Non-Invasive Measurement of Subclavian Arterial Blood Flow as a Parameter of Cardiac Output by the Doppler Ultrasonic Flowmeter

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SUMMARY

The subclavian arterial blood flow as a parameter of cardiac output was measured in 7 patients with ischemic heart disease (3 acute myocardial infarction, 3 angina pectoris, 1 variant form of angina pectoris) and 5 normal subjects. The measurement was continuously and non-invasively made, utilizing the Doppler ultrasonic flowmeter technique before, during and after exercise. The exercise was performed in the upright position on a bicycle ergometer for 3 min at the work load of 230 Kpm/min. In 3 normal subjects, oxygen consumption at various work loads was also measured by the Douglas bag simultaneously with the subclavian arterial blood flow.

In normal subjects, the subclavian arterial blood flow steeply increased soon after the beginning of the exercise and promptly returned to the pre-exercise level after the termination of the exercise. While in patients with ischemic heart disease, the increase in the subclavian arterial blood flow during the exercise was slow, and the time required to return to the pre-exercise level was significantly prolonged. Light to moderate exercise under the work load of 230 Kpm/min increased both the subclavian arterial blood flow and oxygen consumption nearly in the same ratio. With stronger exercise, the increase in oxygen consumption was by far larger than in the blood flow.

Continuous measurement of the subclavian arterial blood flow by the Doppler ultrasonic technique is supposed to be a useful method for the evaluation of cardiac function.

Additional Indexing Words:
Subclavian arterial blood flow Doppler ultrasonic flowmeter Cardiac output Bicycle ergometer Exercise Oxygen consumption

To evaluate cardiac function, clinical examinations are widely performed by traumatic or atraumatic methods. It is well-known that cardiac output provides clinicians with one of the most important pieces of information on the
condition of the heart. Although there are several methods, such as the Fick method, indicator dilution technique and others, for its measurement, it is clinically not always easy to determine it. It may well be said that there is no good means available for us of measuring non-invasively the continuous change in cardiac output during exercise.

The ultrasonic diagnosis utilizing the so-called Doppler effect was first introduced into medicine by Satomura et al.\textsuperscript{1,2} Thereafter, the Doppler ultrasonic flowmeter system has been developed and improved by Franklin et al.\textsuperscript{3,4} and others,\textsuperscript{5} and has been widely applied not only for the examination of peripheral circulation but also for the analysis of central hemodynamics.\textsuperscript{6-9} The change in the subclavian arterial blood flow during exercise has been studied by using the Doppler ultrasonic technique in our laboratory.\textsuperscript{10,11} It has been examined as to whether it is adequate to make the subclavian arterial blood flow obtained by the Doppler technique a parameter to know indirectly the change in cardiac output during exercise. The purpose of this paper is to present our method and some results obtained through it.

**MATERIALS AND METHODS**

The ischemic heart disease group consisted of 3 patients with acute myocardial infarction, 3 angina pectoris and 1 variant form of angina pectoris. The diagnoses were made from clinical findings and laboratory data including electrocardiogram and enzyme activity. The study was also carried out in 5 normal subjects as a control. The probe of the Doppler ultrasonic flowmeter was a plastic unit, 20×10×5 mm in size, on which a piezoelectric crystal was mounted at 60 degrees to the underlying surface. A single mounted piezoelectric crystal was used both as a transmitter and a receiver. The frequency of the transmitted ultrasound was 6 mHz. The Doppler flowmeter and the probe were specially devised and manufactured for this study (NEC, Tokyo). A multichannel data recorder, Model R-200 (TEAC, Tokyo) for recording, and a computer, Link 8 (Digital Equipment, Maynard) for data processing were used.

The probe of the flowmeter was firmly placed on the skin over the subclavian artery utilizing the elasticity of rubber strap and adhesive tape; electrocardiographic electrodes were also placed on the chest wall. A good coupling between the transducer and the skin was obtained by using a commercially available gel. The analogue curve was obtained by zero-crossing counting the Doppler flowmeter signal. After converted by an A-D converter from the analogue curve to the digital number, it was continuously integrated to get the regional blood flow of the subclavian artery. The integration was automatically made by the computer at intervals of 4 sec. The mean heart rate was calculated at the same intervals from R-R interval of the electrocardiogram. The results of calculation, namely, the subclavian arterial blood flow obtained by the Doppler flowmeter and mean heart rate, were successively displayed on a display unit of the computer; it was also possible to type out on a keyboard, as occasion required. In addition, both the
analogue curve and the flowmeter audio signal were continuously monitored throughout the examination by the monitor system which consisted of a cathode ray tube and a loudspeaker. Fig. 1 shows the block diagram used in this study. Exercise was performed in the upright position on a bicycle ergometer (Monark, Varberg) for 3 min at the work load of 230 Kpm/min. Recordings were obtained in succession for 2 to 3 min at rest, 3 min during exercise and 3 min after exercise; for 11 to 12 min in the total length.

In 3 normal subjects, oxygen consumption during ergometric exercise at different work loads as well as the subclavian arterial blood flow obtained by the Doppler flowmeter was measured. Exercise was performed in all subjects at the work loads of 165, 230 and 300 Kpm/min, each for 3 min. Expiratory air was collected by the Douglas bag, and analyzed by the Holdane apparatus.

**Results**

1. Normal group:

As represented in the illustrated case (Fig. 2), the subclavian arterial blood flow obtained by the Doppler technique steeply increased after the beginning of exercise. The increase in the blood flow was 2 to 3 times as resting blood flow level, and its peak was situated in the first half of the exercise in most instances. After the exercise was over, the blood flow swiftly returned to the pre-exercise level. The time required to return to the pre-exercise level after the termination of exercise was about 1 min and a half. The characteristic of the normal subjects was the rapid hemodynamic response in the subclavian arterial blood flow to exercise.

2. Ischemic heart disease group:

The results were summarized in Fig. 3, comparing patients with ischemic heart disease with normal subjects. Generally, in the ischemic heart disease group, the subclavian arterial blood flow obtained by the Doppler technique increased slowly during the exercise, and the maximal rate of its increase remained in lower level. The time required to return to the pre-exercise level...
Fig. 2. Response in the subclavian arterial blood flow to exercise in a 24-year-old healthy man. Recording was continuously obtained throughout the examination: 3 min at rest, 3 min during exercise, and 5 min after exercise. Note the steep increase in the subclavian arterial blood flow soon after the beginning of the exercise, and the quick return of the blood flow to the pre-exercise level after the termination of the exercise. (SABF=subclavian arterial blood flow, HR=heart rate)

level of the blood flow was markedly prolonged in comparison with normal subjects: it took about 3 min to return. It was the characteristic of patients with ischemic heart disease that the slower hemodynamic response in the subclavian arterial blood flow was induced by the same exercise as in normal subject. Fig. 4 was obtained in a patient with acute myocardial infarction.

3. Subclavian arterial blood flow and oxygen consumption:

Fig. 5 shows the correlation between the subclavian arterial blood flow obtained by the Doppler technique and oxygen consumption during exercise in 3 normal subjects. By light to moderate exercise under the work load of 230 Kpm/min both the blood flow and oxygen consumption increased in parallel with each other nearly in the same ratio. However, during the exercise over the work load of 230 Kpm/min, the increase in oxygen consumption
Fig. 3. Comparison of the subclavian arterial blood flow between normal subjects and patients with ischemic heart disease.

was by far the larger than that of the blood flow.

DISCUSSION

Although cardiac output is closely related to myocardial contractility, it is also influenced by such other factors as heart rate, venous return and vascular resistance. That is to say, cardiac output can be taken as one of
Fig. 4. Response of the subclavian arterial blood flow to exercise in a 69-year-old man with acute myocardial infarction. The recording was obtained 30 days after the onset of acute myocardial infarction. Note the small increase in the subclavian arterial blood flow during the exercise, the further increase after the termination of the exercise, and the prolongation of the time to return to the pre-exercise level. This paradoxical phenomenon well be called "output failure".

...the most important indicators for the overall evaluation of cardiac function. Especially, it is possible to know cardiac reserve by continuously measuring the response of cardiac output to exercise. There is no question that such traumatic methods as the Fick method and indicator dilution techniques are desirable for its accurate measurement. Clinically, however, it is almost impossible to perform the procedure for the invasive measurement of the continuous change in cardiac output during exercise, with the exception of some special cases. Accordingly, we have chosen the measurement of the subclavian arterial blood flow as a parameter of cardiac output by the Doppler ultrasonic technique instead of measuring cardiac output itself.

The Doppler effect of ultrasound was first introduced into medicine by Satomura et al and the Doppler ultrasonic flowmeter technique was de-
veloped into clinical use by Franklin and his co-workers.\textsuperscript{3,4} The technique has been used for the study of central hemodynamics in the normal and abnormal heart,\textsuperscript{7,8,14,15} hemodynamics of arrhythmias,\textsuperscript{16,17} coronary blood flow,\textsuperscript{18} cerebral circulation\textsuperscript{19} as well as peripheral circulation.\textsuperscript{20-22}

It seems that the most important characteristic of the Doppler ultrasonic technique is its capability of measuring blood flow both continuously and non-invasively. However, for the atraumatic Doppler method, it is inevitably accompanied with several problems as follows: (1) the transcutaneous measurement by the Doppler method is not the measurement of volume flow, but flow velocity, (2) the blood vessel makes a pulsatile change in its diameter according to blood ejection, (3) peripheral blood vessels such as the subclavian artery must be used for the measurement instead of the aorta, and (4) displacement of the probe from the skin area overlying the blood vessel, especially during exercise. The same limitations of the technique are also pointed out by Benchimol et al\textsuperscript{8} and others.\textsuperscript{5,6} By measuring relative changes in regional blood flow, the technique is appropriate to know the pattern of regional blood flow response to exercise. Although it is possible, estimating the diameter of the blood vessel under the probe, to obtain a rough volume flow, other methods

![Graph showing correlation between subclavian arterial blood flow and oxygen consumption during exercise at various work loads.](image-url)
should be employed if accurate volumetric measurement of cardiac output or regional blood flow is needed.

Since oxygen consumption is determined mainly by the strength of exercise, it goes without saying that oxygen consumption during exercises is not directly related to cardiac function. With light to moderate exercise, both cardiac output and oxygen consumption increase in parallel with each other; and with stronger exercise, the increase in oxygen consumption is by far larger than that in cardiac output.\textsuperscript{12),23} In this study, with the exercise of work loads under 230 Kpm/min, the subclavian arterial blood flow also increased in parallel with oxygen consumption. With stronger exercise, the increase in oxygen consumption was significantly larger than that in the blood flow. That is to say, the relation between the regional blood flow of the subclavian artery and oxygen consumption during exercise is approximately the same as that between cardiac output and oxygen consumption. With respect to oxygen consumption, both cardiac output and the subclavian arterial blood flow are estimated to respond to exercise in an analogous pattern. Hence it seems to be reasonable to choose the subclavian arterial blood flow obtained by the Doppler ultrasonic technique as an indirect index of cardiac output.

Exercise tests, which are performed for the purpose of cardiac function tests, are classified roughly into 2 groups: one is to impose the exercise of a standardized work load, such as the Master two-step test; to impose a maximal or submaximal exercise is the other.\textsuperscript{24} Lighter exercise is desirable, if it is possible to discriminate between normal subjects and patients with heart disease by it, as it can be safely performed even in subjects with impaired cardiac function. In this study, exercise was performed on a bicycle ergometer at the work load of 230 Kpm/min for 3 min. With this exercise, significant differences in the blood flow response of the subclavian artery were observed between normal subjects and patients with ischemic heart disease.

As stated before, one of the important means for the evaluation of cardiac function, especially cardiac reserve, is to examine the response of cardiac output to exercise. In the results of our study, a special state, which may well be called “output failure”, was observed in a patient with acute myocardial infarction. This phenomenon is supposed to be neither more or less than the manifestation of diminished cardiac reserve due to decreased myocardial contractility resulting from acute myocardial infarction. There are marked differences in the response of the subclavian arterial blood flow to exercise between normal subjects and patients with ischemic heart disease. As a simple parameter of cardiac output, the continuous blood flow measurement of the subclavian artery by the Doppler ultrasonic flowmeter is a useful method for the non-invasive evaluation of cardiac function.
REFERENCES