CHARACTERISTICS OF BLOOD FLOW VELOCITY PATTERNS OF CENTRAL SYSTEMIC VEINS IN HEALTHY ADULTS ASSESSED BY DOPPLER ECHOCARDIOGRAPHY

TOSHIKAI MAEDA, M.D.*, MASUNORI MATSUZAKI, M.D., KOHTARO SHIOMI, M.D.
BACKMOON LEE, M.D., KOHJABURO SEKI, M.D., HIDETOSHI NAITO, M.D.
TADAO YOROZU, M.D.*, YOICHI TOMA, M.D.*, YOSHTO ANNO, M.D.
AND *REIZO KUSUKAWA, M.D.

To evaluate the differences in shape and phase lag of the flow velocity curves in the superior (SVC) and inferior (IVC) venae cavae and the hepatic vein (HV), Doppler echocardiographic examination was performed in 40 healthy adults (aged 20 to 67 years, mean ± SD: 39 ± 12 years). Flow velocity patterns in each vein were characterized by 4 major deflections: S wave, a systolic forward flow; D wave, a diastolic forward flow; A wave, a small backward flow or reduction of diastolic forward flow due to atrial contraction; and O wave, a small backward flow or reduction of forward flow after the second heart sound.

Except for a reduced phasic flow in a collapsed IVC, the venous flow velocity recordings in each vein demonstrated very similar pulsatile patterns and small differences in mean time lags of less than 50 msec. In general, the lowest values of peak A/peak S, peak O/peak S and peak D/peak S were observed in HV flow and the highest in IVC flow. Backflows of A and O waves were prominent in HV flow, but small and least frequent in IVC flow. These data suggest that the baseline of the central venous flow recordings might shift downward in HV flow and upward in IVC flow.

However, even if both the baseline shift and amplitude of the flow curve were normalized in each venous flow velocity curve, apparent differences in shape of the flow velocity curves would remain. We concluded that the characteristics and differences of each central venous flow velocity pattern should be noted in studies of these areas.

MANY investigators have previously reported the phasic blood flow patterns during one cardiac cycle in the central veins, such as the superior vena cava (SVC)\(^1\)–\(^{14}\) inferior vena cava (IVC)\(^1\)–\(^{3}, 15–17\) hepatic vein (HV)\(^13, 15, 18, 19\) and in the jugular veins\(^20–22\). Recently, Doppler echocardiography monitored under 2-dimensional echocardiography has permitted the noninvasive examination of flow velocities in these veins. The central and jugular venous flow velocity patterns have been described to be characteristically abnormal in patients after cardiac surgery, or with tricuspid regurgitation, tricuspid stenosis, cardiac tamponade, constrictive pericarditis, atrial septal defects, atrial fibrillation or a variety of

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Division of Cardiology, Saiseikai Yamaguchi General Hospital, Yamaguchi, Japan
*Second Department of Internal Medicine, Yamaguchi University School of Medicine, Ube, Japan.
Mailing address: Toshiaki Maeda, M.D., Division of Internal Medicine Saiseikai Yamaguchi General Hospital, 2-11 Midori, Yamaguchi, Yamaguchi 753, Japan

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other arrhythmias. However, few systematic studies have investigated the differences and characteristics of the flow velocity patterns in each central vein. The purpose in the present study is not only to obtain typical normal flow velocity patterns in the SVC, IVC and HV, but also to examine the characteristic patterns in each vein to achieve better understanding of the hemodynamics in the right heart.

MATERIALS AND METHODS

Study subjects
Forty subjects (23 men and 17 women, aged 20 to 67 years, mean ± SD: 39 ± 12 years) were included in the study. None of the subjects had a history of cardiovascular disorders nor abnormal findings on physical examination, chest X-ray, electrocardiogram and routine echocardiogram. All Doppler recordings of flow velocity curve in the superior vena cava (SVCF), inferior vena (IVCF) and the hepatic vein (HVF) were adequate for analysis. Heart rates, determined with patients in a supine position, ranged 52 to 80 beats/min (mean ± SD: 63 ± 8 beats/min) and all were in sinus rhythm with normal P-Q intervals on the electrocardiogram.

Doppler Recordings
Doppler examinations were made with the subjects in the supine position holding their breath while during quiet expiration. Toshiba medical SSH-40A or SSH-65A Duplex ultrasound instrument was used. The Toshiba Doppler flow analyzer provides real time spectral analysis using microprocessor-based fast Fourier transform techniques. Blood flow velocity curve, lead II of the electrocardiogram and phonocardiogram were simultaneously recorded on a strip-chart recorder at paper speed of 10 cm/sec. A 3.6 MHz or 2.4 MHz transducer for SSH-40A or 3.75 MHz or 2.5 MHz transducer for SSH-65A was used to obtain flow signals. The size of the sample volume is 2 mm in axial length. The transducer was placed on the upper abdomen to obtain HVF and IVCF, where the distance between the sample volume and the right atrium was approximately 1 to 3 cm for HVF and 2 to 4 cm for IVC. To obtain SVCF the probe was placed on the right supraclavicular fossa and the sample volume was located at 3–5 cm below the junction of both right and left brachiocephalic veins, indicating 1–2 cm cranial from the right pul-

Fig. 2. Determination of per cent fractions of the O and D wave velocities to the S wave velocity after standardization of baseline shift. Peak O'/peak S' and peak D'/peak S' are respectively the per cent fractions of the O and D wave velocities to the S wave velocity after the standardization by shifting the baseline to the peak level of the A wave. Thus, peak O' = peak O-peak A, peak D' = peak D-peak A, peak S' = peak S-peak A.

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monary artery. The Doppler display showed flow toward the heart (toward the probe) as deflections below the baseline.

**Measurements**

A representative example of the central venous flow velocity recordings throughout a cardiac cycle is shown in Fig. 1, where the designation of waves and measurements are described. Systolic and diastolic forward flow waves were designated as “S” wave and “D” wave, respectively. A small backward flow or reduction of forward flow due to atrial contraction, and the backward flow or reduction which appeared after the second heart sound were designated as “A” and “O” waves, respectively. To evaluate the phase lags of the flow velocity curve in each vein, three time intervals were measured, i.e., Q-initial S interval, the time interval from Q wave in the electrocardiogram to the onset of the S wave; Q-peak S interval, the time interval from Q wave to the peak of the S wave; and Q-O interval, the time interval from Q wave to the peak of the O wave. The time of the onset of the S wave was defined as the cross point between the baseline and the extrapolation line of the rapid rise of the S wave.

Doppler shifts below the baseline were defined as positive and those above as negative. Therefore, values of peak A were usually negative. Then normalization of the

**TABLE 1** PARAMETERS OF FLOW VELOCITY CURVES IN THE CENTRAL VEINS FROM HEALTHY ADULTS

<table>
<thead>
<tr>
<th></th>
<th>SVCF</th>
<th>HVF</th>
<th>IVCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-initial S interval (N=37)</td>
<td>79 ± 27 msec</td>
<td>77 ± 28 msec NS</td>
<td>86 ± 30 msec*++</td>
</tr>
<tr>
<td>Q-peak S interval (N=40)</td>
<td>241 ± 33 msec</td>
<td>226 ± 25 msec**</td>
<td>267 ± 27 msec***+</td>
</tr>
<tr>
<td>Q-O interval (N=40)</td>
<td>441 ± 31 msec</td>
<td>429 ± 29 msec**</td>
<td>451 ± 33 msec ns+</td>
</tr>
<tr>
<td>peak A/peak S (N=40)</td>
<td>-26 ± 12%</td>
<td>-40 ± 21%**</td>
<td>-16 ± 29% ns+</td>
</tr>
<tr>
<td>peak O/peak S (N=40)</td>
<td>26 ± 20%</td>
<td>-19 ± 30%**</td>
<td>41 ± 26%***++</td>
</tr>
<tr>
<td>peak D/peak S (N=40)</td>
<td>63 ± 17%</td>
<td>58 ± 20% NS</td>
<td>74 ± 19%***++</td>
</tr>
<tr>
<td>peak O'/peak S' (N=40)</td>
<td>41 ± 18%</td>
<td>14 ± 20%**</td>
<td>47 ± 22% ns+</td>
</tr>
<tr>
<td>peak D'/peak S' (N=40)</td>
<td>71 ± 14%</td>
<td>69 ± 16% NS</td>
<td>77 ± 17%***++</td>
</tr>
</tbody>
</table>

Values are mean ± SD. Peak A, peak O, peak D and peak S are peak Doppler shifts or peak velocities of the A, O, D and S waves, respectively. N=number of subjects; SVCF=superior vena caval flow velocity curve; HVF=hepatic venous flow velocity curve; IVCF=inferior vena caval flow velocity curve; peak O'=peak O-peak A; peak S'=peak S-peak A; peak D'=peak D-peak A. Student's t test: NS=not significant, *p<0.05, **p<0.01 vs SVCF; ns=not significant. †p<0.05, ‡p<0.01 vs HVF.
peak velocities of the A, O and D waves was performed by calculating per cent fractions of the A, O and D wave Doppler shifts to the S wave Doppler shifts: peak A/peak S, peak O/peak S and peak D/peak S, where peak A, peak O, peak D and peak S indicated the peak Doppler shifts of the A, O, D and S waves, respectively. To eliminate the effects of baseline shift on the evaluation of the wave shapes, standardization by shifting the baseline to the peak level of the A wave was also performed in each venous flow velocity curve. Thus, peak S’, peak O’ and peak D’ were defined as follows: peak S’=peak S-peak A; peak O’=peak O-peak A; peak D’=peak D-peak A. Next, peak O/peak S and peak D/peak S in each venous flow curve were calculated (Fig. 2).

Note that Doppler recording did not give an absolute flow velocity curve but only a time course of the relative change in flow velocity since the velocity correction by the cosine of the angle between the direction of blood flow and ultrasound beam was not performed in the present study. These measurements were performed on flow velocity recordings for each vein, and the average values of four beats were utilized. The values were expressed as mean±standard deviation. One-way analysis of variance was employed for multiple comparison of data and then the paired Student’s t

test was used to evaluate the significance of the differences between each two samples.

RESULTS

A representative example of flow velocity recordings in each vein is shown in Fig. 3. The flow velocity curves obtained from different central veins showed similar pulsatile patterns and the flow patterns throughout a cardiac cycle were characterized by two major forward flows (S and D waves) and two backward flows or reduction of forward flows (O and A waves). All measurements from the flow velocity curves in each vein are summarized in Table I. Three cases
Fig. 7. A schematic illustration of the average flow velocity patterns in each central vein. The mean values of time intervals and normalized velocities in each wave were used to draw each flow curve. Subtracted values of mean time intervals in SVCF from that in HVF or IVCF were superimposed with horizontal arrows (msec), and subtracted values of mean normalized velocities of the A, O and D waves in SVCF from that in HVF or IVCF were superimposed with vertical arrows (%). Large arrows show significant shift (p<0.05) and small arrows minor differences. SVCF = superior vena caval flow velocity curve; HVF = hepatic venous flow velocity curve; IVCF = inferior vena caval flow velocity curve.

Fig. 8. Comparison of per cent fractions of the O and D wave velocities to the S wave velocity after standardization of baseline shift. SVCF = superior vena caval flow velocity curve; HVF = hepatic venous flow velocity curve; IVCF = inferior vena caval flow velocity curve. ns = not significant; *p<0.05; **p<0.01

values for the three time intervals, studied in SVCF, HVF and IVCF. There was a significant difference between Q-initial S interval values of IVCF and those of the others (p<0.05 vs SVCF, p<0.01 vs HVF). However, the differences of values of Q-initial S intervals in each venous flow velocity curves were very small (SVCF: 79±27 msec, HVF: 77±28 msec, IVCF: 86±30 msec). The values of Q-peak S intervals in SVCF, HVF and IVCF were significantly different from one another (all p<0.01). Q-peak S interval in HVF was the shortest (226±25 msec) and in IVCF the longest (267±27 msec). As for Q-O interval, that in HVF was also the shortest (429±29 msec, p<0.01 vs SVCF 441±31 msec and p<0.01 vs IVCF 451±33 msec). However, the differences between the mean values of time intervals in each venous flow velocity curve were not so large, i.e. the largest value of differences was 41 msec between the mean value of Q-peak S interval in HVF and that in IVCF.

Figure 6 shows the comparison of the normalized velocities of the A, O and D waves in SVCF, HVF and IVCF. Although the values of peak A/peak S, peak O/peak S and peak D/peak S showed relatively large dis-
persions, there were statistically significant differences among central veins. The values of peak A/peak S in HVF (−40±21%) were significantly smaller than those in SVCF (−26±12%, \( p<0.01 \)) and those in IVCF (−16±29%, \( p<0.01 \)), while there was no significant difference between the values of peak A/peak S in SVCF and those in IVCF. Backflow of A wave was most obvious and frequently observed in HVF (95%), and a smaller backflow was seen in SVCF with the same incidence as in HVF. Backflow of the A wave was less frequent in IVCF (73%). Backflow of the O wave was observed in 73% of HVF, but only in 10% of SVCF and in 5% of IVCF. Thus, the value of peak O/peak S in HVF was the smallest (−19±30%) and in IVCF the highest (41±26%) being significantly different in all pair-tests of them (all \( p<0.01 \), Fig. 6). In all the subjects examined, the value of peak D did not exceed that of peak S in SVCF. However, the value of peak D exceeded that of peak S in IVCF in 4 cases (10%) and in HVF in 1 case. The values of peak D/peak S were significantly different both between SVCF (63±17%) and HVF (58±20%, \( p<0.01 \)), and between SVCF and IVCF (74±19%, \( p<0.01 \)). Although the difference of the values of peak A/peak S between SVCF and IVCF, and of peak D/peak S between SVCF and HVF were not significant, they showed a similar pattern with regard to the order of mean values (IVCF>SVCF>HVF).

Figure 7 illustrates the average flow velocity patterns of SVCF, HVF and IVCF assessed from the present study. The subtracted values of the mean values both in the time intervals (horizontal arrows: msec) and in the normalized wave velocities of the A, O and D waves (vertical arrows: %) in SVCF from those in HVF or IVCF are superimposed in Fig. 6. Compared with the flow curve of SVCF, the flow curve of HVF generally shifted upward and, in IVCF downward. Fig. 8 shows the comparison of the per cent fraction of the O or D wave velocity to the S wave velocity in each central venous flow velocity curve, provided the baseline is shifted to the peak level of the A wave. The values of peak O'/peak S' in HVF (14±20%) were lower than those in SVCF (41±18%) and those in IVCF (47±22%, both \( p<0.01 \)). The values of peak D'/peak S' in IVCF (77±17%) were higher than those in SVCF (71±14%, \( p<0.05 \)) and those in HVF (69±16%, \( p<0.01 \)). These results indicate that even if the baseline shift and the amplitude of each flow curve were standardized, apparent differences in shape of flow curves would remain.

**DISCUSSION**

Doppler examination of the central or jugular venous flow pattern is useful for the noninvasive evaluation of hemodynamic disorders in the right heart\(^{10–12,18–22}\). However, little attention has been paid to the differences between each venous flow pattern and there are only a few reports about this subjects in the literature\(^1–13\). Using intravascular electromagnetic flow transducers, Brawely et al reported a small backflow, recorded during atrial contraction, in the SVC, but not in the IVC flow in an animal study\(^1\). They also noted that the peak flow in the IVC was almost always late with respect to that in the SVC. In a pulsed Doppler echocardiographic study of SVCF and HVF in normal subjects, Appleton et al reported more frequent and larger backflows both during atrial contraction and near the end of the systole in HVF than in SVCF\(^13\). In the present study, we found that the central venous flow velocity patterns in healthy adults are fundamentally similar, but small phase lags and apparent differences in wave shapes among central veins exist. Therefore, knowledge of the characteristics of each venous flow velocity curve should be required for clinical studies in these areas.

Even when standardization was done both in baseline shift and in the amplitude of the flow velocity curve, the apparent differences in wave shapes of the flow velocity curves for each central vein still remained. The mechanism by which these differences arise are still unclear, however, earlier reports\(^1–24\) and the results presented here imply some possible mechanisms. The different distance between the sample volume in each vein and the right atrium seems to be one of the major determinants in affecting phase lag. The time lag usually depends both on the transmission velocity of the right atrial pressure and on the distance between the sample
volume and the right atrium as well as viscosity and inertia of blood. In our previous Doppler echocardiographic study on SVCF varying the sample depth \(^\text{14}\) a distance of 2–3 cm produced small time lags but minor effects were detected on the shape of the flow velocity curve, except when that part of the vessel was severely compressed by neighboring structures such as the right pulmonary artery or the ascending aorta. In addition, even when the sample volumes in HV and IVC were placed at almost the same distance from the right atrium, the flow velocity curves also showed different patterns from each other, e.g. backflows of the A and O waves were always larger in HVF than those in IVC. Therefore, small differences in distance from the right atrium to the sample volume were unlikely to have major effects on the difference in shapes of the venous flow velocity curve in the study.

According to the Navier-Stokes equation, the space derivative of the intravascular pressure, and viscous and inertial forces should be significant fractions of the total driving force in the flow in vessels \(^\text{25}\). The time course of the space derivative of the intravascular pressure, which is mainly determined by the time course of right atrial pressure, has been considered to be the most predominant fraction to produce the general features of volume flow curve and flow velocity curve in each central vein \(^\text{1–7,10}\). An experimental report on good correspondence between the shape of the longitudinal pressure gradient and that of superior vena caval flow velocity \(^\text{?}\) and reports on a reciprocal relationship between the right atrial pressure and the instantaneous caval flow or flow velocity curve \(^\text{1–7,9}\) support this concept. Since the peripheral venous pressure pulses were very likely to be nearly flat as demonstrated in the lower IVC of rabbits \(^\text{15}\) the right atrial pressure pulsation appeared to be a predominant fraction to produce the central venous flow curves. One of the causes of baseline shift of venous flow curves might be an increase of the mean pressure in the distal part of the central veins produced by narrowing of the veins in the proximity of the right atrium. In the present study, we could obtain a reduced phasic and baseline-shifted flow velocity curve in a collapsed IVC, which should support the above explanation. Two-dimensional echocardiographic examination sometimes revealed a sharp narrowing of the IVC at the site of the diaphragm and occasionally a widely-collapsed abdominal IVC. Gardner et al. also have reported sharply localized indentation at the level of the diaphragm in 70% of 36 postmortem casts of normal IVC \(^\text{16}\). In the severely compressed IVC, the right atrial pressure pulsations might be no longer transmitted into the abdominal IVC and the pressure in the abdominal IVC would be maintained high with little fluctuation during cardiac actions \(^\text{16}\). A localized narrowing of the SVC was also recognized near the right pulmonary artery in this study, which was, however, less frequent and usually milder than that of the IVC. These narrowings seem to produce a very small pressure gradient but probably enough to somewhat attenuate backflows at the times of the A and O waves.

Differences in mean venous pressure levels could explain only the baseline shift but appeared not to be the only plausible explanation for the differences in the shapes of venous flow velocity curves. Another most possible cause of the differences in these venous flow velocity patterns might be a difference in inertia of blood mass, because the length of blood tube in each vessel is different (IVC>SVC>HV). Under 2-dimensional or M-mode echocardiographic observations in normal subjects, the phasic caliber changes of the IVC varied widely as reported in earlier studies in man \(^\text{23,24}\). Though the phasic caliber changes of the SVC in animal study was reported to be small \(^\text{?}\), those studied here in man appeared to be also widely varied under 2-dimensional echocardiographic observations. Since the caval dimension in normal subjects is reduced during systole, slowly increases in diastole and rapidly expands during atrial contraction, the peak velocity of the S wave should be exaggerated in amplitude, especially when a large phasic caliber change occurs. When the caliber changes of the vessel are small, the flow velocity curves could be considered approximately as relative changes in volume flow rate. Since dimensional changes of the venae cavae are not always small, attention must be paid to the degree of phasic caliber changes as well as to the flow velocity curve in order to estimate

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the phasic volume flow pattern in the central veins. Paying attention to these considerations, Doppler examination of the central venous flow velocity patterns could be a very useful modality to investigate the physiology and the hemodynamic abnormalities of the right heart.

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