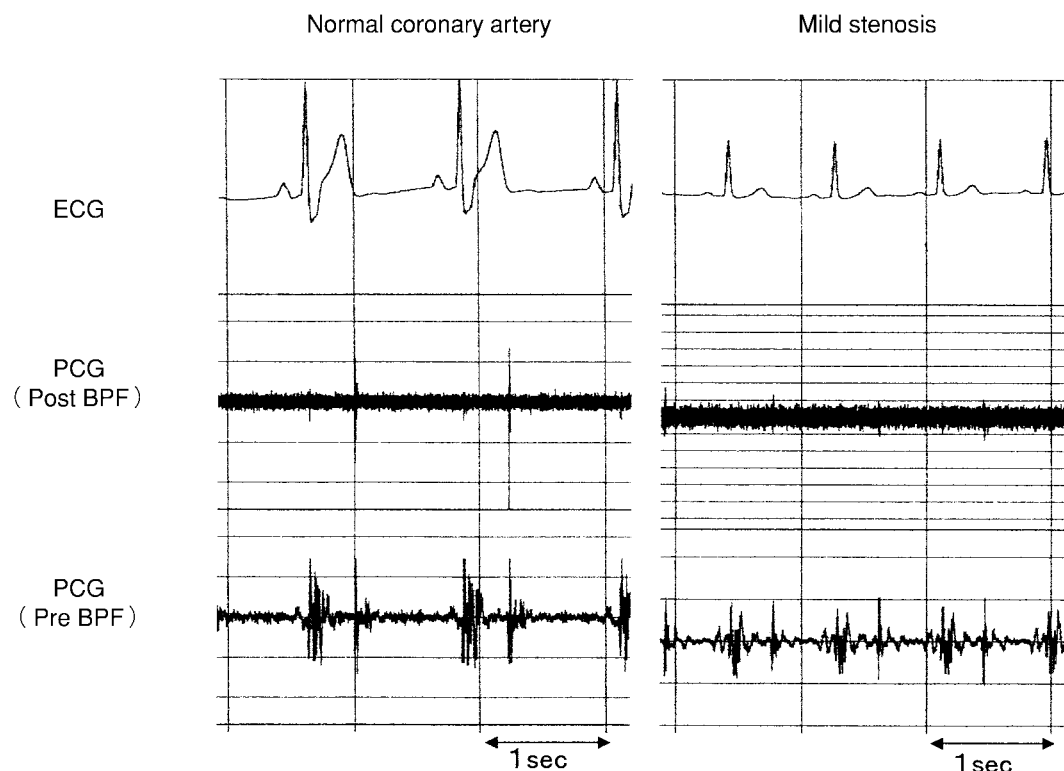
The heart sound power ratios showed increases

Normal coronary artery          Mild stenosis



ECG

PCG
（Post BPF）

PCG
（Pre BPF）

1 sec                    1 sec

**Fig. 1   Phonocardiograms of a normal subject** *left* **and a patient with coronary stenosis** *right*
There was no significant difference between the phonocardiograms of the normal subject *left* and the
patient with 50% stenosis of the LAD *right* .
ECG  electrocardiogram ; PCG  phonocardiogram ; BPF  band-pass filter 400  1,500Hz . Other
abbreviation as in Table 1.

in the range 400  700 Hz in cases of aortic valve
incompetence and pulmonic valve incompetence,
and these two types were difficult to distinguish[6]
**Table 2** .

### 3   Clinical application

**Fig. 5** shows the heart sound power ratios  in the
400  700 Hz range of stenotic and non-stenotic
lesions normal and severe cases  in cases of com-
plex LAD or LMT stenosis. The power ratio was
significantly higher in stenosis cases  46.6± 2.6%
than in non-stenosis cases  43.8± 3.4%    $p$
0.005 . With the cut-off level set at 45%, the sensi-
tivity of detection of stenosis was 71%, with 65%
specificity, and 66% accuracy.

### DISCUSSION

Angiostenosis sounds can be heard in the renal
artery, which is approximately equal in thickness to
the coronary arteries, so sounds may be produced
by stenosis present in the coronary arteries.
However, such sounds are extremely difficult to
distinguish in the coronary arteries in practice, so

that only a handful of studies have been made[7] [11] .
The stenosis sounds are attenuated before they
reach the chest wall, and are masked by the inter-
ference from sounds produced by the organs in the
region of the heart and by the extracorporeal noise
frequencies[12] in the local environment, so stenosis
sounds can hardly be distinguished with an ordi-
nary stethoscope. Therefore, sound spectrum analy-
sis has recently been used to try to detect coronary
artery stenosis sounds[2,13] . The frequency band of
stenosis sounds is relatively limited, so the heart
sound frequency components in the same frequency
band can be quantitatively assessed using spectrum
analysis, and the presence of stenosis sounds can be
identified from the amplitude of those components.
In a basic experiment using a phantom, we reported
that the stenosis sounds yielded a power spectrum
showing peaks in a constant frequency range[14,15] .
In addition, a clinical study showed these peaks
were distributed in the 400  700 Hz band. On the
basis of these results, the present study examined
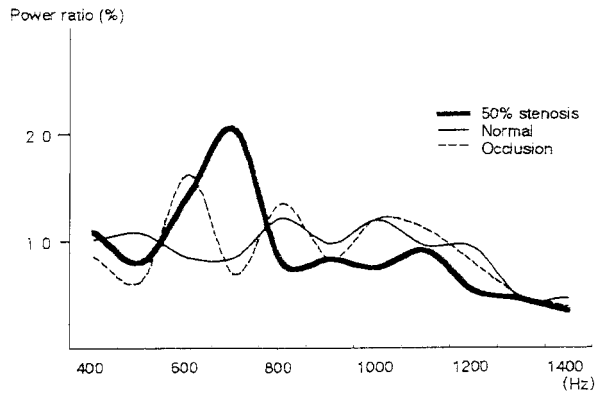the clinical usefulness of phonocardiography for

**Fig. 2  Power spectra of the diastolic heart sounds**

Power spectra in a patient with 50% stenosis of the LAD, in a normal subject, and in a patient with complete occlusion. A power peak was observed in the 700 Hz band in the patient with stenosis, but the spectrum differed from the normal subject and the patient with complete occlusion.
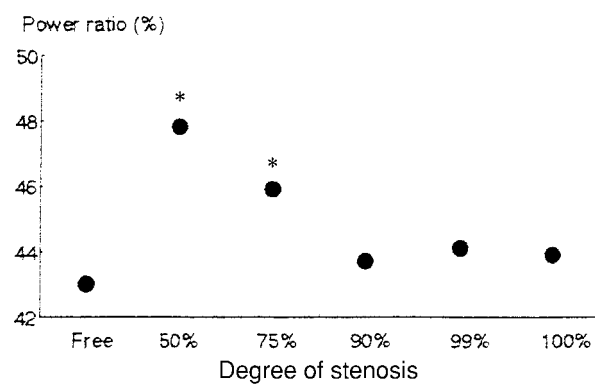
Abbreviation as in Table 1.



**Fig. 3  Changes in the power ratio according to the degree of coronary stenosis**

The power ratio was higher when 50  75% coronary stenosis was present  $p$   0.05 vs stenosis-free subjects Free , but was similar to normal subjects when the degree of stenosis reached 90% and over.



**Fig. 4  Recording sites showing differences in power ratio between the mild 50  75% coronary stenosis group and the other groups**

The recording sites are shown where significant differences  $p$   0.05 were detected between the stenosis group and the other groups valvular heart disease, severe stenosis, normal young men, and no stenosis .

*Upper*: Cases of moderate stenosis at LAD or LMT.

*Middle*: Cases of severe stenosis   90% in a vessel other than the moderately stenosed vessel complex cases .

*Lower*: Cases with moderate stenosis in double- or triple-vessels.

 $p$   0.05.

NYM  normal young man ; VHD  valvular heart disease ; L2, L3, L4  left border of the second, third and fourth intercostal spaces ; R2, R3  right border of the second and third intercostal spaces. Other abbreviations as in Table 1, Fig. 3.

the detection of coronary artery stenosis sounds.

## 1. Changes in diastolic heart sounds associated with stenosis

Severe stenosis, above 95% occlusion, might not cause sounds because of the very low blood flow[2] . However, there has been no study of this question in clinical patients. We studied the changes in stenosis sounds in single-vessel cases of stenosis in the LAD or the LMT. The results showed that the power ratios within the 400  700Hz band were

Table 2    Power ratios of diastolic heart sounds   400   700 Hz

|     | Mild stenosis | | Complex | Severe | Normal | NYM | VHD |
|-----|---------|---------|---------|--------|--------|-----|-----|
|     | LMT/LAD | MVD | | | | | |
| L2 | 44.8± 3.7 | 44.6± 2.4 | 49.9± 13.3 | 45.1± 2.8 | 44.6± 2.5 | 45.5± 3.2 | 52.1± 15.1 |
| L3 | 46.6± 2.6 | 44.7± 2.7 | 49.2± 10.8 | 44.5± 2.9 | 43± 3.8 | 44.7± 3.1 | 57.2± 12.9 |
| L4 | 33.4± 2.3 | 32.6± 3.3 | 37.3± 11.6 | 32.5± 2.8 | 31± 2.8 | 32.8± 3.2 | 44.6± 12.9 |
| R2 | 45.6± 1.6 | 43.1± 1.9 | 48.3± 12 | 44.7± 2.9 | 44.9± 3.7 | 44.8± 3.1 | 51.6± 6.2 |
| R3 | 44.9± 3.9 | 47.5± 12.1 | 44.5± 3.3 | 44.9± 3.1 | 44.7± 3 | 44.5± 2.7 | 48.8± 3.5 |

Values are mean± SD.   $p$   0.05 vs severe, normal or NYM.

MVD   multivessel disease. Other abbreviations as in Table 1, Fig. 4.
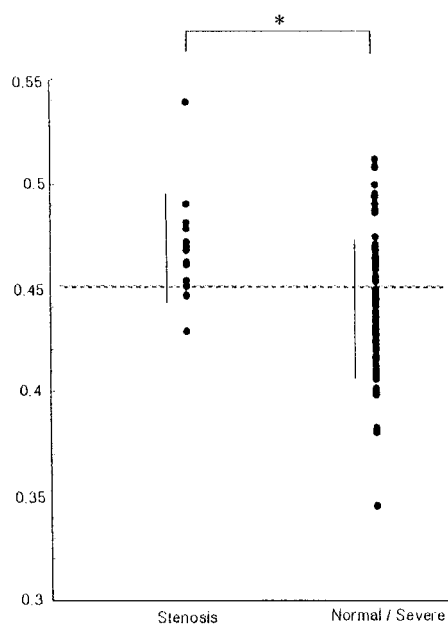


**Fig. 5   Power ratio in case of left anterior descending artery or left main trunk stenosis**
The power ratio in the 50% stenosis group was higher than those in the normal and severe stenosis groups. $p$   0.005.

greater in patients with stenosis than in normal subjects, but patients with stenosis over AHA 90% showed no difference from normal subjects Table 2 . The sounds of angiostenosis are caused by increased rate of blood flow through the narrowing of the lumen, forming eddies and turbulent flow. However, severe stenosis reduces the blood flow, so that the stenosis sounds are no longer produced[16 18] . Therefore, the sounds are detected only in cases of mild stenosis, and our detection system was only useful within the range of AHA 50% to AHA 75%. Therefore, we investigated whether the system could distinguish patients with

stenosis within the range AHA 50% to AHA 75% from normal subjects or patients with severe stenosis  AHA 90% or more .

### 2. Clinical study

Comparison of single-vessel disease with the stenosis in the LAD or LMT with normal subjects and cases of severe stenosis showed a significant increase $p$   0.005  in the power ratios of the heart sounds within the frequency band.

The vascular vibrations of coronary artery stenosis sounds generated immediately after the stenosis are transmitted to the surface of the body for recording. Therefore, the anatomical relationship between the site of the stenosis and the site of the recording device on the body surface has a major influence. The LMT and LAD arise at the origin of the aorta, and run along the anteroseptal wall of the ventricles, clinging to the surface of the heart. L4 is the point on the surface closest to the LAD, so is the most appropriate site for picking up clear stenosis sounds Fig. 4 .

### 3. Clinical usefulness, and future problems

The most clinically valuable contribution of the present study is the demonstration that the sounds of coronary artery stenosis can be detected noninvasively at the body surface. In addition, the coronary artery stenosis sounds are absent in severe stenosis.

The sounds of mild stenotic lesions are difficult to detect in an outpatient environment. Clinical use of our detection system will allow detection of stenotic lesions at an early stage, which will help to overcome the continuing difficulties of preventing the development of coronary artery disease and aid in understanding its progress by regular monitoring of coronary artery stenosis sounds rather than by

detection of the disappearance of the sounds after stenosis has already advanced. However, the present system can be used only for single-vessel cases affecting the LAD or the LMT, and the accuracy of 66% is low. Vibration of the microphone attachment due to noise seemed to be an important cause of low accuracy. Pulmonic valve incompetence was an important origin of such noise because mild pulmonic valve incompetence was detected by Doppler echocardiography in many patients. The distinction between coronary stenosis and aortic valve incompetence is possible because of the difference of spectral pattern[16] . Furthermore, a new detector was recently proposed using a semicon-

ductor pulse laser for the detection of vascular oscillations, so there are hopes for its clinical application[18,19] .

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| : |   |   |   |   |   |
| : | 128 |   | 40 | 168 |   |
|   |   | 2  3  4 |   |   | 2 |
| 3  5 |   |   | 400  1,500 Hz |   |   |
|   | 400 msec |   |   |   |   |
|   | 400  700 Hz |   |   |   |   |
| : |   |   |   |   |   |
| 50  75% |   |   | AHA | 50 |   |
| 75% | AHA  90  100% |   |   |   |   |
|   | 1 |   |   |   |   |
| *p*  0.005 | 45% |   | 71% | 65% |   |
| 66% |   | 4 |   |   |   |
| : |   |   | 50  75% |   |   |

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