Flow Measurement Techniques from Medical Modalities for Computational Fluid Dynamics

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Abstract

As the boundary condition, flow velocity and pressure is important. Here, medical techniques to obtain such boundary conditions were reported. Doppler sonography is the usual method for this purpose. Scan from the body surface is the common manor. Moreover, transcranial Doppler method and endoluminal data acquisition is reported. In the filed of magnetic resonance, phase contrast angiography is routine method. Alternative methods using pre-saturation pulse were also reported.

Introduction

Computational fluid dynamics should have large benefit for medical field. For example, cerebral aneurysms are common disease. In younger (younger than 60 years old) population, 0 - 3.1 % of male and 0 - 3.4 % female have aneurysm(s). In older (older than 60 years) ages, 4.3 - 4.9 % of male and 7.4 - 12.0 % of female

have aneurysm(s). And rupture rate is 0.05 % - 3 % per year.
If the rupture rate is 2 % per year, the aneurysm will rupture 20 % in 10 years. If the rate is 3 %, it will rupture 45 % within 20 years.
Once ruptured, passing away at the initial rupture is 30 - 40 % and 33 % of patients suffer re-rupture. 10 % of patients will pass away in their course. We can say the course from the statistics. However, for each patients, their own course IS the information they want. We, neurosurgeons, really hope to solve this problem from the field of CFD.
Moreover, ischemic stroke is getting more frequent because of successful control of hypertension and the life style is getting "westernized". What is the best way for revasculization? We can connect extra-cranial artery to the intracranial arteries (Superficial temporal artery - middle cerebral artery anastomosis, STA-MCA anastomosis). Such kind of new pathway is really effective if the normograde flow persists?
Not only in neurosurgical field, aortic aneurysms, iliac artery stenosis or iliac vein stasis (so called economy class syndrome) also hope CFD analysis. The other fields may be cerebrospinal fluid and air ventilation.
Flow pattern depends upon the shape of vessels. We can get detailed structure by three dimensional computer tomographic angiography (3D CTA), three dimensional reconstruction from rotational angiography (3D DSA) and three dimensional magnetic resonance angiography (3D MRA). The spatial resolution is 0.2 mm in 3D CTA and 0.5 mm by MRA.
We can get such high resolutional 3D structure by our diagnostic modalities. At the same time, boundary condition is the other important factor for CFD, such as pressure and flow velocity.
Pressure and flow velocity are the important boundary conditions. In this paper, assessment of flow pattern and pressure are reported from clinical modalities.

Assessment of Boundary Condition

Pressure

We can easily measure the pressure by diagnostic catheter and pressure transducer

at the proximal vessels. The diameter of such vessel should larger than 5 or 3 mm. We must use larger than 3 French size (1 French size is equal to 1/3 mm at outer diameter) catheter for this purpose. So we can use this method at the neck carotid or vertebral arteries.

Measurement at distal vascular structure is not very easy. We can place microcatheters whose diameter is smaller than 1 mm. Measurement from such small catheters are remarkably dumped. Only mean pressure is reliable. In such situation, we can place pressure transducer mounted at the tip of microguidewire which is a little bit rigid.

Velocity

We have some modalities to measure flow velocity. Doppler sonography is the most common way for this purpose.

Magnetic resonance imaging has several ways for this purpose. One is phase contrast magnetic resonance angiography. Please refer Dr Kato' paper for this area. The other is tagged magnetic resonance imaging.

Doppler sonography measures the Doppler shift from the echo of red blood cells. It can measure the velocity and its distribution at the same time.

The last one is so called particle tracking method. We can trace the front line of contrast materials while angiography.

Tracking Contrast Material (Particle Tracking)

Digital Subtraction Angiography (DSA)

DSA is the essential technique for intravascular surgery.

In DSA, image data were obtained like followings. At first, a fluoroscopic image is gotten before injection of contrast materials. Then the contrast material is injected. Fluoroscopic images were kept getting. Clear contrast materials (= vascular structure) is visualized by real-time subtraction between image before administration of contrast materials and the live image with contrast materials.

Tracking contrast material on DSA is the most easy way to know the flow velocity. In usual DSA, we can get the image of vessels at the rate from 5 frame per second

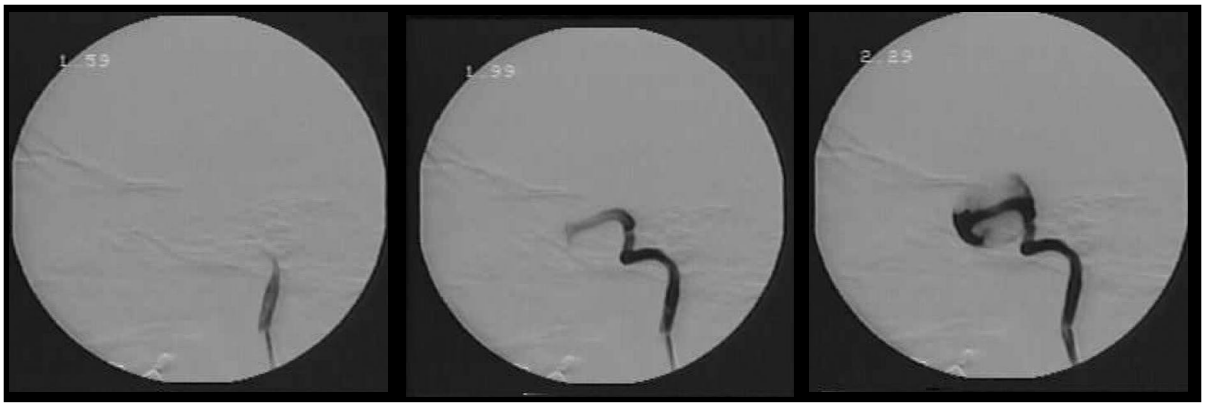


Figure 1 DSA

DSA (left internal carotid artery with giant aneurysm)
DSA can detect the front line of contrast materials These images were taken at three frames per second and measurement is not difficult. We can calculate flow velocity.

to 1 frame per second. To find the front line of contrast material is not very difficult. We can measure the distance between the series of angiography. (Figure 1)
Using this method, we have large risk. The vascular structure had three dimensional structure, and angiography is two dimensional projection image. To measure real distance is not easy. Co-registration of 2D-3D angiography is necessary which is not very easy.
On injection of contrast materials, contrast materials themselves has kinetic energy. This energy affects the flow pattern. And contrast materials are given as bolus. However the concentration of contrast materials has gradient, so to decide frontline is not always easy.

Contrast Enhanced MR Angiography

With contrast enhanced magnetic resonance angiography, we can use particle tracking method, too. With MR, we can obtain three dimensional structure and the flow of contrast material at the same time and same imaging modality. However, temporal and spacial resolution is not satisfactory at present. By Enhanced MR angiography, contrast materials were injected from venous route, so this method is

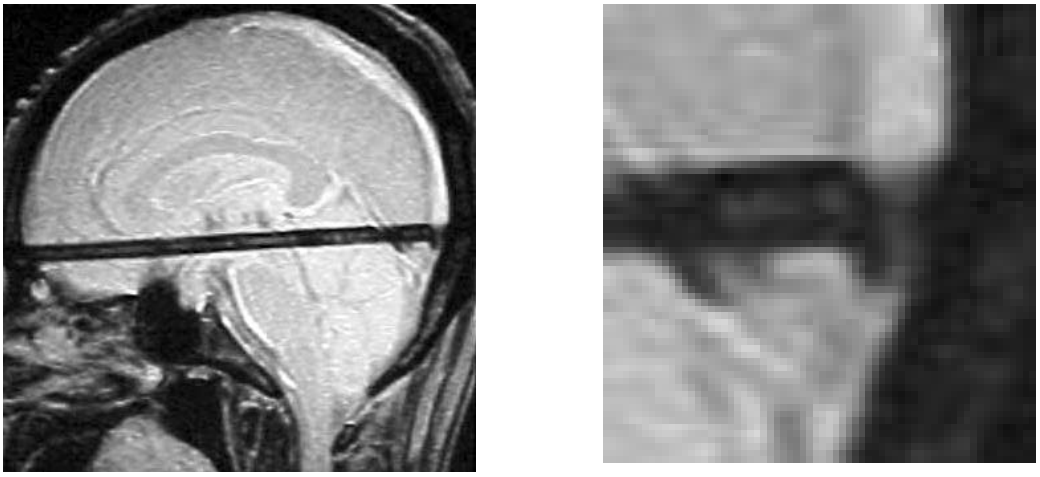


Figure 2 Tagging MR

Pre-saturation slub is displayed as the dark band. The pre-saturation pulse is given as a plane. At the superior sagittal sinus, the slub is deformed because of the blood flow at the sinus. See the magnified view.

less invasive comparing DSA.

Tagging MR

Phase contrast magnetic resonance angiography is one of the common modality for assessment of flow. MR imaging has other possibility for visualize flow pattern.

MR imaging can accumulates image data by cardiac gating, i.e. to get image data synchronizing with electrocardiogram. So we can get MR image at any cardiac phase. R wave of ECG is the trigger of cardiac gating.

MR imaging takes relatively long time to get imaging data. Using ECG gating technique, temporal resolution is improved to be able to get images at any cardiac cycle. (Figure 2)

Tagging is another interesting method. A pre-saturation pulse is given to a plane to erase all signal from it. Then Accumulate image data with cardiac gating to have movement of tagged plane. By giving pre-saturation to blood, we can give intrin-

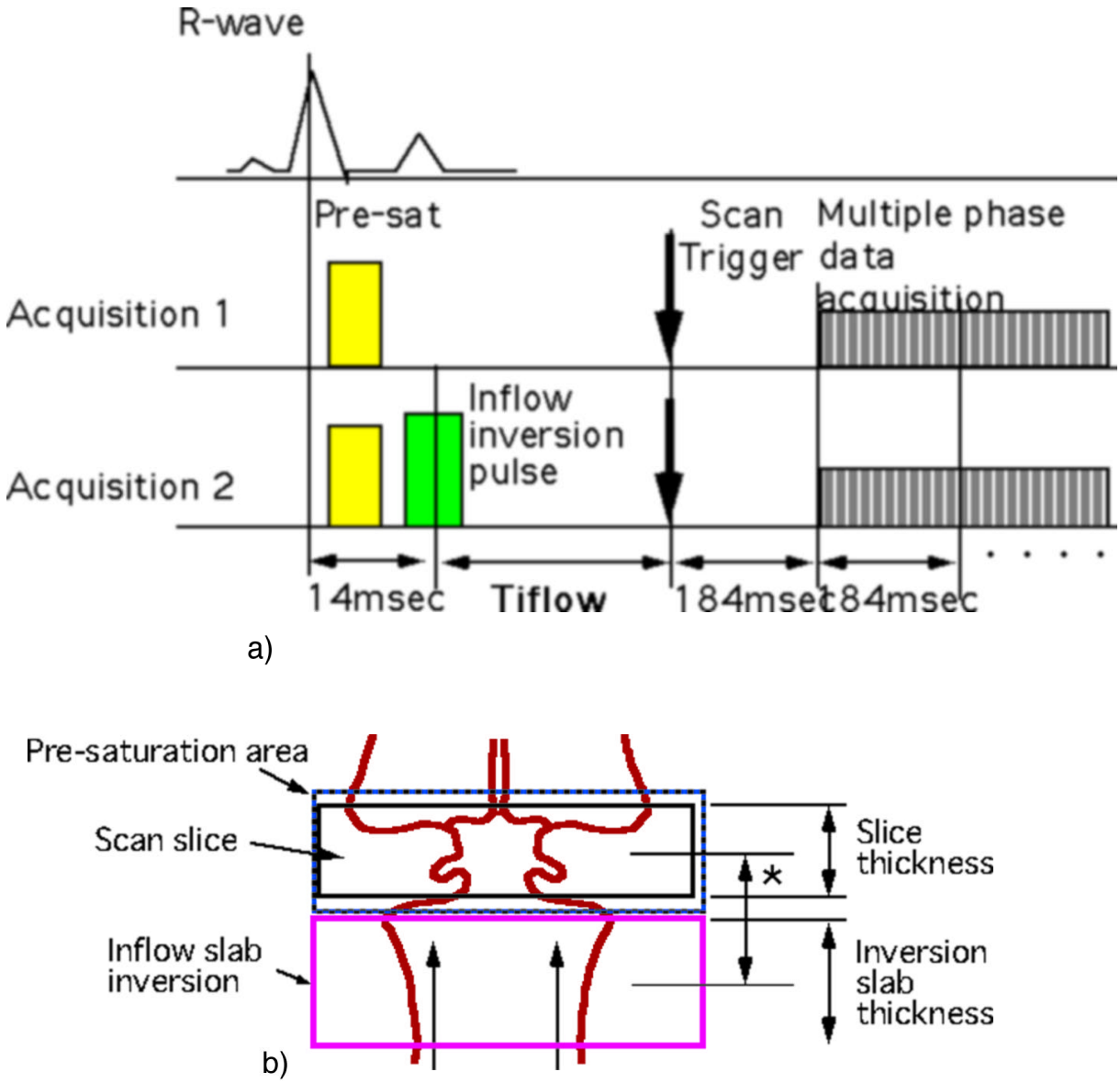


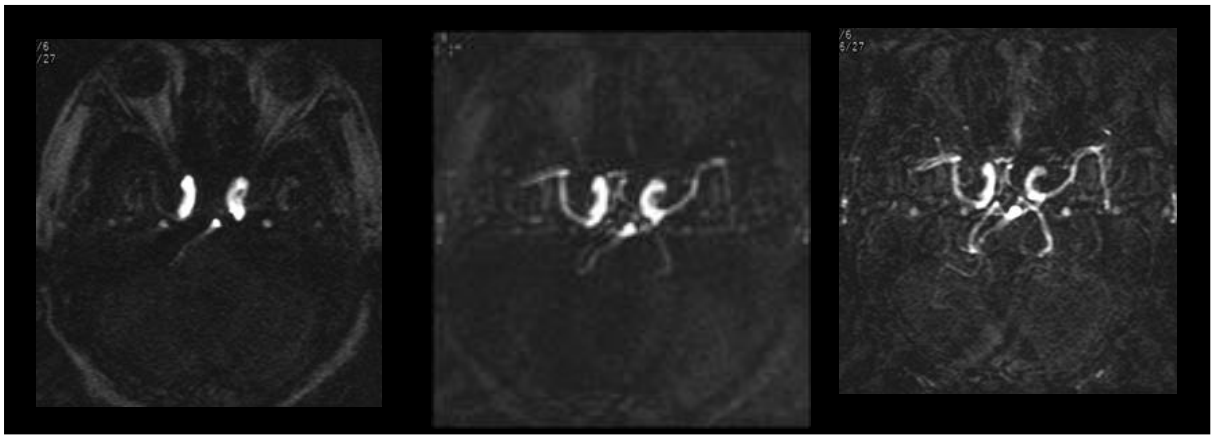
Figure 3 Arterial Spin Labelling
Signal Targeting with Alternating Radiofrequency (STAR)

a) Two data sets are acquired “Ti Flow” m sec after R wave of ECG (electrocardiogram). For acquisition 2, pre-saturation pulses are given at the proximal side of artery to erase signal from inflow (= arterial blood flow).
b) Blood flow comes from the lower side. Imaging data are acquired from “Scan slice” and pre-saturation (inversion) pulse are given at the proximal side of flow.

sic contrast material wherever we want without kinetic energy.

Arterial Spin Labelling

The other possibility from MR imaging is arterial spin labelling. This is the other technique to use pre-saturation pulse. In this technique, two data sets are needed. (Figure 3) Acquisition #1 is usual acquisition. Acquisition #2 is acquisition after several milli-second delay giving pre-saturation pulse at the proximal area to saturate the proton in the artery. On acquisition #1, all structure is visualized and on acquisition #2, inflow protons are not visualized. Subtracting #1 and #2, inflow proton only are visualized. This is arterial structure. By regulation of “delay” time (Ti Flow) we can get arterial structure, inflow protons at any time delay. (Figure 4)



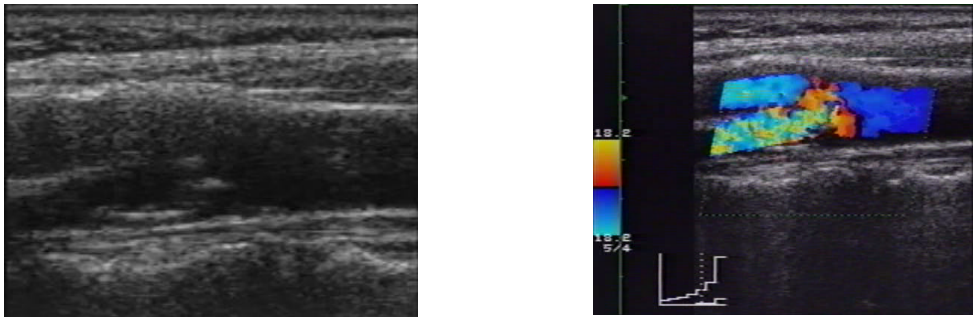
a) b) c)

Figure 4 STAR Image

These three images are acquired from the same location (at the level of Willis ring, an arterial structure). Ti Flow on the image a) is 100 m sec, b) 300 m sec and c) 500 m sec. Longer Ti flow gives distal arterial structure.

Ultrasound Imaging and Dopper Shift

Doppler sonography is the most common way in medical field to obtain flow velocity information. Usual way is to send ultrasound from the body surface and get the echo from the moving red blood cells with Doppler shift then evaluate the flow

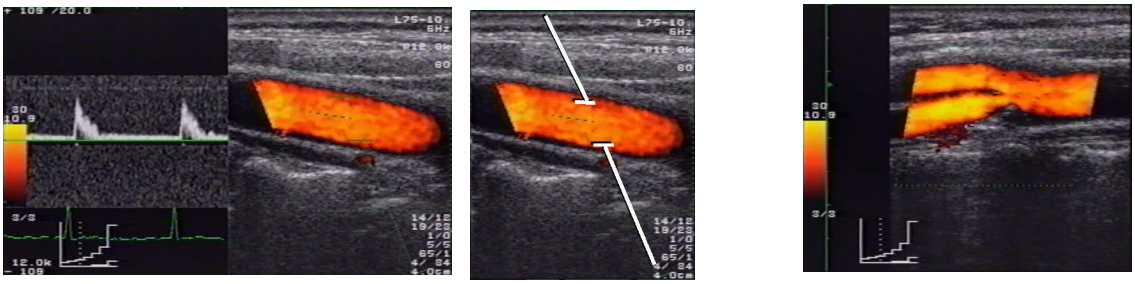


a) b)

Figure 5 Ultrasound tomographic scan

a) So called B mode scan image. Echo lucent (dark on image) area is the vascular lumen.
b) Doppler image. The signal in the echo lucent on Fig A is the echo affected by Doppler shift. On colour display, the signal from red blood cells toward the probe has red colour and the signal from the RBC (Red Blood Cell) off the probe.

velocity. (Figure 5)
Conventional way for Doppler sonography is to place probe at the body surface. We can get slice image with Doppler shift image at the same time.
Ultrasound image is two dimensional image. Three dimensional information is the limitation of this method.
Measurement of flow velocity is affected by the angle between the axis of ultrasound and the axis of vessels. Correction is possible (Figure 6) while the angle is smaller than measurement is not easy and quantitative detection of Doppler shift itself became uneasy. Even if the angle is vertical, some echo with Doppler shift comes back and beneficial for detection of vessels, this method is called Power Doppler. (Figure 6)
Ultrasounds can pass through the soft tissue but cannot through bone and air. If air bubble, bone or hard calcification exist in the pathway of ultrasound, measurement is impossible. When air bubble or some solid material such as thrombi run in



a) b)

Figure 6 Velocity Measurement and Power Doppler

a) Flow velocity measurement. Long white line (*) is the axis of ultrasound. Short white parallel bars are displaying the axis of target vessel (Common carotid artery in this case) While the angle between the axis of ultrasound and vessel is smaller then 60 degrees, the correction is reliable.
b) Power Doppler Display. Echo lucent area on Figure 5 a has Doppler shift so the signal is shown. In power Doppler mode, the direction of flow is not considered.

the blood stream, artifacts called HITS is detacted.
Probe of ultrasound, the device which send and catch the echo, is held by operator by hand. At present, manual technique is important for accumulation, so the results were affected by the skill of operators. The quality of image is different by the operator's skill even if examined for a same patient.
Doppler sonography is really less invasive technique, so it is easy to use.

Variations of Doppler Soonography

Doppler sonography has some variations. One is transcranial Doppler sonography and the other is intraluminal Doppler sonography.

Transcranial Doppler (TCD)

Skull is a hard bone structure so unable to get image with ultrasound by usual manner, However, using low frequency ultrasound, Doppler shift is possible to observe. Using Transcranial Doppler (TCD) measurement ultrasound is given from temporal, orbital and foramen magnum window at the frequency of 2 MHz. The original TCD system has small hand holding ultrasound probe. So we can measure Doppler signal and depth of interest, only. (Figure 7) Another system is transcranial Doppler mapping which has mechanical tracking system to detect angle of echo. We can draw the signal and its direction. The other is Transcranial Colour

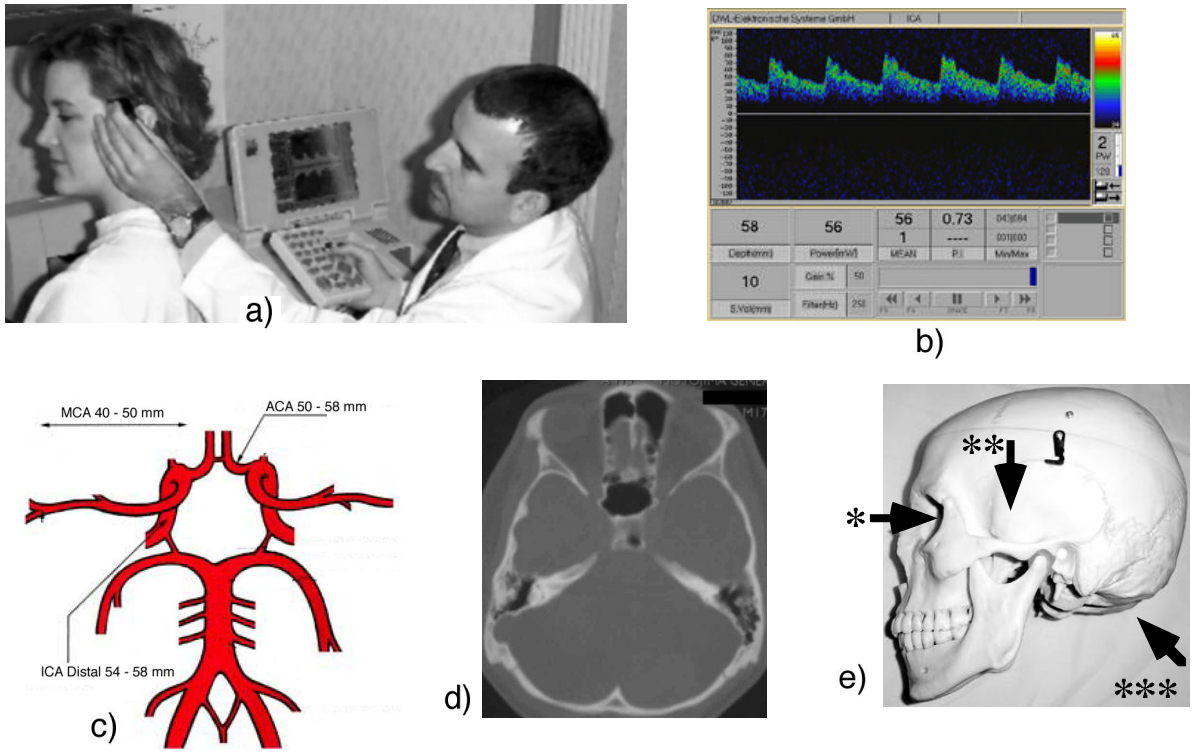
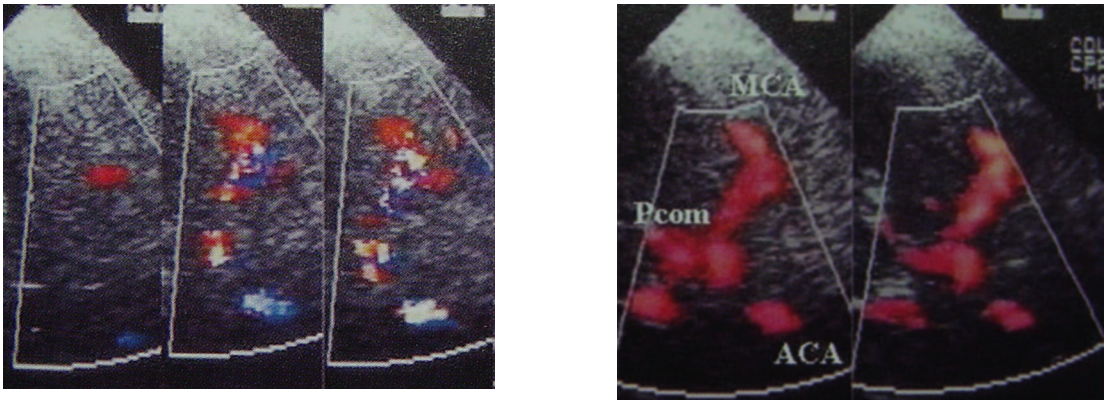


Figure 7 Transcranial Doppler Sonography (TCD)

a) Measurement of TCD. An operator manually hold the probe nand attach it to the temporal area of a patient. There is no guide for the probe. The only information to identify the vessels is the depth (c) and the direction pointed by the operator.
b) Image of TCD. One peak to the next peak is one cardiac cycle. X axis is time (seconds) and Y is velocity (cm/sec). The colour code is the intensity at each velocity. So we can get the information of peak and lowest velocity and proportion of RBCs at each velocities.
c) The distance from the temporal bone window to each vessel.
d) CT scan at the level of temporal window. Please note the temporal bone is very thin, so has possibility to pass the ultrasound.
e) Windows for TCD. Orbit * , Temporal ** and Foramen Magnum***

Flow Imaging which can display flow image like slice image. (Figure 8)
In some cases, temporal bone window is not accessible.

Endoluminal Doppler Sonography

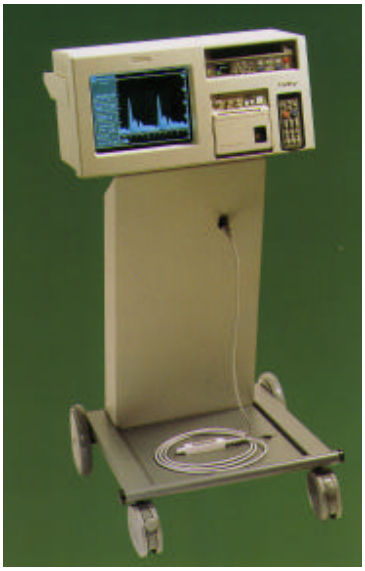


a) b)

Figure 8 Transcranial Colour Flow Imaging

a) With Transcranial Colour Flow Imaging, The Doppler signals can be displayed continuously.
b) Ultrasound contrast enhance material Injecting contrast materials (micro bubble) can enhance the signal.

We can place fine Doppler probe in the vascular lumen itself and measure the flow signal directory.
The 0.014 inch Doppler guide wire (Smart Wire or FloWire, Cardiometrics) consists of a 15 MHz ultrasound transducer mounted at the tip of a 175 cm long flexible guide wire. The distal flexible part is 45 cm in length, and can pass through the standard microcatheter to reach the intracranial peripheral vessels. The sampling volume is 5 mm^3. The Doppler signal is processed by the FloMap analyzer. (Figure 9) The tip of the Doppler wire with vascular structure can be visualized by Roadmap technique. (Figure 9)
We compare the result by Doppler wire and TCD in some cases with brain vascular diseases. In seventeen cases (six arteriovenous malformations, three dural arteriovenous fistulas, six aneurysms and two other diseases) TCD and Doppler wire was compared. TCDs were obtained from the orbital window for internal carotid arteries and temporal window for the middle cerebral arteries.



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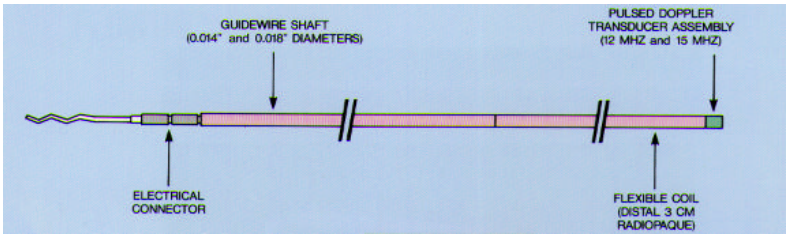

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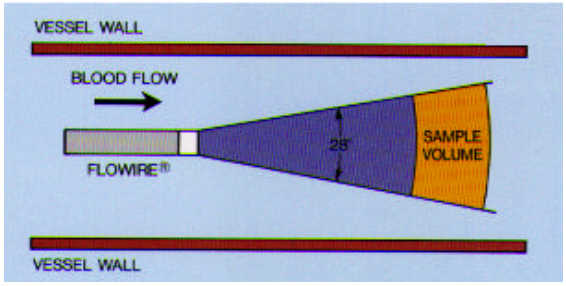

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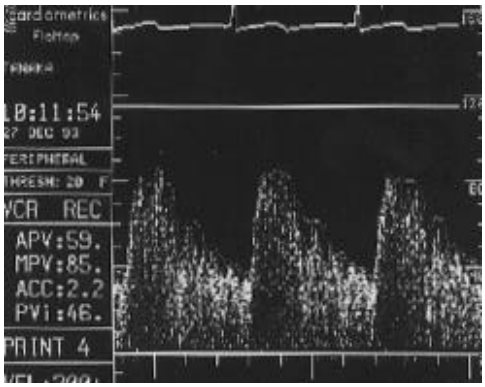

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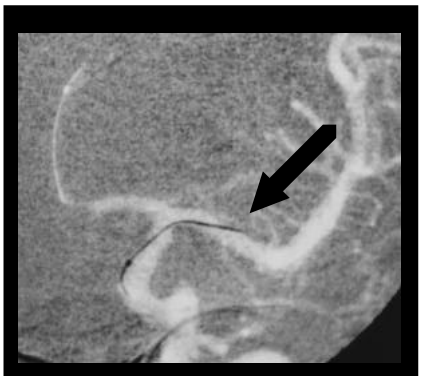

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Figure 9 Endoluminal Doppler (FloWire)

a) FloMap analyser.
b) FloWire (SmartWire) structure. The diameter is 0.014 inch and the length is 175 cm, so can be use as guide wire for standard microcatheters. At the tip of wire, Doppler transducer is mounted and the other end should be connected to the connection cable from FloMap.
c) Sampling volume is about 5 mm^3 from the tip of guide wire.
d) Display on FloMap. Same as TCD.
e) FloWire in the middle cerebral artery. On roadmap display, the vascular structure and the FloWire can be displayed together.

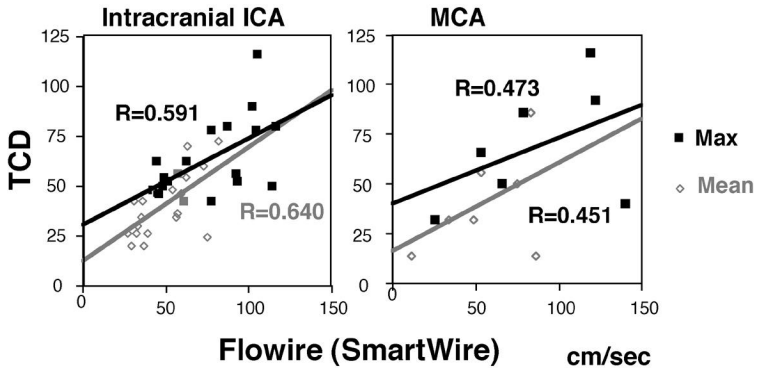


Figure 10 Correlation between FloWire and TCD

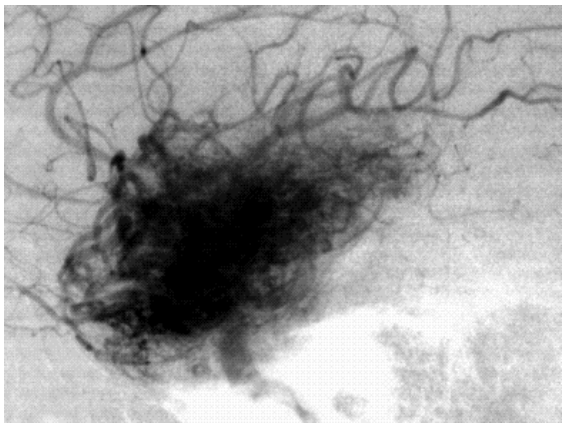
Measurement at distal internal carotid artery (ICA) and middle cerebral artery (MCA). The results from FloWire and TCD are well correlated.

Figure 10 shows the result. Both results were well co-related.

illustrative Cases

Case 1: left temporal arteriovenous malformation (Figure 11)
Arteriovenous malformation is a disease that arterial blood flow shunts directly to the veins without capillary networks. Venous structure must endure high arterial blood pressure. AVM has risk of rupture, so embolization,surgical removal with/ without radiosurgery is needed.
In this case, transarterial embolization was indicated. Tracker 18 catheter was placed in the feeding artery and liquid embolus was injected.
The digital subtraction angiography reveals decrease of vascular bed and Flowire also shown decrease of flow velocity.

Case 2: Carotid cavernous fistula
Carotid cavernous fistula is also a shunt from internal carotid artery to the cavernous sinus. The cavernous sinus is a venous structure in which the internal carotid artery pass through. The flow pattern in the cavernous sinus was arterialized. In this situation, venous hypertension has possibility to cause intra-cerebral hemor-



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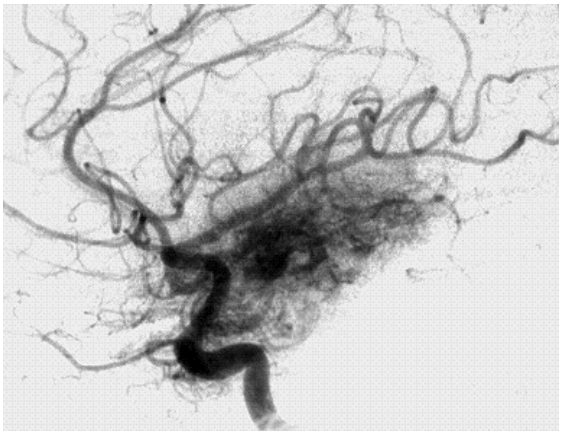

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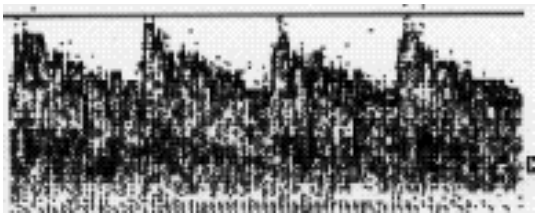

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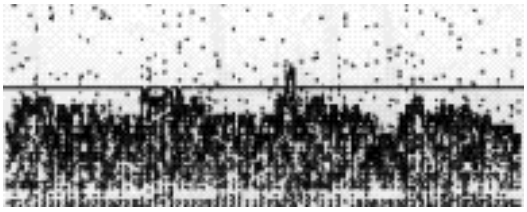

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Figure 11 Case 1

a) DSA (Left Internal Carotid Angiogram, Lt ICAG) before treatment
b) DSA Lt ICAG post embolization
c) Doppler signal from FloWire before embolization
d) Doppler signal from FloWire after embolization

Decrease of vascular bed on DSA and decree of flow velocity are displayed by DSA and FloWire. On series of DSA, decrease of low also recognized.

rhage. Nerves passing around the cavernous sinus are also affected. In serious case, brain ischemia due to steal of arterial flow to the venous structure course brain ischemia. This disease is a good indication for intravascular procedure. Placing detachable balloon is a traditional treatment. In this case, the fistulas part is not large enough to pass the detachable balloon(s). Coil embolization was selected. From femoral vein, a guiding catheter was place at the jugular vein. Through the

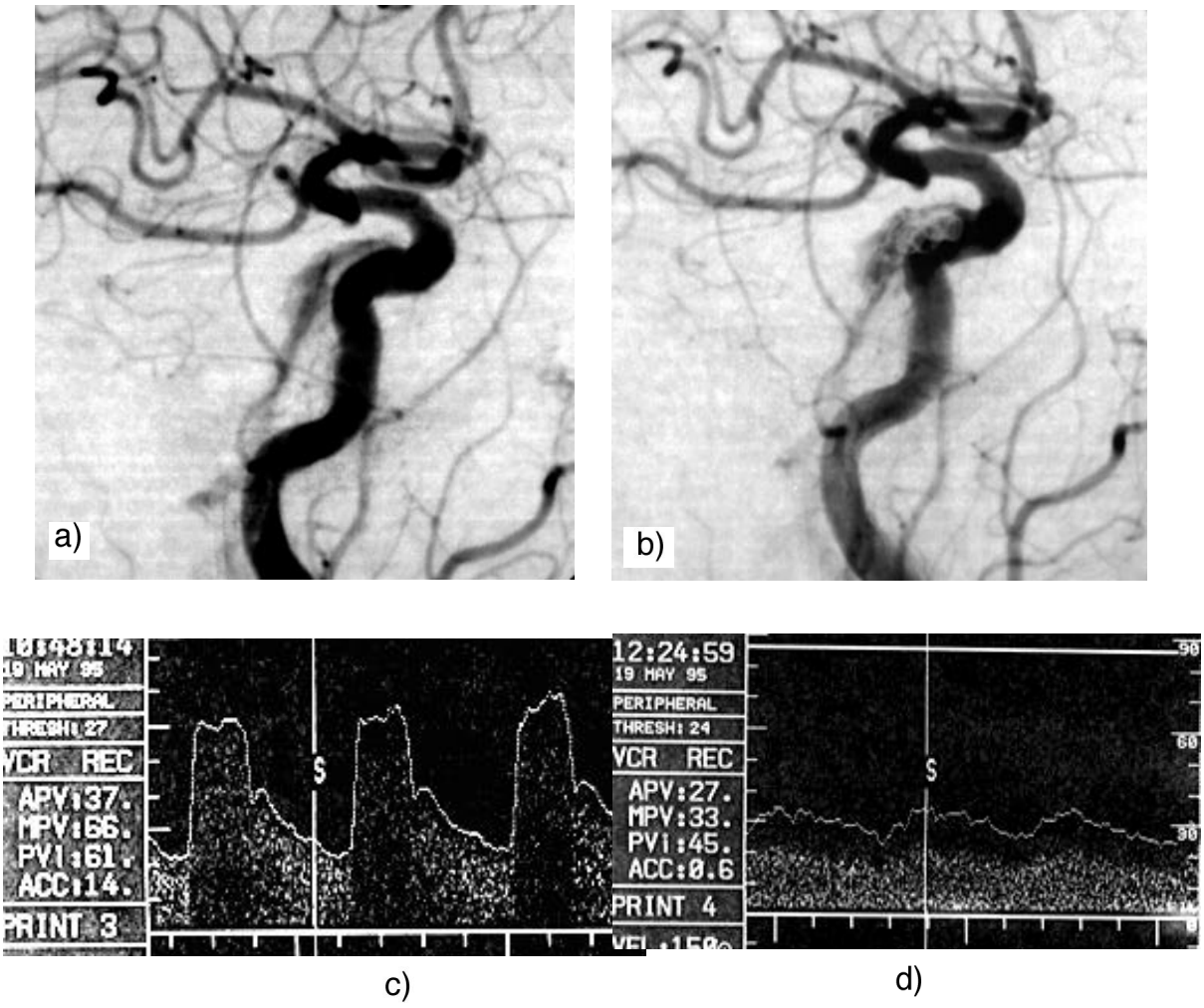
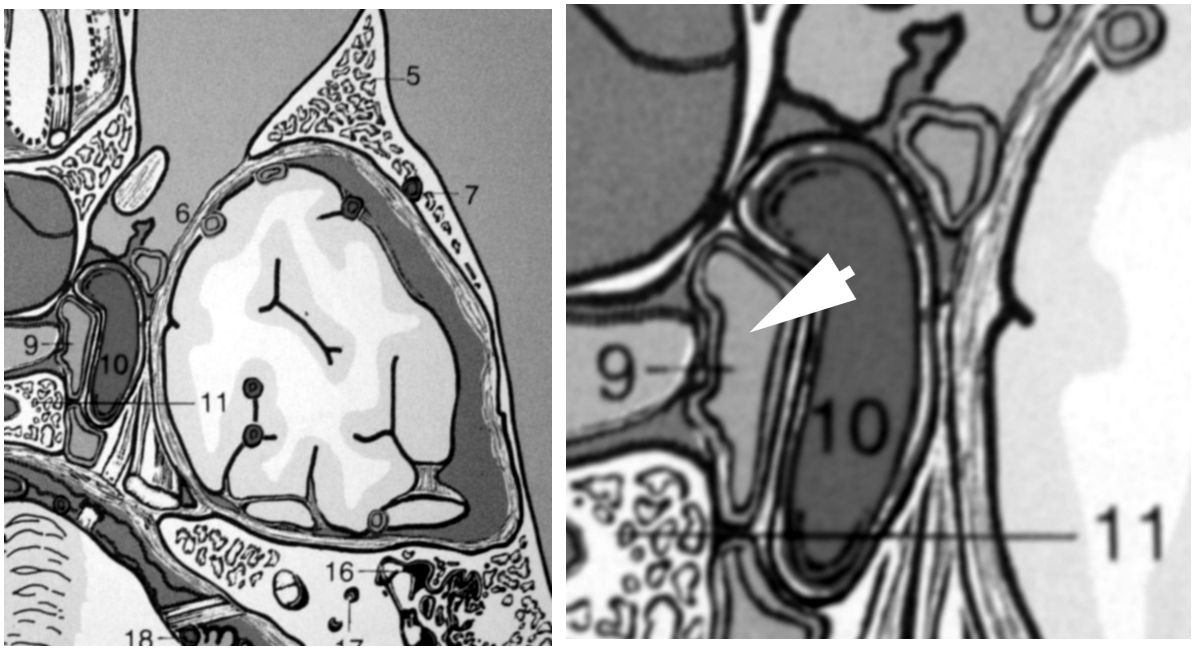


Figure 12 Case 2

a) DSA Rt ICAG before treatment
b) DSA Rt ICAG white embolization. Arrow is the embolic coils.
c) Doppler signal from FloWire before embolization
d) Doppler signal from FloWire after embolization
Arterialized flow pattern in the cavernous sinus recovered to the venous pattern.

guiding catheter microcatheter was navigated to the cavernous sinus through inferior petrosal sinus. Platinum coils were placed in the sinus. After coil embolization of the cavernous sinus, the flow pattern recovered to the venous pattern. (Figure 12)



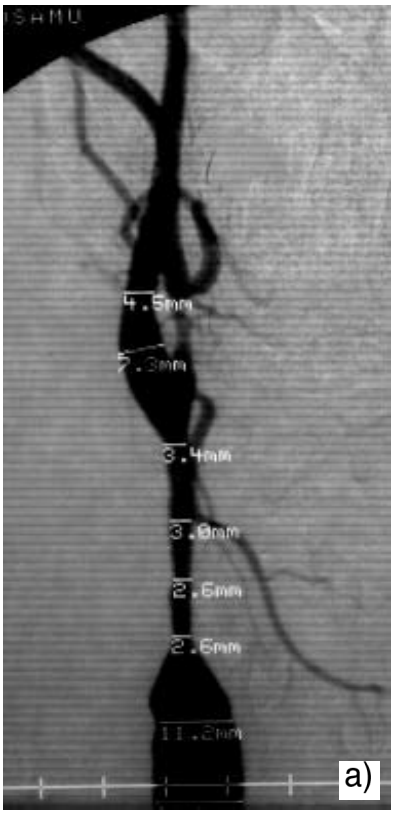
a) b)

Figure 12 Illustration of the cavernous sinus

a) Cavernous sinus “9” is the venous structure which locate at the entrance of internal carotid artery “10”.
b) In case of carotid cavernous sinus, arterial blood shunts to the cavernous sinus line the white arrow.

Figure 13 Case 3 (opposite page)

a) DSA before angiplasty
b) DSA after angiplasty
c) Endoluminal Doppler signal obtained by FloWire. The wave form is dumped.
d) FloWire at the stenosis. Remarkable increase of flow velocity and peak.
e) Transcranial Doppler (TCD) at the middle cerebral artery (MCA).
f) FloWire at the distal side of the stenosis after angioplasy.
g) FloWire at the stenosis after angioplasy.
h) TCD at the MCA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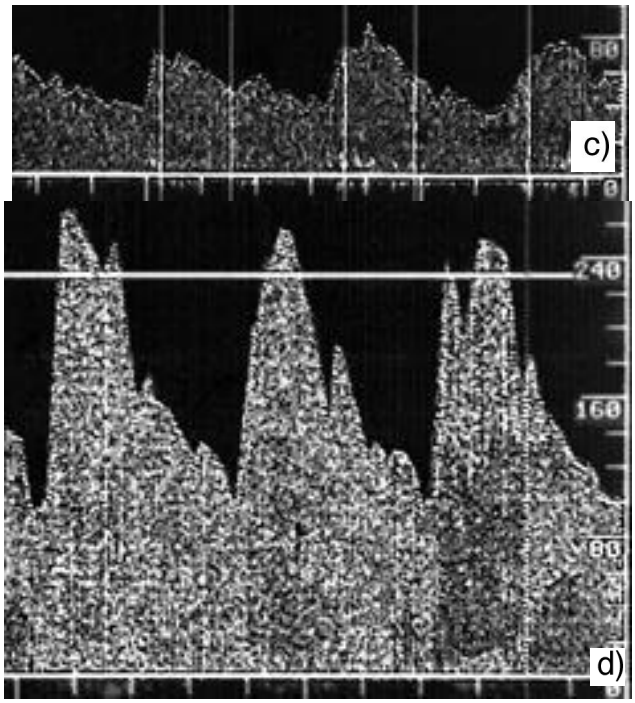
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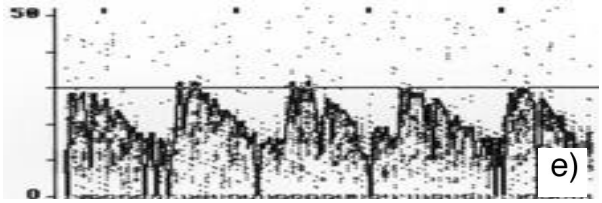
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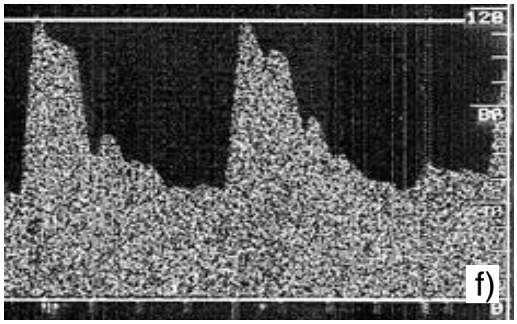
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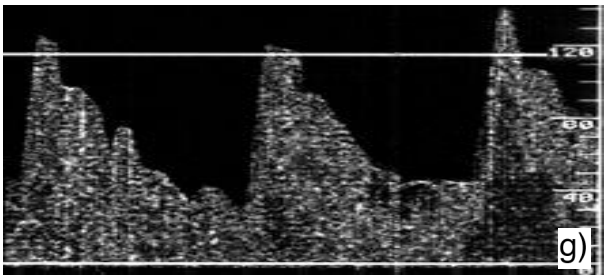
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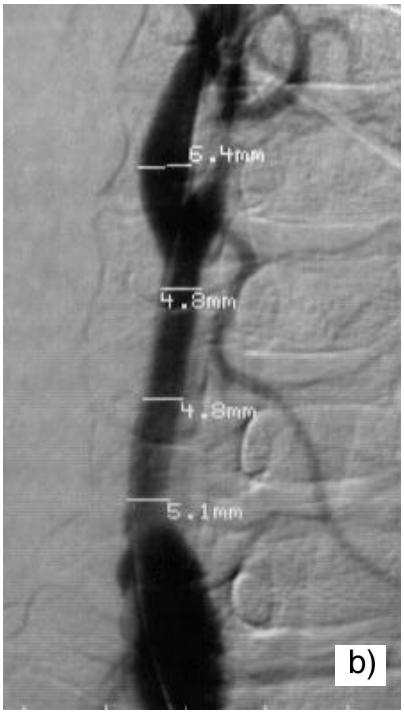
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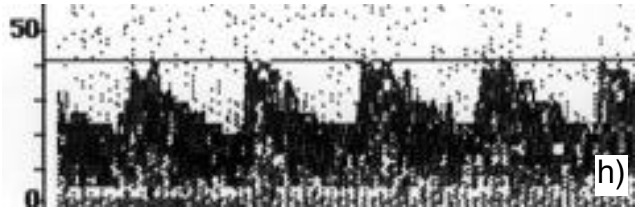
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Case 3: Aortitis syndrome

Aortitis syndrome is an autoimmune disease that major arteries such as common carotid artery, brachiocephalic artery or subclavian artery. Inflammation occurs at the arterial wall. Aortitis syndrome is good indication for balloon angioplasty. Before angioplasy, the flow velocity remarkably elevated at the stenotic segment and decrease the distal part. (Figure 13) After angioplasy, the flow pattern was also normalized.

Navigation of Doppler Wire

With Doppler wire, once again, we can not get the three dimensional position in the vascular structure, again. The possible solution is navigation of catheter tip. Magellan, magnetic catheter navigating system is one of commercially available system, however, the diameter of Magellan system is 5 Fr size, far from intracranial use. The other way should be co-registration of catheter tip the three dimensional modalities.

Conclusion

Medical field, especially vascular surgery, demands CFD information.

On the other hand, medical imaging modalities can offer 3D structure of vessels. At the same time, some information about boundary condition, medical modalities can offer, too.

As the boundary condition, flow pattern assessment by magnetic resonance and Doppler sonography is presented in this paper.

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