Determination of Cardiac Output by Echocardiography

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Abstract. To determine cardiac output using a non-invasive manner, we examined correlations between cardiac output values determined by ten different kinds of echocardiography and those determined by the thermodilution method. With respect to the M-mode method, one of the rotary ellipsoid approximation methods using a short axial section at the papillary muscular level, namely the GIBSON method, showed the highest correlation with the thermodilution method (r=0.84; p<0.01). Among the Doppler mode method, the highest correlation (r=0.93; p<0.01) was exhibited by the method in which the area of the luminal section of the outflow tract was accurately measured using a trace method on a short axial cross section of the tract flowing out of the left ventricle. These findings suggest that it is possible to determine cardiac output by echocardiography in the same was as with the thermodilution method. Moreover, non-invasive determination methods using echocardiography have been confirmed to be highly beneficial in clinical settings.—Key words: cardiac output, Doppler method, echocardiography, M-mode, thermodilution method.


Observation of cardiac output (CO) is very important in understanding the pathological features of heart diseases. The thermodilution method has conventionally been used as one of the representative methods of CO measurement in clinical diagnosis of a wide range of circulatory diseases in humans.

Application of this method to the clinical veterinary field for routine examinations of circulatory diseases is extremely difficult and invasive and therefore problematic in high risk patients. Repeat examinations are difficult, and the device and expendable supplies for the test are expensive.

It has been shown in human medicine that echocardiography makes it possible to evaluate cardiac function and measure CO with M-mode, as well as with Doppler method, and that there is a relative high correlation between these procedures and the thermodilution method.

Although much of research dealing with CO measurement by the Doppler method has only been focused on the basic aspects in echocardiography [2, 7], few attempts has been made in comparison of CO measurements by Doppler method with the thermodilution method.

Therefore, we investigated the significance and accuracy of CO values determined using echocardiographic devices by comparing them with values obtained by the thermodilution method.

Materials and Methods

(1) Materials

We selected 14 healthy mongrel dogs ranging from 5.1 kg to 16.0 kg in body weight and from 6 months to 2 years in estimated age. The dogs were confirmed as not having heart diseases by mean of auscultation, electrocardiography, radiography and echocardiography, before being subjected to the experiment.

(2) Devices

A thermodilution CO measuring device, the MTC-6210 model (Nippon Koden Kogyo Corp.), was used for CO measurement by the thermodilution method. A Swan-Ganz Catheter 93A-131-7F (Edwards Corp.) was also used in the test. In addition, an Alganc Path Finder Catheter 5F (Catex Corp.) was used for the injection of cold water.

An echocardiographic device, EUB-165 (Hitachi Medical Corp.), was used for CO determination by echocardiography, and search units of 5.0 MHz electronic sector transducer were employed.

(3) CO determination using the thermodilution method

Experimental dogs were placed in a left lateral recumbent position under pentobarbital Na venous anesthesia or continuous OF anesthesia, and a Swan-Ganz catheter was inserted from the right cervical vein. The tip was confirmed to be residing somewhere between the pulmonary trunk and the basal part of left pulmonary artery, on an X-ray TV device and according to the characteristics of pulmonary arterial pressure waveforms. An Alganc Path Finder Catheter was prepared for cold water injection whenever necessary, and was inserted into the right atrium. The position of the tip was confirmed on an X-ray TV device and an echocardiographic device. Cold water, 3 ml or 5 ml, was injected at one time according to the size of the dog. CO was determined five times, and the average of these values was used as the CO value.

(4) Images of the sections depicted on echocardiography

Experimental animals were placed in a left or right (only M-mode of short axis view) lateral recumbent position. The sternal margin of the third to fifth intercostal spaces or the center of the costochondral joint on the left side, or the same site on the right side were used as echo windows.

M-mode and pulsed Doppler methods were used for the determination of CO. The short-axis view at papillary
muscle level and the long-axis view were used for M-mode determination, and the long-axis left ventricular outflow view and the short axis view were used for the Doppler-mode (D-mode) determination.

a: M-mode method

1) Image of the short-axis view at papillary muscle level

The transducer was placed at the level of right costochondral junction, with the scan plane perpendicular to the short axis of the heart.

The image which showed the entire left ventricular space in a circular shape, as fully as possible, was selected. Moreover, the anterior and posterior papillary muscles were depicted equally and clearly. The M-mode beam line on the short axis was adjusted so as to pass through the center of the circle, as well as the center of the anterior and posterior papillary muscles (M-mode short axial scanning; Fig. 1).

For determination of the diameter of the left ventricle, the difference in left ventricular capacity between diastole and systole was calculated from the left ventricular diameter in late diastole (Dd) and that in the late systole (Ds). The value was multiplied by the heart rate to obtain the CO per minute. The difference in the left ventricular capacity was calculated using three different rotary ellipsoid approximation methods, namely, the Pombro method (P method), the Gibson method (G method), and the Teichholz method (T method). Calculation software, incorporated in the echocardiographic device was used for the calculations.

For Dd and Ds measurement, following criteria were used in this study: Dd was measured at a level of the peak of R wave and Ds at the end of T wave of ECG which was well corresponded to the end systolic movement of ventricular septum. However, the timings of the maximal diastole and systole in the ventricular septum did not always coincide with the ECG indicators. In such cases, it was possible to deviate the timing of determination by placing greater emphasis on movement of the ventricular septum (M-mode). This “deviation” was often relative and in parallel, as compared to the timing of electrocardiography.

2) Image of the long-axis view

The transducer was placed at the level of right costochondral junction, with the scan plane perpendicular to the long axis of the heart. For the purpose of depicting the central region of the left ventricular space, the left ventricular space was depicted as extensively as possible. The M-mode beam line was adjusted so as to pass through the chorda tendinea level slightly closer to the papillary muscle, and microadjustment was made so that the line crossed the posterior wall of the left ventricle at right angles, to the greatest extent possible (M-mode long axial scanning).

b: D-mode method

1) Image of the long-axis left ventricular outflow view

For the purpose of scanning the central part of the aortic vessel, the aorta was depicted as extensively as possible and microadjustment was made to minimize the angles against the Doppler beam. The commissural area of each valve was depicted as an indicator for scanning the central part of the vascular lumen. The beam line on the D-mode was set so that the line would be parallel to the direction of blood flow. Angle correction was always necessary in this view.

The time velocity integral (TVI) was calculated from the Doppler wave forms obtained, and aortic diameter was determined on this view (DIOMET method). These values were multiplied with the automatically calculated section area of the tract flowing out of the left ventricle to calculate the CO volume (D-mode long axial scanning; Fig. 2).

With respect to Doppler waveform, the scan angle was adjusted to as to provide high sensitivity, obvious waveforms and clear color Doppler indications, and the sample volume (SV) was set at the center. Accordingly, the SV position was set mainly at the valvular ring region or at the basal part of the aorta. The length of the SV was always adjusted to 1 mm. The diameter was determined when the image of the section showed a clear border. If the border was unclear, it was estimated from the 2-D image by adjusting the sensivity of color Doppler, and repeating on and off of color image. For determination, a line which

[Fig. 1. Short-axis view at the level of papillary muscle and M-mode determination. IVS = interventricular septum; APM = anterior papillary muscle; PPM = posterior papillary muscle; RV = right ventricle; LV = left ventricle; LVPW = left ventricular posterior wall; PCG = phonocardiogram; ECG = electrocardiogram.]
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Fig. 2. TVI is obtained by tracing of the Doppler waveform, and is multiplied by the area of the tract flowing out of the left ventricle (three different measurement methods) to calculate stroke volume. AO=aorta; RA=right atrium; RVOT=right ventricular outflow tract; PA=pulmonary artery; RPA=right pulmonary artery; PCG=phonocardiogram; ECG=electrocardiogram.

crossed the beam line vertically at the SV was drawn, and the distance to the vascular wall was determined. For recording Doppler waveforms, a maximal sweep speed of 240 mm/sec was used in principle, but was replaced with a lower velocity whenever necessitated by decreases in the heart rate.

2) Image of the short axis view at level of aortic root

To determine the luminal area of the aortic vessel more accurately, the area of an almost circular luminal section was determined on a slightly peripheral part of the Valsalva sinus (Fig. 2).

3) Image of the short axis view at level of pulmonary artery

The site which primarily provided depiction of the commissural region of the aortic valve, together with the best depiction of the pulmonary trunk and bilateral pulmonary artery, was selected. Microadjustment was made so that the angle against the Doppler beam would be minimized. SV was set at the center of the region of the pulmonary trunk under color Doppler guidance. Angle correction was unnecessary.

4) Determination methods

CO was measured five times by means of the thermodilution method and the average was calculated. This value was compared with the value determined once by echocardiography. To avoid time-related effects, the echocardiographic measurement was made between the third and fourth measurements of CO by the thermodilution method.

In Experiment 1, one CO value determined by the thermodilution method was compared with each value obtained using the nine kinds of echocardiographic methods. Fifty-two pairs of the CO values were obtained in seven experimental animals.

In Experiment 2, five different determination methods which showed good correlations with the thermodilution method in Experiment 1, were selected, and additional examinations were conducted.

Another seven dogs were selected for Experiment 2. The standard determinations by the thermodilution method were conducted separately for three M-mode method types and two D-mode method types to reduce the time-related differences between determinations. To minimize errors, three measurements were made with each echocardiographic method, and the average was compared. For the same purpose, a part of the measurement procedure was modified in D-mode determination. Thus TVI was obtained using the same procedure as described above. Then, the screen was replaced, and the method was changed to the TRACE method in which the area of the vascular luminal section obtained by D-mode aortic short axial scanning was directly traced in a circular shape (Fig. 2).

As in Experiment 1, 52 pairs of values were obtained in this experiment. Since these values may vary depending on the depth of anesthesia, measurements were conducted at different times in order to provide values as different as possible.
RESULTS

(1) Experiment 1
In Experiment 1, the standard CO values determined by the thermodilution method were 0.83, 3.47, and 1.52 l/min at minimum, maximum, and on average, respectively. These values were compared with the values obtained by the following methods.
- M-mode method
  1) Short-axial scanning
     The minimum, maximum and average CO values were 0.71, 3.11 and 1.34 l/min, respectively, when calculated with the P method, 1.23, 4.82 and 2.19 l/min, respectively, when calculated with the G method, 0.93, 3.94 and 1.68 l/min, respectively, when calculated with the T method. Good correlations with the values determined by the thermodilution method were obtained (r=0.80, r=0.85, and r=0.84 for P, G, and T methods, respectively; Fig. 3).
  2) Long-axial scanning
     The minimum, maximum and average CO values were 0.18, 2.35 and 1.11 l/min, respectively, when calculated with the P method, 0.57, 3.57 and 1.89 l/min, respectively, when calculated with the G method, 0.23, 3.01 and 1.36 l/min, respectively, when calculated with the T method. Correlations with the value determined by the thermodilution method were r=0.25, r=0.35 and r=0.24, respectively. 
- D-mode method
  1) Aortic long axial scanning
     The minimum, maximum and average CO values obtained were 0.49, 2.83 and 1.30 l/min, respectively. A good correlation with the values obtained by the thermodilution method (r=0.73) was obtained. The average degree of angle correction was 39.90±6.60.
  2) Aortic short axial scanning (DIAMET)
     The area of the luminal section of the aortic vessel was more accurately determined by the trace method. The minimum, maximum and average CO values obtained by multiplying the section area with the remaining TVI were 0.70, 2.78 and 1.54 l/min, respectively. A good correlation with the value obtained with the thermodilution method was obtained (r=0.83).
  3) Pulmonary arterial long axial scanning
     The minimum, maximum and average CO values calculated in the same way as described above, in sections 1 and 2, were 0.35, 1.78 and 0.99 l/min, respectively. A correlation of r=0.31 was noted.
(2) Experiment 2
- M-mode
  1) Short axial scanning
     The standard CO values determined by the thermodilution method were 0.59, 2.76 and 1.35 l/min, at minimum, and on average, respectively. The minimum, maximum and average values obtained by short axial scanning were 0.49, 2.88 and 1.31 l/min, respectively, when determined by the P method, 0.88, 3.95, and 2.07 l/min when determined by the G method, and 0.64, 3.01 and 1.52 l/min when determined by the T method. Correlations with the thermodilution method were relatively low (r=0.75, r=0.81 and r=0.80) respectively.
- D-mode
  1) Aortic long axial scanning
     The standard CO values determined by the thermodilution method were 0.67, 2.28 and 1.32 l/min at the minimum, maximum, and on average, respectively.
     The minimum, maximum and average values obtained by the aortic long axial scanning method were 0.56, 2.00 and 1.08 l/min, respectively. The correlation with the thermodilution method (r=0.81; average degree of angle correction; 34.42±9.99°) was slightly higher than that in Experiment 1.
  2) Aortic short axial scanning (TRACE)
     The minimum, maximum and average values determined by the TRACE method were 0.65, 2.17 and 1.34 l/min, respectively, and a very close correlation (r=0.93) with the thermodilution method was obtained (Fig. 4).
     Table 1 shows the summary of above results.
     It was our original experimental design to use the average of five CO values obtained by the thermodilution method for comparison. However, there were variations

Fig. 3. Correlation between the cardiac output obtained by the M-mode method on short axial section (axis Y) and the cardiac output (axis X) obtained by thermodilution. Pombo, Gibson and Teichholz method from the left.
in each of these values. Accordingly, one value was randomly extracted from the five CO values determined, and then, compared with the average of all five values including this value. As a result, a correlation of \( r = 0.93 \) was obtained. This value was similar to the value obtained by the TRACE method using D-mode aortic short axial scanning \( (r=0.93) \). These findings suggest that the accuracy of the current method is comparable to that of the thermodilution method.

**DISCUSSION**

The following observations were made during the current study:

1. An extremely poor correlation was obtained using the rotary ellipsoid approximation method based on M-mode determination of the left ventricular diameter on the long-axis view I. The following factors are considered to account for this findings:
   a. Scanning of the central part of the left ventricular space is the most important step in evaluating the image of the left ventricular long axial section. Confirmation is, however, based on whether or not a large left ventricular space is depicted. This may have resulted in underestimation of the output volume.
   b. The M-mode beam is set at the chorda tendinea level [4]. Moreover, it is a principle rule to set the beam vertically against the posterior wall of the left ventricle. However, it was difficult to satisfy this condition in many experiments. This may have resulted in overestimation of the output volume.
   c. In determining the diameters of the left ventricle in the late stages of diastole, the lines of numerous structures, including the chordae tendinae, are depicted by M-mode examination of the posterior wall of the left ventricle, and some experience was necessary for evaluation of these lines.
   d. The timing of determinations of diameters also varied. The diameter of the left ventricle during (Dd) was determined either at the peak of the R wave [3] or at the Q wave [4, 5] on electrocardiography. Similarly, some textbooks suggest that the diameter of the left ventricle during (Ds) be determined at the end of the T wave [3], while others suggest the period during which the II aortic valve component emerges on a photocardiograph [6].

2. Relatively high correlations were obtained using the same method based on M-mode of the short-axis view at papillary muscular level. This seems to be attributable to the following factors:
   a. Since the left ventricular space is expressed as a round shape on the image of the left ventricular short axial section, it was easy to depict the central part on the M-mode beam line. Moreover, since the short axis of the rotary ellipsoid is used as the indicator, errors in measuring the maximum left ventricular space with the scan angle

| Table 1. Correlation coefficients between CO measurements by echocardiography and values by thermodilution method |
|---------------------------------------------------------------|----------------|----------------|
|                  | Value by single measurement | Average of three measurements |
| POMBO            | \( r = 0.25 \)             | —               |
| Long axial scanning | \( r = 0.35 \)             | —               |
| GIBSON           | \( r = 0.24 \)             | —               |
| TEICH            | \( r = 0.80 \)             | 0.75            |
| M-mode           | \( r = 0.85 \)             | 0.81            |
| Short axial scanning | \( r = 0.84 \)         | 0.80            |
| POMBO            | \( r = 0.73 \)             | 0.81            |
| GIBSON           | \( r = 0.83 \)             | —               |
| TEICH            | \( r = 0.93 \)             | —               |
| Aortic long axial scanning | \( r = 0.31 \)         | —               |
| Aortic short axial scanning (DIAMET) | \( r = 0.83 \)         | —               |
| Aortic short axial scanning (TRACE) | —                  | 0.93            |
| Pulmonary arterial long axial scanning | —                  | —               |
are considered to be minimized.

In light of the principle of measuring the maximum left ventricular space in humans, some scholars have suggested that determination be made at the chorda tendinea level even on left ventricular short axial section images [4, 5]. In the current study, papillary muscular level was selected for the following reasons. It facilitates the standardization of depicted sections because of a depiction of very close area to the chorda tendinea level by extensive depiction of bilateral papillary muscles and can be applied for small animal in which short section is often difficult to see.

When compared with the output cardiac volume determined with the thermodilution method, the results obtained in the current study did not always underestimate the values, but rather tended to overestimate them. This also suggests that careful examinations are necessary in applying the principles generally adopted in humans to animals.

b: The phenomenon described in the above section (1) was also noted with this method. In both Methods (1) and (2), the Gibson method showed a good correlation.

(3) D-mode method
a: D-mode aortic long axial scanning (DIAMET) method
Relatively high correlation was obtained by this method.

The most important point in applying this technique is to obtain good Doppler waveforms, and combination with the color Doppler method was very useful for achieving this aim. This color display reflected well the presence of blood flow. A good display of left ventricular outflow was noted in the aortic valve and other parts, including the left ventricular side, valvular ring, aortic sinus, and the basal part of the ascending aorta. Accordingly, SV was set at the center of the area displayed in color. Eventually, it was most frequently set at the valvular ring region, and occasionally at the region of the valvular orifice. If valvular movements were exhibited on the Doppler waveforms, which interfere with the determination, the position of the determination was moved slightly forward or backward. The color display could also be used as a means of depicting the maximum diameter of the tract flowing out of the left ventricle.

When the area of the luminal section is determined on the long axial (longitudinal) section image, the aim is to depict the lumen as extensively as possible, and it is technically difficult to accurately determine the diameter of the luminal circle on this image.

b: D-mode aortic short axial scanning (DIAMET) method
This method is advantageous in that the diameter can be determined relatively accurately. An even higher correlation was observed.

c: D-mode aortic short axial scanning (TRACE) method
This method caused only a few determination errors, and a highly significant correlation was obtained. In determining the length of the distance between the vascular walls on D-mode, the line vertically crossing the blood flow at the SV on the Doppler beam is generally used [1, 2]. This is also true when the measurement is made on short axial sections. In our experience using this principle, however, the border of the vascular wall may be difficult to distinguish, making determination of the areas inaccurate. On the other hand, only a slight of SV position caused no significant alternation of Doppler waves (TVI), so that it seemed to be more advantageous to measure the peripheral side of Valsalva sinus which was clearly imaged by the methods of a, b and c. Better results can also be obtained when the aortic luminal area is determined more accurately. In other words, the values obtained by a single determination using aortic long axial scanning \( r=0.73 \) and aortic short axial scanning (DIAMET method; \( r=0.83 \)), and the average of the values obtained by three determinations using aortic long axial scanning \( r=0.81 \) and aortic short axial scanning (TRACE method; \( r=0.93 \)) were based on the same TVI values, respectively. The only difference was the method of determining the aortic luminal area. This observation suggests that factors causing errors in this technique are closely associated with the methods utilized for determining the aortic luminal area. This can be considered a very meaningful finding in examining the accuracy of this method.

d: Long axial scanning (DIAMET) method at the pulmonary arterial bifurcation level
Since the color Doppler method used as guide often provided good demonstration from the pulmonary arterial ring to the pulmonary trunk, SV was set at this site. The other conditions were the same as those used for determining the tract flowing out of the left ventricle. Depiction of the lateral wall of the pulmonary artery, in particular, was difficult in some cases, and we were often forced to guess the border of the vascular wall from the color demonstration. Moreover, the only means of examining this region was the DIAMET method, and accordingly, the correlation was poor.

Brown et al. [1] have reported the same result at this site showing the left ventricular outflow tract by the Doppler method. However, there was no attempt made for correlations with thermodilution method.

Generally speaking, the most significant factor causing errors in determining CO volumes with echocardiography was the overall shape of the basic section depicted, followed by automatic calculation involving squaring of the radius, as well as identification of the borders of the walls of the structures being examined.

The CO value obtained by the thermodilution method represents the value at the moment of cold water injection, while the CO value obtained by echocardiography represents one pulse on an ECG. Accordingly, there were variations among the several values obtained by either method, even if the values were from a single animal.

Variations obtained during measurement with the aortic arterial short axial scanning (TRACE) method \( r=0.93 \)
were similar to those among the values obtained by the thermodilution method (r=0.93). Thus, these two methods produced very similar values.

In determinations with the aortic arterial short axial scanning TRACE method using Doppler mode, it is possible to eliminate one of the above factors causing errors, namely, squaring of the radius. Accordingly, we confirmed that careful depiction of the basic sectional image and careful identification of the wall borders facilitates obtaining values similar to those obtained by the thermodilution method. Because of its non-invasiveness, this technique was found to be highly useful as a method of clinical examination.

REFERENCES


