Arch. Jap. Chir., 46 (3), 214~225, Mai. 1977

Analysis of Sound Spectrographic Pattern for Assessment of Vascular Occlusive Disorders by Continuous Wave Ultrasonic Doppler Flowmeter

HAJIME HANDA, HIDEYUKI NIIMI*, KOUZO MORITAKE,
ATSUSHI OKUMURA, ISAO MATSUDA and KOZABURO HAYASHI**

Department of Neurosurgery, Kyoto University Medical School and Hospital
(Directer : Prof. Dr. HAJIME HANDA)
* Department of Aeronautical Engineering, Science, Kyoto university
** Department of Engineering Science, Kyoto University

Received for Publication March, 10, 1977

1. Introduction

With recent advances in technology of ultrasonic flowmeters, it has been made possible to measure blood flows in vessels transcutaneously, including the flow-direction[3,6,13,14]. The sound spectrograph display by the ultrasonic Doppler technique may be valuable in analysis of flow patterns in vessels under various pathological conditions[10]. In the vascular surgery, the Doppler flow measurement is desired to be available for detecting the location and the grade of vascular diseases such as occlusive disorders[5,11,16].

The ultrasonic technique is fundamentally based on the Doppler shift principle whereby the sound scattered by moving corpuscles is shifted in frequency from the incident sound waves by an amount proportional to the blood velocity. The hemodynamics in stenosis or in bifurcations of vessels are patently different from those in straight segments. In the regions, the blood flows are very distorbed due to the flow-separation, the vortex formation or washing down[1,2,4,8,12b]. Therefore, it is an urgent need to clarify the hemodynamical properties which the output of the Doppler signals may indicate in such distorbed flows.

The ultrasonic flowmetry on vessels of complex geometry was first studied by NIIMI et al[12a]. In this paper, the ultrasonic flowmetry is applied to the vascular surgery. The relationship between the sound spectrographic patterns and the flow patterns in stenosed vessels is examined and the sound spectrographic pattern is analyzed for assessment of cerebrovascular occlusive disorders.

2. Ultrasonic flowmetry

Let us here remark about the blood flowmetry on vessels of complex geometry by continuous wave ultrasound. The ultrasound beam radiated into a fluid flow is partially scattered by small particles suspended in the fluid. If the wave-length of the sound waves

---

Key Words : Ultrasonic Doppler Method, Sound Spectrographic Pattern Analysis, Vascular Occlusive Disorder, Distorbed Flow, Post-Stenotic Region

Present address : Department of Neurosurgery, Kyoto University Medical School, Sakyo-ku, Kyoto, 606, Japan.

is large enough compared with the particle size, and is small enough compared with the size of the flow structure, the frequency shift, f_d, of the ultrasound waves due to scattering of a particle can be approximated by the equation :

$$f_d = \frac{V}{c} f \ (\cos\theta_I + \cos\theta_R) \quad (*)$$

Here, f is the frequency of the incident ultrasound beam, c is the sound velocity in the fluid, and V is the velocity of the particle which also represents the fluid velocity if the particle density is nearly equal to the fluid density. The quantity θ_I or θ_R represents the angle between the motion of the particle and the incident direction of transmitted waves or the receiving direction of scattered waves, respectively. Since c is approximately 1500 m/sec in blood and the size of a corpuscle is approximately several microns, the above generalized Doppler formula (*) may be applied to the blood flow of a structure larger than 300 microns for the ultrasonic flowmeter of 5 MHz.

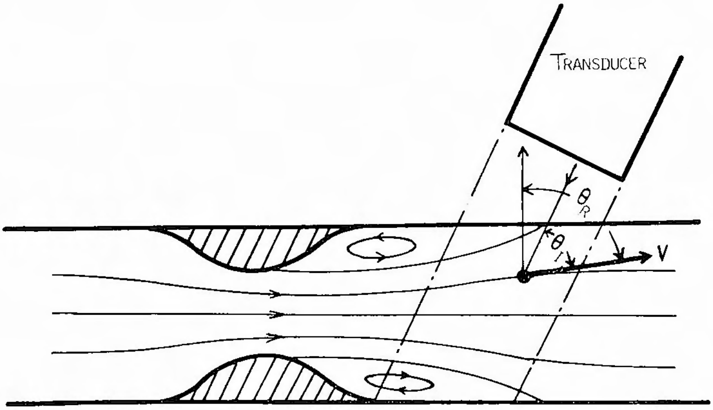


Fig. 1. Principle of flowmetry on a stenosed vessel by continuous ultrasound.

If the transducer composed of emitting and receiving halves is placed over the vessel or on the skin, the output of the signals in the continuous wave ultrasonic system includes all the Doppler signals integrated over the whole area of cross-section of vessel (Fig. 1). Since the velocity, V, the angles θ_I, θ_R may in general vary with the location of scattering corpuscles in the vessel, the Doppler output is closely related to the geometrical relationship between the flow field and the field pattern of the ultrasound. The flow field is not unidirectional, but distorted in stenosed or bifurcated segments differently from that in long straight segments. In such distorted flows, we can not neglect effects of dependence of the quantities on the location of scattering corpuscle in the vessels. It must be pointed out that the formula (*) becomes invalid rigorously for turbulent flows where the size of vortices is smaller than 300 microns. Therefore, the generalized Doppler formula must be used with precaution in measuring distorted flows in vessels.

3. Sound spectrographs and flow patterns in model experiments

Model experiments were performed to examine the relationship between the ultrasonic flowmetry and the flow pattern. Fig. 2 shows schematically the testing apparatus used. Pulsatile (sinusoidally oscillating), or non-pulsatile (steady) flows of water were carried out in stenosed tubes of poly-vinyl-chloride within a physiological range of dynamical parameters. These parameters are the Reynolds number $R_e = \frac{UD}{\nu}$, the Womersley number $\alpha = \frac{D}{2}\left(\frac{2\pi f}{\nu}\right)^{\frac{1}{2}}$ and the unsteadiness parameter $\lambda = U'/U$ where U, U′ are the mean velocity, the amplitude of oscillating velocity, respectively, and D is the diameter of tube, f is the frequency of oscillation and ν is the kinematic viscosity of fluid. These numbers are useful to obtain fluid-dynamically analogous flows of different fluids in vessels of different sizes. (For the physical meanings of the parameters, see MacDonald[9].) Aluminium dust of the comparable size to a blood corpuscle was added into the flow so as to scatter the ultrasound beam and to visualize the flow pattern. The flow patterns were observed or cinematographed. The sound spectrograph was displayed by means of the model EUD-4 ultrasonic Doppler flowmeter (Hitachi Med. Co.). The transducer was placed on the tube covered with ultrasonic Sol with an incident angle of 60 degrees to the tube axis and the transmitted frequency of 5 MHz.

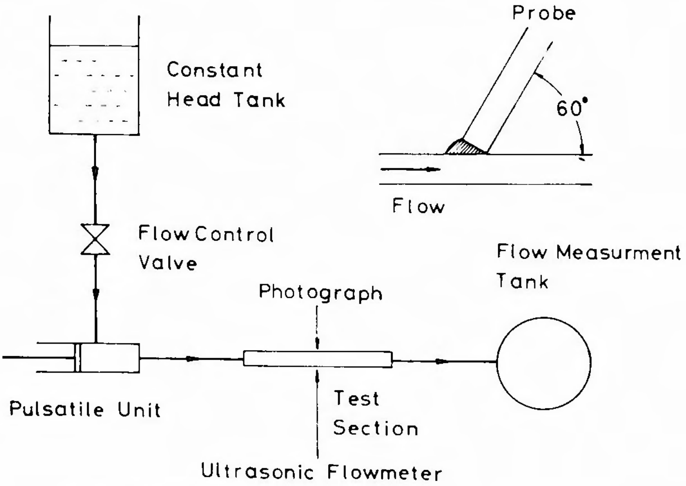
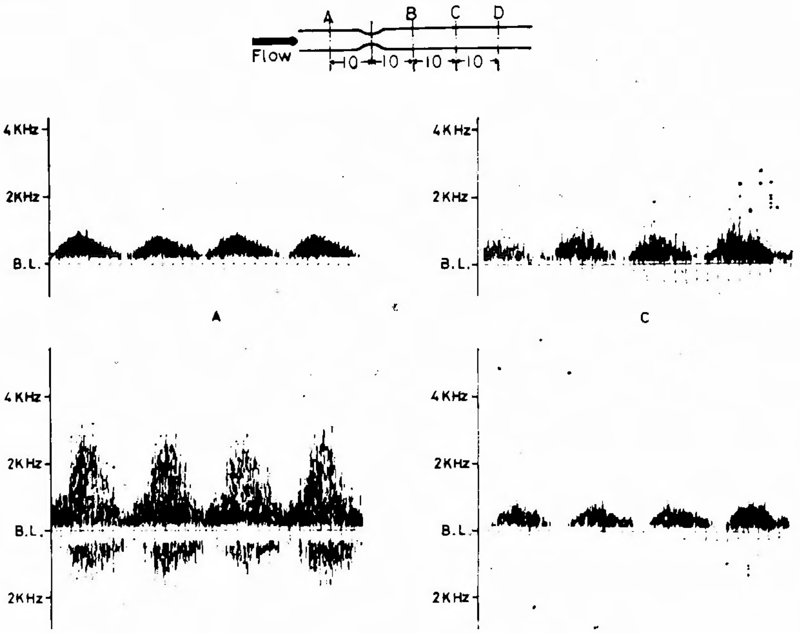
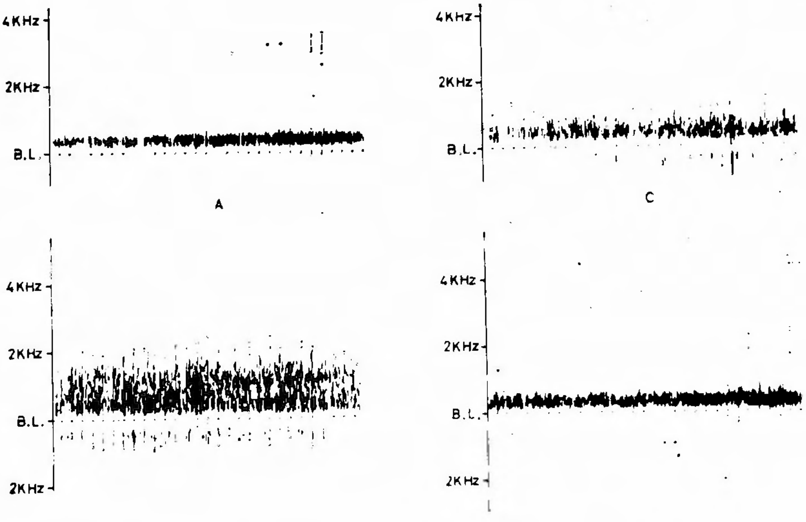


Fig. 2. Schematic diagram of the testing apparatus.

Let us show typical examples of flows in a stenosed tube. In Fig.3 are shown the sound spectrographs for a pulsatile (sinusoidally oscillating) flow of $R_e = 260$, $\alpha = 5$ (the mean flow velocity = 9cm/sec, and the pulse rate = 1.3Hz (77 cycles/min)). For sake of comparison, the spectrographs for a steady flow of the same Reynolds number are also shown. The spectrographic pattern (A) was recorded at the 10 mm proximal to the stenosis and B, C, D were recorded at the 10 mm, 20mm, 30mm distal to the stenosis, respectively. The grade of constriction of tube is estimated to be approximately 65% in terms of the cross-sectional area by use of the photograph for the flow-visualization (Fig. 3). In the sound spectrograph, the ordinate represents the Doppler shift frequency, while the abscissa



Pulsatile Flow (Re=260, α=5)



Steady Flow (Re=260)

Fig. 3. Sound spectrographs for pulsatile (sinusoidally oscillating) flow of $R_e=260$, $\alpha=5$ and for steady flow of $R_e=260$.

represents the time. For a uni-directional flow, 1 KHz of the Doppler shift corresponds to 30 cm/sec of the particle speed by virtue of the formula (*). The base line (B.L.) is useful for the detection of the flow-direction. The flow toward and away from the transducer is recorded below and above the base line, respectively. The darkness of the pattern correlates to the output voltage, which is supposed to be nearly proportional to the number density of particle. Marked variations are seen in the patterns (A)—(D) recorded along the

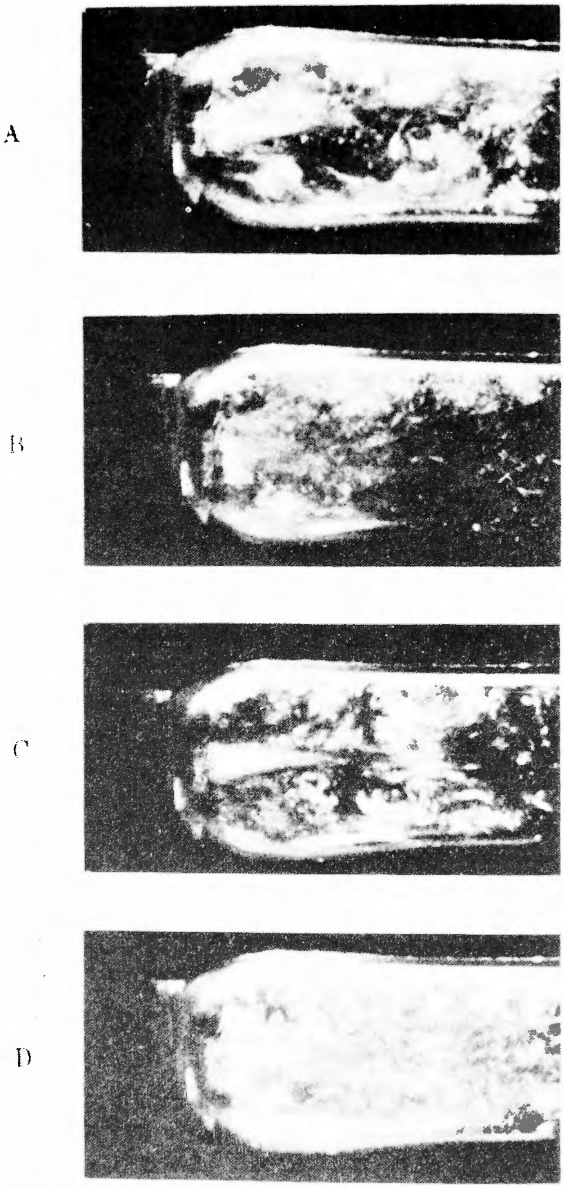


Fig. 4. Flow patterns at consecutive stages of the pulsatile flow past the stenosis ($R_e = 260$, $\alpha = 5$).

stenosed tube. The pattern (B) shows a peculiar feature that not only high frequency components but also negative frequency ones below the base line appear. It is clear that the pattern develops distally in the post-stenotic region, until at 30 mm distal site it becomes similar to that in the pre-stenotic region.

The feature of the spectrographic patterns can be understood by examining the flow patterns in the stenosed tube. In Fig. 4 are shown a series of the flow patterns at the consecutive stages of the pulsatile flow which are photographed at 3 frames/sec with the shooting speed of 1/125 sec. A series of photographs (A)—(D) provide evidences of distorbed flow due to the flow separation and vortices in the post-stenotic region. Vortices are periodically generated and washed downstream. Since the fluid (the alminium dust) moves oscillatingly in the whole cross-section, the output of the Doppler signals includes components of high frequency shift and of negative frequency shift, correspondingly to the motion toward and away from the transducer, respectively. It must be pointed out that the motion away from the transducer does not necessarily correspond to the reverse flow.

Fluid-dynamical properties are influenced by the Reynolds number. Here we show another typical example of flow of a different Reynolds number in the stenosed tube. In Fig. 5 are shown the sound spectrographs recorded at the proximal and the distal to the stenosis

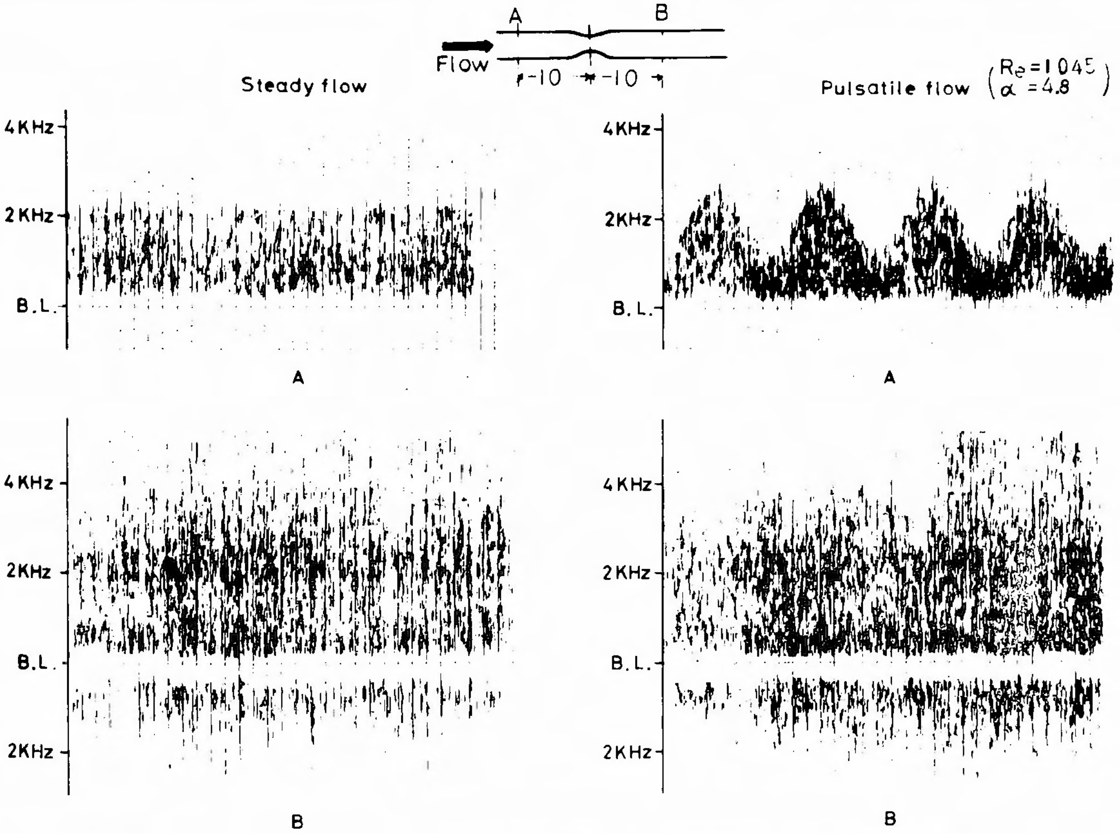


Fig. 5. Sound spectrographs for a steady flow and a pulsatile flow ($\alpha=4.8$) of $R_e=1045$.

for a steady flow and a pulsatile flow ($\alpha=4.8$, the pulse rate $=1.3$ Hz) of Re $=1045$ (the mean flow rate $=36$cm/sec).

For a pulsatile and a non-pulsatile (steady) flow, distinct variations are seen between the specrographic patterns (A) and (B) recorded proximally and distally to the stenosis, respectively. The patterns (B) are composed of very high frequency and negative frequency components as those in the previous example. It is noteworthy that the pattern (B) for the pulsatile flow is so widespread that it does not show marked difference from that for the non-pulsatile flow. Since the Reynolds number is high compared with the previous example, the flow is very distorbed or turbulent distally to the stenosis. Then, the effect of turbulence in the sound spectrographic pattern is more predominant than the effect of pulsation in the flow.

4. Blood flow measurement in experimental animals

When our result obtained in model experiments is applied to the measurement of blood flows in arteries, many effects must be taken into account. These are that (1) the aluminium dust used for a scattering particle is different from the blood corpuscle in regard to the acoustic impedance relating with the shape and the flexibility, (2) the pressure wave form

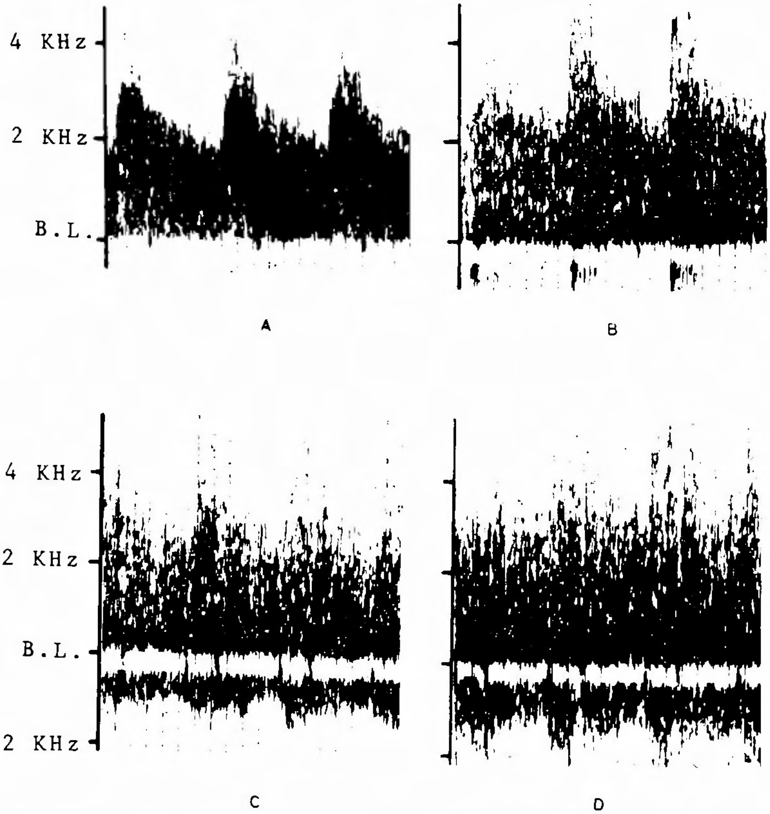


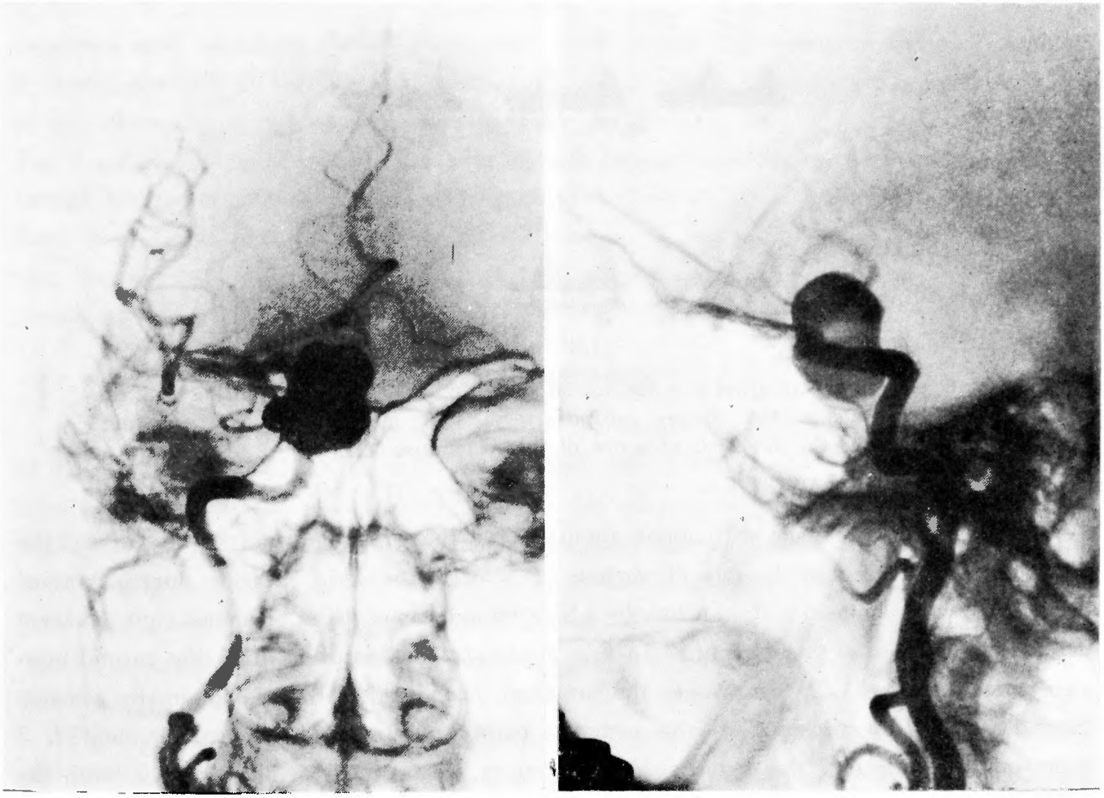
Fig. 6. Sound spectrographs at the distal to the constriction of the common carotid artery of an adult dog. (A, B, C, D correspond to the constriction ratio of 0, 20, 50, 65%, respectively.)

in our pulsatile (sinusoidally oscillating) flow does not simulate that in arteries so well, and (3) our experimental tube is not so distensible as arterial walls.

In order to examine whether our result is valid *in vivo*, we measured blood flow directly in the common carotid artery of an adult mongrel dog. In Fig.6 are shown the spectrographs recorded at approximately 10 mm distal to the constriction when the common carotid artery of approximately 3. 5 mm external diameter was constricted gradually. The pattern (A) represents a recording when the common carotid artery is not constricted at all, and (B), (C), (D) represent recordings for the constriction ratio of approximately 20, 50, 65%, respectively, in terms of the cross-sectional area. The patterns become widespread with the increase in the grade of constriction, retaining components of high frequency shift and of negative frequency shift. This feature is identified qualitatively with the result obtained in model experiments. Thus, it can be concluded that this peculiar pattern arises from very distorbed or turbulent flow in the post-stenotic region of artery.

5. Example of application to cerebrovascular surgery

The analysis of spectrographic patterns will be applied successfully to a variety of cases of the vascular surgery. Let us here show an example of application relating to cerebrovascular surgery.



(A) (A-P view) (B) (Lateral view)

Fig. 7. Right common carotid angiogram of a 57-year-old female.

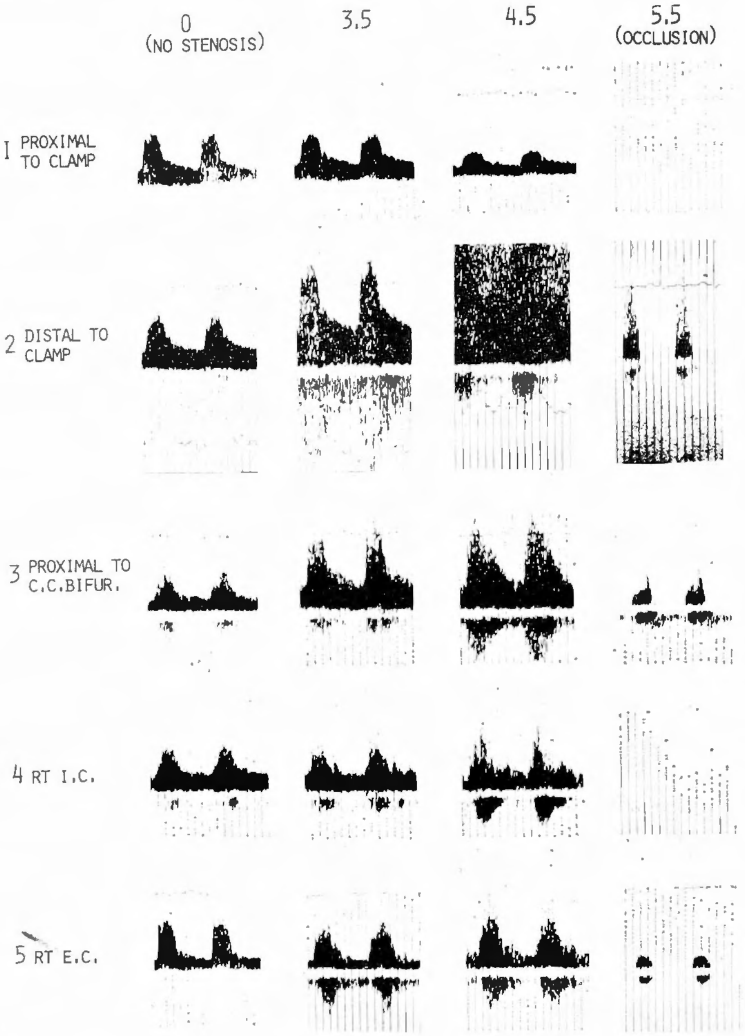


Fig. 8. Sound spectrographs at various sites of the carotid arteries during gradual occlusion of the common carotid artery. (The number over the recordings denotes the devisions of screw of the Selverstone clamp.)

In a 57-year-old female with giant aneurysm of the right internal carotid artery, the blood flow was measured directly at various sites of the carotid arteries during gradual occlusion of the common carotid artery by a Selverstone clamp. (Fig. 7 shows right common carotid angiograms of this patient.) In Fig. 8 are shown recordings from the carotid arteries where the line 1, 2, 3 represent the proximal, just distal to the clamp on the common carotid artery, just proximal to the common carotid bifurcation, respectively, and 4, 5 represent the internal, the external carotid artery, respectively. The number over the recordings denotes the divisions of screw, that is the grade of occlusion, of the Selverstone clamp. In the spectrographic patterns, marked changes are seen to develop when the

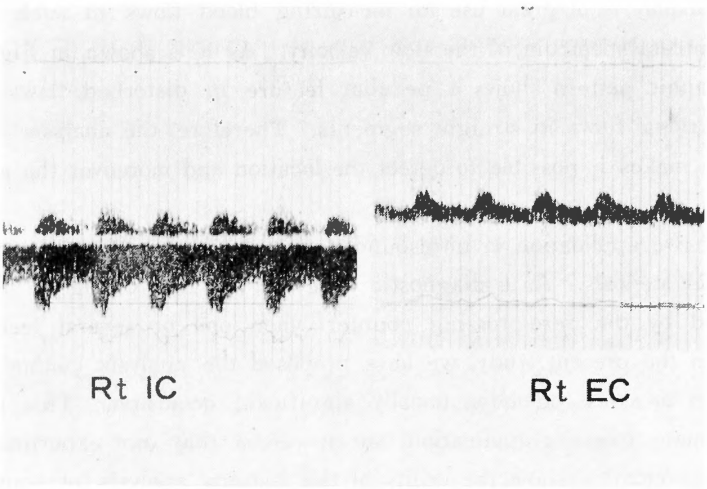


Fig. 9. Sound spectrographs recorded from the right internal and the right external carotid artery when the common carotid artery was completely occluded.

common carotid artery is gradually occluded. The most prominent change is seen on line 2, that is the post-stenotic region. Components of high frequency shift and of negative frequency shift appear at the distal portions to the clamp. According to our result obtained in model experiments and the experimontal animal, it can be concluded that the blood flow is very distorbed or turbulent in the post-stenotic region.

Fig. 9 are recordings from the right internal and external carotid arteries when the common carotid artery was completely occluded in the same patient. It is to be noted that the blood flows from the internal carotid artery to the external carotid artery. This is an interesting case that the total obstruction changes the flow-direction from the internal to the external carotid artery.

6. Discussion

Transcutaneous measurement of blood flow in vessels has been made possible by use of the ultrasonic Doppler method. The Doppler output is usually displayed by the zero-crossing counter or the sound spectrograph. 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 spectrum of Doppler frequency shift. In addition, Doppler signals can be distinguished between from blood corpuscles and from adjacent vessels by displaying the complete velocity spectrum, which would be indistinguishable with zero-crossing detection.

The blood flows in arteries are composed of various velocity components. The flows are uni-directional in long straight segments, but the radial velocity components are observed in stenosed portions (Fig. 4). Their presences would cause errors in the mean flow velocity indicated on basis of the assumption that the flow velocity is uni-directional. The sound spectrographic display is of great use for measuring blood flows in such vessels, since it includes the complete spectrum of the flow velocity. As it is shown in Figs. 3, 5, 6, 8, the sound spectrographic pattern shows a peculiar feature in distorbed flows differently from that in uni-directional flows in straight segments. Therefore, the analysis of sound spectrographic patterns makes it possible to detect the location and moreover the grade of vascular disorders.

The noninvasive application of ultrasound devices has proved to be most promising in detecting vascular stenosis. As a diagnostic criterion, the flow change is used in the mean velocity displayed by the zero-crossing counter when one or several feeding vessels are compressed7) In the present study, we have proposed the analysis method of sound spectrographic pattern to assess hemodynamically significant occlusion. This method must be followed up by many cases of application, but it seems that our experimental results and cerebrovascular application show the utility of the pattern analysis of sound spectrograph for assessment of vascular occlusive disorders.

References

1) Azuma, T. and Fukushima, T. : Disturbance of blood flow as a factor of thrombus formation. Thromb. Res. Suppl. II, **8** : 375, 1976.

2) Forrester, J. H. and Young, D. F. : Flow through a converging tube and its implications in occlusive disease. I Theoretical developments. II Theoretical and experimental results and their implications. J. Biomech. **3** . 297, 1970.

3) Franklin, D. L., Schlegel, W. and Rushmer, R. F.: Blood flow measured by Doppler frequency shift by backscattered ultrasound. Science, **134** : 564, 1961.

4) Giddens, D. P., Mabon, R. F. and Cassanova, R. A. : Turbulence measured distal to subtotal vascular stenosis. Proc. 1975 ASME Symp., p. 23.

5) Johston, K. W. Detection and localization of early peripheral occlusive disease. Digest 11 Intern. Cong. Med. Biol. Eng., Ottawa, p. 104, 1976.

6) Kato, K. and Izumi, T. : A new ultrasonic Doppler flowmeter that can detect flow directions. Med. Ultrasonics, **5** : 28, 1967.

7) Lee, J. S. and Fung, Y. C. Flow in locally constricted tube at a low Reynolds number. J. appl. Mech., **37** : 9, 1970.

8) Keller, H., Meier, W., Yonekawa, Y. and Kumpe, D. Noninvasive Angiography for the diagnosis of carotid artery disease using Dopper ultrasound (Carotid artery Doppler). Stroke, **7** : 327, 1976.

9) MacDonald, D. A. : Blood flow in arteries. Edward Arnold. 1974.

10) Matsuo, H., Nimura, Y., Kitabatake, A. and Hayashi, T. : Analysis of flow patterns in blood vessels with the directional ultrasonic Doppler technique through a transcutaneous approach. Japan. Circ. J. **37** : 735, 1973.

11) Moritake, K., Handa, H., Okumura, A., Matsuda, I, Sugimoto, T. Waga, S., Hayashi, K. and Niimi, H. : Flow pattern anaysis with ultrasonic Doppler flowmeter for evaluation of cerebrovascular occlusive disorders. Proc. X Intern. Cong. Angiol., p. 547. Tokyo, 1976.

12) Niimi, H., Kawano, Y., Hayashi, K., Handa, H., Moritake, K., Okumura, A. and Matsuda, I. : (a) Blood flowmetry by directional ultrasonic method-Relationship between sound spectrograph and flow pattern. Digest. 11 Intern. Cong. Med. Biol. Eng. Ottawa, p. 166, 1976.
(b) Hemodynamic study on pathogenesis of Atherosclerosis-Flow characteristics in arterial bifurcations. Proc. X Intern. Cong. Angiol. p. 595, Tokyo, 1976.

13) Reneman, R. S. (ed.) : Cardiovascular application of ultrasound. American Elsevier Publ. Comp., 1973.

14) Roberts, C. Ultrasound in the assessment of vascular function. Med. Progr. Technol., **4** : 3,

1976.
15) Satomura, S. : Study of the flow patterns in peripheral arteries by ultrasonics. J. Acoust. Soc. Japan, **15** : 151, 1959.
16) Strandness, D. E., McCutcheon, E. P. and Rushmer, R. F. : Application of a transcutaneous Doppler flowmeter in evaluation of occlusive arterial disease. Surg. Gynaec. Obstet., **122** : 1039, 1969.

和文抄録

超音波流速計による閉塞性血管障害の診断のための音スペクトルのパターン解析

京都大学医学部脳神経外科学教室（主任：半田　肇教授）
*京都大学工学部航空工学教室，**京都大学工学部物理工学教室

半田　肇，新見英幸*，森竹浩三
奥村　厚，松田　功，林紘三郎**

超音波による血流測定法が閉塞性血管障害の部位や程度を診断する目的のために研究された．連続波超音波ドップラー流速計による音スペクトル表示と血流動態の関係が血管狭窄に関して詳しく調べられた．音スペクトルのパターンを脳血管閉塞障害に関連して解析し，パターン解析法の有用性を示した．