

The Terminology and Diagnostic Criteria Committee of The Japan Society of Ultrasonics in Medicine\*

## Standard measurement of cardiac function indexes

### Introduction

The Cardiovascular Subcommittee of The Terminology and Diagnostic Criteria Committee of The Japan Society of Ultrasonics in Medicine created the “Standard Measurement of Cardiac Function Indexes”.

Evaluation of cardiac function is indispensable for the diagnosis and treatment of any cardiovascular disease. In particular, the echocardiographic indexes of cardiac function have been commonly used because they allow simple, accurate, reproducible, and noninvasive evaluation. This is why these indexes should be measured correctly in conformity with the standard and every effort should be made to minimize differences among investigators or institutions. It is also necessary to gain an understanding of the meaning and problems of each index. With the advance of ultrasonic technology, new echocardiographic techniques have been developed, and various new ideas have been introduced to cardiac function indexes. In this paper, however, we select and expound only the basic cardiac function indexes that have become widely known as standard indexes and allow measurement without any special diagnostic devices or software.

### 1. Left ventricular systolic function

Indexes can be classified into two types: Indexes to evaluate pumping functions focusing on the ejected blood volume and the efficiency of ejection, and indexes to evaluate myocardial functions focusing on the strength of myocardial contraction. Although both of these measurements by echocardiography are affected by preload and afterload to the left ventricles, they are frequently used because measurements can be easily done. Especially, accurate measurements of the left ventricular volume are essential for the evaluation of pumping functions.

#### 1) Left ventricular ejection fraction (EF)

Definition: The left ventricular ejection fraction (EF) is expressed as the ratio of the left ventricular stroke volume (SV) to the left ventricular end-diastolic volume (LVEDV). SV is obtained by subtracting the left ventricular end-systolic volume (LVESV) from LVEDV. Therefore, EF is calculated by the following formula:

$$EF = \frac{LVEDV - LVESV}{LVEDV} \times 100(\%)$$

M-mode and 2D echocardiograms are used to measure the left ventricular volume.

To obtain the left ventricular volume using M-mode echocardiograms, the maximum minor axis of the left ventricle at end-diastole (LVDd) and end-systole (LVDs) is measured on the parasternal long-axis or short-axis view, on the assumption that the left ventricle is a spheroid. Left ventricular volumes are usually calculated by the following formula of Teichholz:

$$V = \frac{7.0}{2.4 + D} \times D^3.$$

It is acknowledged that this formula can be applied to the left ventricle that has enlarged and become almost

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spherical, and correlates well with the volume obtained by left ventriculography. It cannot be applied to patients whose left ventricular shapes deviate from a spheroid, and to those with regional left ventricular wall motion abnormalities during cardiac contraction (asynergy).

To obtain the left ventricular volumes on 2D echocardiograms, (1) the single plane area-length method, which calculates the volume based on the area of a single cross-section, and (2) the modified Simpson method (disc method) are available.

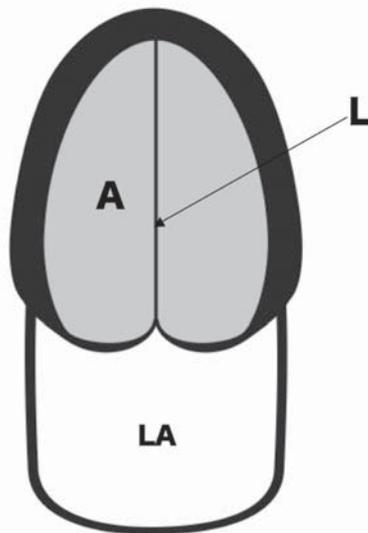
(1) When the single plane area-length method is applied, area of the cross-section of the left ventricle ( $A$ ), and length of the long axis of the left ventricle ( $L$ ) are measured, and length of the short axis of the left ventricle ( $D$ ) is calculated from these data using the following formula on the assumption that the left ventricle is a spheroid.

$$D = \frac{4A}{\pi L}$$

The volume is calculated by the formula  $V = \frac{\pi}{6} D^2 L$ .

That is, it is calculated by the formula

$$V = \left( \frac{\pi}{6} \right) \left( \frac{4A}{\pi L} \right)^2 L \rightarrow V = \frac{0.85A^2}{L}$$

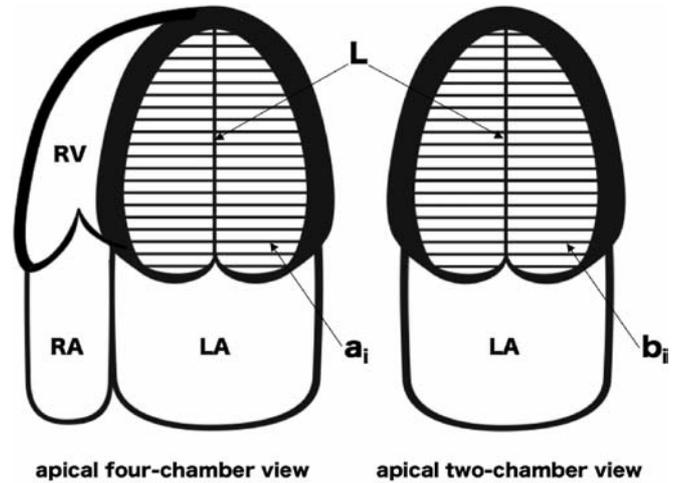


**apical two-chamber view**

(2) When the modified Simpson method (disc method) is used, the long axes ( $L$ ) of apical two- and four-chamber views are divided equally into 20, and the inside diameters of the short axes ( $a_i$  and  $b_i$ ) of 20 disks in directions perpendicular to the long axes are obtained. Left ventricular volume is calculated from the total sum of the cross-sectional areas of the 20 discs. The areas of the left ven-

tricular cavity are obtained on the assumption that each disc is oval.

$$V = \frac{\pi}{4} \times (a_1 b_1 + a_2 b_2 + \dots + a_i b_i) \times \frac{L}{20}$$



Since it is often difficult to accurately image the cardiac apex by transthoracic 2D echocardiography, the long-axis length measured may be shorter than the actual length, and the trace of the lumen may become smaller due to trabeculae or papillary muscle. For this reason, the left ventricular volume obtained by this method is usually smaller than the volume obtained by left ventriculography. However, the modified Simpson method is also applicable to patients whose left ventricles are not spheroidal, such as in those with ischemic heart disease. Left ventricular end-diastolic volume obtained by this method is used as an index of preload to the left ventricle. Although EF is affected by preload and afterload in theory, it does not fluctuate largely in response to acute changes in loads that are observed clinically. Therefore, it is suitable for semi-quantitative evaluation of inherent systolic function (good, fair, poor, extremely poor). At present, this index is most frequently used to determine whether surgery is indicated in patients with cardiac disease and to estimate the patient prognosis. It may not be suitable to detect subtle changes in systolic function before and after the administration of a drug. A normal EF value is 55% or higher.

## 2) Stroke volume (SV) and stroke index (SI)

SV, the volume of blood ejected from the left ventricle during systole, is an index of the left ventricular pumping function. It is obtained by calculating the end-diastolic volume and end-systolic volume using M-mode or 2D echocardiography as described before, and the difference between these volumes is SV. When assessing SV value as an index of left ventricular function, it should be recognized

that the cardiac output and SV can be maintained by dilating the left ventricle even in patients with impaired myocardial systolic function.

### 3) Cardiac output (CO) and cardiac index (CI)

CO, the volume of blood ejected from the left ventricle to the aorta per minute, is an index of the left ventricular pumping function that is obtained by multiplying the stroke volume by the heart rate per minute. The cardiac index is obtained by dividing the cardiac output by the body surface area to correct for body size.

### 4) Left ventricular percent fractional shortening (%FS)

Left ventricular %FS is an index of systolic function that is obtained by measuring the left ventricular end-diastolic dimension and left ventricular end-systolic dimension, dividing the difference by the left ventricular end-diastolic dimension, and shown as percentage in accordance with the following formula:

$$\%FS = \frac{LVDd - LVDs}{LVDd} \times 100(\%)$$

A normal value is between 30% and 50%.

### 5) Mean velocity of circumferential fiber shortening (mVcf)

Mean Vcf is an index of myocardial systolic function that is obtained by correcting the percent fractional shortening with the ejection time (ET) using the following formula:

$$\text{Mean Vcf} = \frac{LVDd - LVDs}{LVDd} \times \frac{1}{ET}$$

Left ventricular ejection time is the time from the rising edge of the carotid pulse to the dicrotic notch (DN), or the time from the start of ejection blood flow from the left ventricle to the end of it. Because ET is affected by blood pressure, it is not recommended to evaluate the myocardial systolic function based solely on this value. Evaluation of variation in blood pressure is necessary. A normal value is between 0.9 and 2.0 circ/sec.

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## 2. Left ventricular diastolic function

Symptoms of heart failure may be seen in patients who have normal left ventricular wall contraction. Therefore, it is important to evaluate left ventricular diastolic function independently of left ventricular systolic function. For this

purpose, a left ventricular inflow velocity pattern and pulmonary venous flow velocity pattern measured by Doppler echocardiography are used.

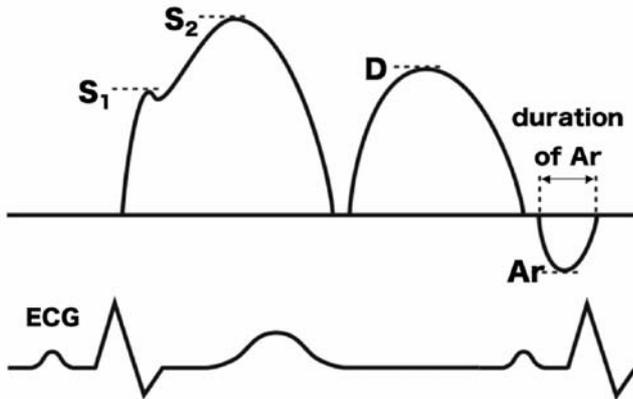
### 1) Left ventricular inflow velocity pattern or transmitral flow velocity pattern (TMF)

The velocity waveform of blood flow from the left atrium into the left ventricle through the mitral valve during diastole is an effective index for evaluating the left ventricular diastolic function, because the waveform reflects the left ventricular filling characteristics. The waveform is measured by pulsed Doppler ultrasound, by placing a sample volume at the tip of the mitral valve on the apical left ventricular long-axis or four-chamber view, and aligning ultrasound beam direction with the left ventricular inflow tract. In subjects with normal diastolic function, the peak early diastolic filling velocity (E-wave) is higher than the peak atrial filling velocity (A-wave). When the left ventricular relaxation is deteriorated, the isovolumic relaxation time (IRT) is prolonged, E-wave is attenuated, and the E-wave deceleration time (DT) is prolonged. Because this condition involves a compensatory rise of the A-wave, the E/A ratio becomes lower than 1. This indicates abnormal relaxation pattern of TMF. Because the TMF is determined by the pressure gradient between the left atrium and left ventricle, the IRT is reduced, E-wave is increased, and DT is reduced when the left ventricular diastolic pressure rises as left ventricular diastolic dysfunction progresses. In this case, the E/A ratio becomes 1.0 or higher, which appears as if it is normal. This condition is called pseudo-normalization of TMF. In patients with severe congestive heart failure or restrictive diastolic dysfunction, the E/A ratio becomes more than 2, IRT becomes less than 60 msec, and DT becomes less than 150 msec.

### 2) Pulmonary venous flow velocity pattern

Transesophageal echocardiography can detect pulmonary venous flow, or if available, lately developed echo machine also can detect it in transthoracic approach. In normal subjects, pulmonary venous flow velocity pattern consists of the antegrade flow during ventricular systole (S-waves: S<sub>1</sub> and S<sub>2</sub>), antegrade flow during early ventricular diastole (D-wave), and retrograde flow (atrial systolic wave: Ar-wave) during atrial systole. The S<sub>2</sub>-wave is usually higher than the D-wave. When the left ventricular end-diastolic pressure (LVEDP), left atrial pressure, and pulmonary artery wedge pressure rise, the S<sub>2</sub>-wave is attenuated, D-wave is increased, and Ar-wave is also increased. When the duration of the Ar-wave becomes longer than the duration of the A-wave of TMF, an elevation of the LVEDP or left atrial pressure is indicated. The D-wave DT correlates well with that of E-wave in TMF. The D-wave DT is shortened in patients with restrictive diastolic dysfunction.

### Pulmonary venous flow velocity



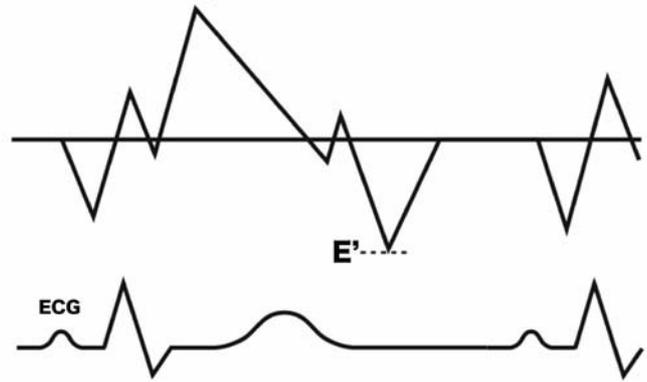
### 3) Flow propagation velocity ( $V_p$ ) during rapid filling period

Blood flow velocity from the mitral valve orifice into the left ventricle is recorded using apical M-mode color Doppler ultrasound, and an aliasing area in the left ventricular rapid filling flow is created using a baseline shift technique, and the flow propagation velocity ( $V_p$ ) is measured as the slope of initial aliasing border or slope of the line along peak flow velocity. This index correlates well with peak negative  $dP/dt$  and time constant of the left ventricular pressure decay ( $\tau$ ), which are indexes of left ventricular relaxation. The slower becomes the relaxation, the lower becomes the negative  $dP/dt$  and the longer becomes the time constant ( $\tau$ ). This method can differentiate patients with pseudo-normal TMF and true normal subjects.

### 4) Peak early diastolic velocity of the mitral annulus ( $E_a$ , $E'$ )

Tissue Doppler sample volume is set on the mitral annulus (left ventricular posterior wall, lateral wall, or interventricular septum) in the apical long-axis or apical four-chamber view, and velocity in the long-axis direction is measured by tissue pulsed Doppler ultrasound. The peak early diastolic velocity (abbreviated as  $E_a$  or  $E'$ ) is sensitive to left ventricular relaxation and not easily affected by preload, as compared to the E-wave of the left ventricular inflow velocity pattern. That is,  $E_a$  ( $E'$ ) does not show so-called pseudo-normalization and decreases as the left ventricular relaxation deteriorates. It should be noted that the value slightly varies depending on the site for recording, and if there is myocardial infarction in the sampling area, the value of the site does not reflect the diastolic function of the whole left ventricle.

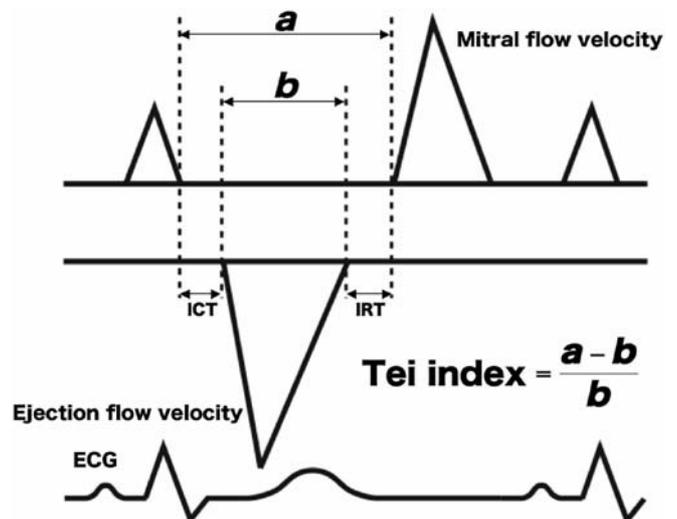
### Mitral annular velocity



## 3. Comprehensive index of both systolic and diastolic functions

**Tei index.** Background: Many patients with heart diseases show decreases in both systolic and diastolic functions. Existing indexes of cardiac functions were designed to assess systolic function alone (including left ventricular ejection fraction, positive  $dP/dt$ , and  $E_{max}$ ) or diastolic function alone (including left ventricular negative  $dP/dt$ ,  $\tau$ , and compliance). In clinical settings, however, it is often necessary to assess the functions of the heart comprehensively. Therefore, a practical index to express global function combining systolic and diastolic function has been invented.

Measurement of the Tei index and its meaning: As shown in the figure below, the time from the start to the end of transmitral or tricuspid blood flow (interval  $a$ ) and the time from the start to the end of aortic or pulmonary ejection (interval  $b$ ) are measured by pulsed Doppler ultrasound.



Interval  $a$  is the sum of the isovolumic contraction time (ICT), ejection time (ET), and isovolumic relaxation time (IRT), and  $a - b$  is the sum of ICT and IRT. ICT and IRT, which are indexes of systolic and diastolic functions, respectively, are prolonged as the systolic or diastolic function deteriorates, but are highly dependent on the heart rate. ET, which is determined by the stroke volume, is shortened as the systolic or diastolic function deteriorates, but is also dependent on the heart rate. By dividing ICT by ET (ICT/ET), this index becomes independent of the heart rate and a decrease in the systolic function is reflected more

clearly. In the same way, IRT/ET is an index of the diastolic function that is independent of the heart rate. The sum of the ICT/ET and IRT/ET is the Tei index, which worsens (increases) when either the systolic function or diastolic function deteriorates. It is the first comprehensive index of cardiac functions that covers both systolic and diastolic functions.

Tei index normal values:  $0.28 \pm 0.04$  in the right ventricle and  $0.38 \pm 0.04$  in the left ventricle. If the value is 0.40 or higher in the right ventricle or 0.45 or higher in the left ventricle, it is regarded as abnormal.