Analysis of Flow Patterns in Blood Vessels
with the Directional Ultrasonic Doppler Technique
through a Transcutaneous Approach

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Measurements of the blood flow have come to be more important in clinical medicine. The development of the ultrasonic Doppler technique has made it possible to measure instantaneous velocity of the blood flow without surgical intervention. Transcutaneous application of this technique seems safe, being repeatable and providing useful information about the circulatory dynamics in both arterial and venous systems.

With the recent advance in technology, a detection of forward and/or reverse blood flow has become possible. This bidirectional Doppler method has a great advantage over the ordinary unidirectional flowmeter.

The purpose of this study was to define the blood flow patterns in both healthy subjects and patients, and to confirm the usefulness of the Doppler method.

Methods

The technique is fundamentally based on the Doppler shift principle proposed by Satomura and his associates, and the principle for the detection of blood flow direction is based on a frequency shift method. The details about the method have been reported previously.

The transmitted frequency “f” used was 5 MHz. The frequency of back-scattered ultrasound is higher than that of transmitted ultrasound when the blood corpuscles flow toward a transducer working on the Doppler principle, and it becomes lower when the corpuscles flow away from the transducer. The frequency of back-scattered ultrasound is represented by (f + fd), where “fd” means frequency shift. This “fd” is derived from the formula fd = 2vf cos θ/c. Here, c is the ultrasound velocity, θ is the angle between the motion of the corpuscle and the ultrasonic beam, and v represents the velocity of the corpuscle. The velocity v may take either a positive or a negative value depending upon the direction of movement of the corpuscle, i.e., v is positive or negative, as the corpuscles approach or leave the transducer.

A beat occurs when transmitted ultrasound is mixed with backscattered ultrasound. By using the local oscillation instead of transmitted ultrasound, the beat is also obtained. In this study, 5.004 MHz was adopted as the local oscillation frequency of (f + fl), hence “fl” equals 4 KHz. Therefore, the frequency of beat becomes |(f + fl) - (f + fd)|, that is, |fl - df|. Thus, the blood flow patterns toward and away from the transducer are recorded below and above the base-line (4 KHz), respectively.

Patients were examined in a supine position under their casual respiration. An electroacoustical transducer made of PZT was placed on the skin with an incident angle of 60 degrees in order to obtain satisfactory recordings. The calculation of flow velocity from the Doppler shift frequency was done on the assumption that

Key Words:
Directional Ultrasonic Doppler Method
Blood Flow Measurement
Velocity Spectrum
Sound Spectrographic Display
Non-invasive Technique

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* This paper was presented at the Symposium on “Hemodynamics in the Cardiovascular System” on the 36th Annual Meeting of the Japanese Circulation Society in Kanazawa, April 10, 1972.
Fig. 1. An example of a sound spectrographic display. The ordinate represents the Doppler frequency, i.e., the speed of blood corpuscles. A blood flow away from and towards the heart is presented below and above the base-line, respectively. The abscissa represents time. The darkness correlates to the output voltage. This pattern was obtained from the femoral artery of a healthy subject.

Fig. 2. The blood flow pattern in the carotid artery of a healthy subject. (S. K., a 30-year-old man)

the vessel was almost running parallel to the skin. However, this assumption was not considered to be the case for the subclavian artery or the vertebral artery.

The Doppler output was once recorded on a magnetic tape and later displayed by a sound spectrograph. The sound spectrograph can analyze the Doppler event in 2.4 seconds upon a sheet of developing recording paper. A sound spectrogram of the blood flow pattern of the femoral artery is represented in Fig. 1. In this figure, the ordinate represents the Doppler frequency, which is proportional to the velocity of blood corpuscles. A blood flow towards and away from the transducer is displayed below and above the base-line, respectively. Presently the transducer was applied towards the proximal, so that a forward flow in the artery was displayed below the base-line. When the transmitted frequency was 5 MHz and the angle of incidence 60 degrees, 1 KHz of Doppler frequency corresponded to the corpuscular speed of

Fig. 3. Change of the blood flow pattern in the common carotid artery by advanced age. On top is recording from a 27-year-old man, and on the bottom from a 78-year-old woman.

30 cm per second. The darkness of the pattern on the paper correlates to output voltage, which.

*Japanese Circulation Journal Vol. 37, July 1973*
Fig. 4. Change of the flow pattern after inhalation of amyl nitrate. On top is before the test, on the bottom is after inhalation, suggesting an increased blood flow volume. (H. M., a 37-year-old man)

Fig. 5. Change of the flow pattern following a cold pressure test. On top is a control at room temperature 25°C. On the bottom is a recording immediately after ice is placed on the palm. (K. K., a 29-year-old man)

is proportional to the square root of the number of blood corpuscles per unit volume of the blood, as previously reported by Kato and his associate.

Results

1) Arterial blood flow patterns in healthy subjects.
### TABLE I

<table>
<thead>
<tr>
<th></th>
<th>No.</th>
<th>Velocity Peak cm/sec</th>
<th>Appearance Time sec</th>
<th>Inclination of First Forward Flow cm/sec²</th>
<th>Reverse Flow No.</th>
<th>Peak Velocity cm/sec</th>
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<td><strong>Common Carotid Art.</strong></td>
<td></td>
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<td></td>
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<td>Young Subjects</td>
<td>23</td>
<td>113.1 (20.04)</td>
<td>0.11 (0.018)</td>
<td>1438 (515.1)</td>
<td>4</td>
<td>9.5</td>
</tr>
<tr>
<td>Old Subjects</td>
<td>21</td>
<td>70.1 (17.52)</td>
<td>0.11 (0.018)</td>
<td>1044 (301.5)</td>
<td>9</td>
<td>11.0 (7.28)</td>
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<td><strong>Brachial Art.</strong></td>
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<td></td>
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<tr>
<td>Young Subjects</td>
<td>22</td>
<td>92.1 (18.75)</td>
<td>0.18 (0.018)</td>
<td>1072 (225.9)</td>
<td>8</td>
<td>17.9 (4.79)</td>
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<tr>
<td>Old Subjects</td>
<td>21</td>
<td>78.5 (17.07)</td>
<td>0.16 (0.022)</td>
<td>1077 (186.2)</td>
<td>15</td>
<td>14.3 (5.03)</td>
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<tr>
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<td></td>
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<tr>
<td>Young Subjects</td>
<td>15</td>
<td>75.3 (16.99)</td>
<td>0.21 (0.013)</td>
<td>915 (203.5)</td>
<td>2</td>
<td>13.3</td>
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<td>Old Subjects</td>
<td>21</td>
<td>64.2 (16.33)</td>
<td>0.17 (0.017)</td>
<td>1130 (253.8)</td>
<td>7</td>
<td>10.2 (2.25)</td>
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<td><strong>Femoral Art.</strong></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young Subjects</td>
<td>18</td>
<td>88.2 (10.52)</td>
<td>0.21 (0.019)</td>
<td>824 (157.7)</td>
<td>18</td>
<td>31.6 (6.80)</td>
</tr>
<tr>
<td>Old Subjects</td>
<td>18</td>
<td>101.8 (29.11)</td>
<td>0.16 (0.019)</td>
<td>1043 (288.2)</td>
<td>18</td>
<td>23.4 (9.36)</td>
</tr>
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**p < 0.01 * 0.01 < p < 0.1 NS p > 0.1**

![Diagram](image)

Fig.6. Transmission of the velocity wave. On the bottom is a blood flow pattern in the femoral artery; on top the radial artery. Both forward and reverse flow phases proceed from proximal to distal.

Blood flow patterns in various arteries located in the vicinity of the body surface were obtained. In the carotid artery, the blood flow pattern showed the rapid forward phase in systole and the slow forward phase in diastole (Fig. 2). The rapid forward phase exhibited two peaks. The first peak showing larger amplitude was a higher velocity than the second peak of lower amplitude.
The third peak subsequently occurs in early diastole, gradually decreasing until the beginning of the next pulse cycle. In this artery the flow pattern was generally unidirectional, except for the occasional appearance of a minor momentary reverse flow between the second and third peak. The occurrence of this minor reverse corresponded to a diastolic notch in carotid pulse tracing. With aging, the first peak became lower and the second peak higher (Fig. 3). Immediately after inhalation of amyl nitrate, the blood flow velocity increased (Fig. 4).

In the subclavian artery, the reverse phase was usually recorded more clearly than that in the carotid artery. But, as for its velocity, it was not always correctly measured because of the course of running unparallel to the skin as mentioned above.

The blood flow pattern in the brachial artery was easily obtained. In some subjects the blood flow pattern was unidirectional through a pulse cycle, while in others it had the reverse flow phase following the rapid forward phase. Even in the same individual the unidirectional flow occasionally showed the reverse phase during a short examining period. Such change of flow pattern was related to emotional state, room temperature, and so on. A marked reverse phase was observed in a cold pressure test. Before the test, the blood flow of the brachial artery was forward and continuous. As soon as the test began, the pattern showed an interruption of the flow in diastole and the appearance of the reverse phase (Fig. 5).

In the femoral artery, the reverse flow phase was obviously following the early forward phase (Fig. 1). Sometimes, in late diastole another reverse phase was observed after the slow forward
Fig. 9. The flow pattern in the stenotic portion of the common carotid artery in aortitis syndrome. (M. N., a 43-year-old woman)

Fig. 10. Cyclic change of flow velocity in a case of pulsus alternans with primary myocardial disease. The tracing obtained from the femoral artery. (K. Y., a 49-year-old man)

Fig. 11. Deceleration of the forward flow and increased reverse flow in ventricular premature beat. The tracing obtained from the femoral artery. (R. F., a 77-year-old man, complete left bundle branch block)

Phase in diastole.

One group of twenty-three subjects under 40 years of age and another group of 22 subjects over 60 years of age were studied (Table I). The peak velocity was measured at a maximum point of the envelope. The envelope represents an instantaneous maximum speed. The peak velocity in the carotid artery was higher in young subjects than in the old. However, the peak velocity in the femoral artery was higher in the old than in the young. In the old the velocity of the femoral artery was higher than that of the carotid artery.

The time interval from Q wave in ECG to the beginning of the first forward flow phase, i.e., appearance time was measured. This interval in the femoral artery was shorter in the old than in the young, indicating that the transmission of velocity wave was faster in the old. Inclination at the acceleration period of the first forward flow was measured. This inclination was formed with the base-line and the line connecting the beginning of the forward flow phase and the point of peak velocity. In the carotid artery, this inclination was steeper in the young than in the old, but, for the femoral and radial arteries, the reverse was true. A number of cases in various arteries in which the reverse flow phase appeared was also listed on Table I. As mentioned above, the blood flow in the brachial artery is easily affected by minor interventions. The results shown here were obtained while the examines were lying quietly with minimum interference. In the brachial artery, the appearance of the reverse phase in the old was more frequent than in the young; so was also the case in the radial artery. The occurrence of reverse flow phase in the radial artery was about half that in the brachial artery. It was observed in the femoral artery in all cases.

2) Velocity spectrum and velocity wave

The frequency spectrum of Doppler output of the blood flow is the velocity spectrum of blood corpuscles in a cross section of a vessel. The
velocity spectrum was contineous at any instant in a pulse cycle. However, as typically shown in Fig. 2, the frequency spectrum showed a periodical change. The output was mainly ranged near the instantaneous maximum frequency in the acceleration period of the first forward flow, and was a relatively homogeneous band spectrum at the latter half of the first forward phase and at the flow forward phase. It was also noted that, in the process of cyclic change of the flow pattern, there were phases when the forward and reverse flows co-existed (see Fig. 1).

When the recordings were performed simultaneously as the proximal and distal portions of an artery, the beginnings of forward and reverse flows at a distal portion were delayed over those were observed at a proximal portion (Fig. 6).

3) Survey on arterial blood flow patterns in patients.

In case of aortic regurgitation the reverse flow appeared in diastole. The carotid artery showed a marked reverse flow in the latter half of diastole (Fig. 7). In the subclavian artery, the blood flow was reversed throughout diastole. The peak velocity was markedly higher in patients with aortic regurgitation than in healthy subjects.

The carotid artery flow pattern in idiopathic hypertrophic subaortic stenosis showed characteristic features. In the middle of the ejection period, the reverse phase was markedly observed in four of 5 patients with idiopathic hypertrophic subaortic stenosis (Fig. 8). It seemed to correspond to an anomalous ejection mechanism of the left ventricle in the middle of systole. An inclination of the first forward phase was steeper than that in healthy subjects.

In cases of aortitis syndrome, the velocity spectrum of the flow pattern recorded at the stenotic portion was quite different from that of healthy subjects, that is, the frequency spectrum became rather irregular through a range from the base-line to the maximum frequency (Fig. 9). The envelope of instantaneous maximum frequency was not smooth but rugged. Another feature was co-existence of the reverse component with the forward flow in systole.

An examination was performed in a patient of pulsus alternans with primary myocardial disease.

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The blood flow pattern showed beat to beat changes, from high velocity forward and large reverse flows to low velocity forward and small reverse flows (Fig. 10).

In ventricular premature beat, the forward flow was slower and reverse flow was more marked than those of the preceeding normal beats (Fig. 11). In post-extrasystolic beat, the forward flow was accelerated.

4) Venous blood flow patterns in healthy subjects and patients.

The venous flow was also transcutaneously detected with this technique.

The standard form of the normal flow pattern in the internal jugular vein was unidirectional toward the heart, being composed of two peaks which were designated as “S” and “D”, respectively (Fig. 12). A simultaneous tracing of the venous pulse revealed that the initial peak “S” corresponded to systolic collapse and the second peak “D” to diastolic collapse of the venous pulse. There was no definite flow coincident with the “a” wave of the venous pulse in the internal jugular vein, while it was sometimes noted near the confluence of the jugular and the subclavian veins.

The venous flow pattern was easily influenced by physiological or pathological conditions. Deep breathing influenced the flow pattern of the internal jugular vein. During inspiration, the two peaks, especially the initial peak, grew larger, resulting in fusion of both peaks, and was followed by an apparent fusion of all peaks (Fig. 13).

In cases of pericarditis with effusion, the flow pattern of the internal jugular vein showed the reverse phase coincidently with atrial contraction, even in the recordings at a site more distal than the confluence of the jugular and the subclavian veins (Fig. 14), while the reverse phase was not observed above the confluence in healthy subjects. Such a finding was also observed in constrictive pericarditis.

In some cases of interatrial septal defect of a secundum type, two reverse phases were recorded in a pulse cycle being coincident with atrial contraction and the conversion phase from ventricular systole to diastole (Fig. 15). Shortly after recording of the venous flow pattern, pressure measurements were made with a double -hole catheter placed at the internal jugular vein and the superior vena cava near the right atrium. There were two phases of negative pressure gradient between the internal jugular vein and superior vena cava. These two phases coincided with two reverse flow phases on the venous flow.

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Fig. 15. The flow pattern of the internal jugular vein in interatrial septal defect, and pressure measurements with a double-hole catheter at the internal jugular vein and the superior vena cava near the right atrium. The details referable to the text. (T. Y., a 27-year-old man)

Fig. 16. The venous flow pattern in a case of tricuspid regurgitation. The reverse flow phase appears in ventricular systole. (K. T., a 55-year-old man)
DISCUSSION

The principle of the ultrasonic Doppler method was developed by Satomura in 1956 and was applied clinically for the detection of heart motion and blood flow. This method made it possible to record transcutaneously the instantaneous velocity of blood flow in vessels. The original technique permitted one to measure the velocity but not the direction of blood flow.

In 1966, Kato and his associate contrived the frequency shift method which could detect the direction of flow, and in 1967 McLeod developed the phase shift technique for the same purpose. The Doppler output usually is displayed by zero-crossing counter or sound spectrograph. The sound spectrographic display has a disadvantage of allowing no real time data processing. Recently, Light challenged this point by his real time recordings of the frequency spectrum of the Doppler beat. However his technique does not seem to have been developed to allow its routine use. An advantage of the sound spectrographic display is that it is able to express more additional information than the display of the zero-crossing counter by demonstrating the frequency spectrum.

The velocity spectrum of the carotid artery in healthy subjects was continuous, but high output represented by dark density on the sound spectrogram was mainly recorded on the spectrum area of high frequency, especially during the first half of the first forward phase (Fig. 2). If the flow velocity profile is parabolical, the output voltage is constant in the range from the base-line to maximum frequency. However, the results obtained do not support this assumption. It is considered that the major part of the stream consists of rather uniform velocity components.

The frequency spectrum at the latter half of the first forward phase and at the slow forward phase showed a relatively band spectrum, in comparison with the first half of the first forward phase. On the basis of fluid dynamics, the band spectrum indicates that the flow in a vessel is composed of various velocity components and might be rapid in the center of stream and slow in the vicinity of the vessel wall.

Periodical changes of the frequency spectrum mean that the configuration of the velocity profile changes successively in a pulse cycle.

Simultaneous occurrence of forward and reverse flow was demonstrated in this study. Womersley and his associates theorized that, in a pulsatile oscillatory flow, the reverse flow began at the vicinity of the vessel wall in participation with fluid viscosity, while the central stream flowed still forward. The present result seemed to correspond to the above authors' theoretical considerations.

It was ascertained that the reverse flow phase in arteries of the extremities proceeded from proximal to distal following the forward flow with a certain phase delay, so that the reverse flow phase did not rebound from the periphery to the center. The blood flow in a middle-sized artery can be approximately regarded as the propagation of longitudinal wave of a damped oscillation from proximal to distal, undergoing modification of its configuration and amplitude.

In the brachial artery, the flow pattern was easily influenced by emotional state, and the reverse flow appeared in response to minor sympathetic interventions. The reverse phase in the brachial blood flow pattern observed more frequently in the old than in the young. Thus, it is assumed that such an appearance of reverse flow is related to an increase of peripheral resistance. Other evidence supporting this assumption was the response of the blood flow pattern in the cold pressure test.

The reverse flow in the femoral artery occurred in all of the healthy subjects examined, as was revealed in the reports of Rittenhouse et al and Strandness et al.

A marked change of blood flow pattern in the carotid artery was observed in cases of idiopathic hypertrophic subaortic stenosis. It was an occurrence of reverse flow in the middle of maximum ejection, possibly caused by the constriction of the outflow tract of the left ventricle in mid-systole. It is assumed that accelerated blood is allowed to flow forwards on inertia after the constriction and then pulled back towards the aorta.

In cases of aortitis syndrome, the velocity spectrum was rather irregular, suggesting that blood corpuscles flowed at various speeds probably due to the occurrence of a turbulent flow at the stenotic portion. A reverse component co-existing with a forward flow is likely due to a vortical current.

The present findings in cases of ventricular premature beat and pulsus alternans coincided with those by Benchimol and his associates who employed the catheter-tip Doppler flowmeter. Presently it was also found that the
reverse flow phase of ventricular premature beat increased in its velocity and the reverse flow of pulsus alternans was paralleled with the forward flow phase in respect to velocity.

The normal blood flow pattern in the internal jugular vein was without a reverse flow corresponding to atrial contraction. Benchimol et al.22 and Kalmanson et al.23 demonstrated the existence of a reverse flow coincident with atrial contraction in the right atrium with a catheter tip Doppler flowmeter. The reverse flow following contraction of the atrium did not extend to the internal jugular vein in healthy subjects.

The reverse phase coincident with atrial contraction in pericarditis with effusion and in constrictive pericarditis may be a manifestation of diminished ventricular diastolic relaxation.

Two reverse phases observed in interatrial septal defect may result from a large left to right shunt flow at the level of the atrium. Levin and his associates24 pointed out two phases of shunt in interatrial septal defect, one coincident with atrial contraction and the other with the interval phase between systole diastole.

In diagnosing tricuspid regurgitation, it is useful to detect the reverse flow or a decrease of the initial peak in the internal jugular vein during ventricular systole.

**SUMMARY**

1. The bidirectional ultrasonic Doppler method enables one to detect transcutaneously the flow patterns in blood vessels. The velocity spectrum consisting of various velocity components in the vessel can be shown by sound spectrography.

2. In healthy subjects, the arterial blood flow pattern of a single pulse cycle consisted of a rapid early forward flow which was usually followed by a small reverse phase, and a subsequent forward flow in diastole. It was noted that the conversion phase of flow direction showed a simultaneous existence of forward and reverse in the vessel.

3. The arterial flow pattern in such diseases as aortic regurgitation, aortitis syndrome and idiopathic hypertrophic subaortic stenosis showed respective features.

4. Venous flow patterns were also examined. The flow pattern in the internal jugular vein consisted of two peaks in a pulse cycle. This fundamental pattern was easily modified by certain physiological or pathological conditions.

**Acknowledgement**

The authors wish to express their heart felt thanks to Prof. Hiroshi Abe for his advice.

**REFERENCES**


8. NIMURA, Y., MATSUO, H., MOCHIZUKI, S., AOKI, K., WADA, O., & ABE, H.: Analysis of a cardiac cycle of the left side of the heart in case of left ventricular overloading or damage with the ultrasonic Doppler method. Am. Heart J. 75: 49, 1968.


