Computational Biomechanics from Neurosurgery

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Abstuct. *In neurosurgery, stroke, brain tumor and congenital anormay are the common diseaseds to be treated. Using recently advance d imaging modalities, detailed structure of each patient can be obtained acuurately. Based on three dimensional structure, computational biomechanics can solve a lot of clinical problems such as decision of prognosis of diseases and indication of treatment. Surgical procedure is highly mechanical. Tailor mmade madicine will be avilable with computational biomechanics. Expectancy to the computational biomechanics from neurosurgical field is reported.*

1. Introduction

Most of medical techniques are base on historically long experiences. Most logics are following the experience. The other source of information is mass study. Randomized controlled clinical studies give a lot of important evidences. Randomized study must be the base for decision making, if the study is designed ideally.
Advanced biomechanical technique will be one more modality. Biomechanics can be based on each patient's body structure. Recent advance of imaging technology let it possible to get individual body structure. So biomechanics based on imaging technology can progress tailor made medicine, ideal treatment for individuals.
The other important factor for tailor made medicine is genetic analysis. Here, expectancy from neurosurgical field will be reported.

2. Benefits of biomechanics in neurosurgical field

2.1. Neurosurgical disease and biomechanics

In neurosurgical field, vascular accident (stroke) is the most frequent diseases to treat. Brain tumor and congenital anormal, anormaly based disease are also treated surgically. Biomechanics for neurosurgical diseases are reported here.

2.1.1. Subarachnoid hemorrhage (SAH) and aneurysms

SAH is not a rare disease. About 12 patients suffer SAH from 100,000 people per year. The most common reason of SAH is rupture of cerebral aneurysms. The aneurysms generally locate at the subarachnoid space, where major brain arteries exist. When such aneurysms rupture, blood spreads to the subarachnoid space, so it is called subarachnoid hemorrhage. Aneurysms are common disease. One or two percent of people have aneurysms incidentally in non-SAH related autopsies. Recent advance of diagnostic modalities let possible to detect aneurysms before rupture. Especially in Japan, brain screening study (brain dock) detects a lot of incidental aneurysms. The highest rate of aneurysms is reported about eight percent in brain dock report, which is biased because people having headache or family history of SAH visit such screening. Treatment for aneurysms is performed by craniotomy (open skull surgery, then place a clip to the neck of aneurysm) or endovascular approach (embolization, filling aneurysm lumen with embolic materials) with low risk, NOT no risk.

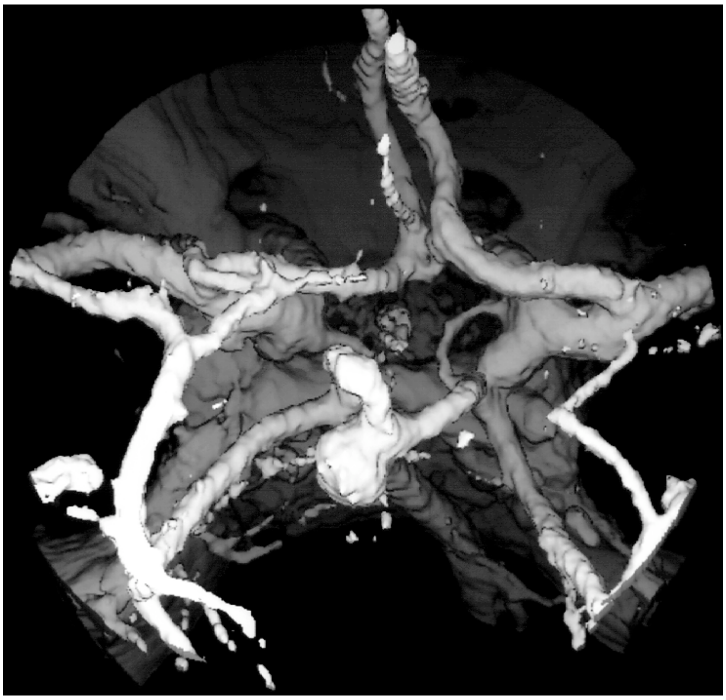

Fig 1 3D CTA of multiple aneurysms.

So, it is important to know whether the aneurysm will rupture or not, i.e. the aneurysm is a risky one or not. From clinical experience, larger aneurysms (larger than 5 mm or 10 mm), aneurysms with daughter and non-spheric shaped aneurysms are risky ones. However, in SAH patients, small spherical aneurysms also rupture. By three dimensional computer tomographic angiography (3D CTA Fig 1), three dimensional magnetic resonance angiography (3D MRA) or three dimensional angiography (3D DSA) detailed three dimensional structure of aneurysms and parent artery can be obtained. Based on such three dimensional structures, computational fluid dynamics (CFD) is possibly applied in this field and must be helpful. Three dimensional structure can be obtained but the boundary conditions are not easy, which is important for CFD. Doppler sonography (Fig 2) is the easiest way with risk to angle. The direction of the angle between the axis of the probe and axis of the flow is difficult to decide. Doppler wire and navigation system is a possible solution. Magnetic resonance can be the other solution. Intracranial vessels are too small in caliber for the MR machine at present. Higher magnetic field can be a possible solution.

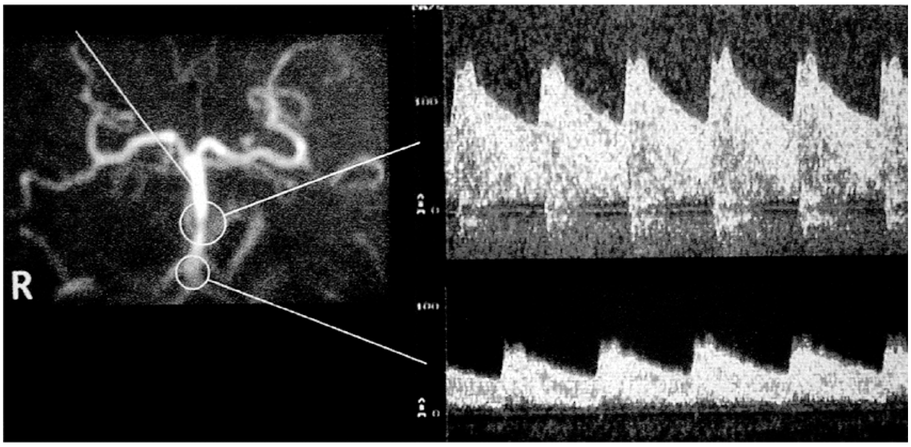

Fig 2 Doppler sonography from arterial lumen. (SmartWire or FloWire)
Showing flow pattern at the basilar artery and vertebral artery

The resolution of CFD might have other problems. Vascular wall consist from intima, media and adventitia. The most inner surface is covered with endothelium, which has flow signal receptor.

Share stress is sensed by adhesive factors like PECAM-1 (Fig 3) at the surface of endothelium. The wall of vessels has stretch sensor so blood pressure can be sensed. So at least, shear stress and pressure can affect biological modification of vascular structure. Concerning molecular shear stress sensor, CFD might improve its spacial resolution to cell surface level.

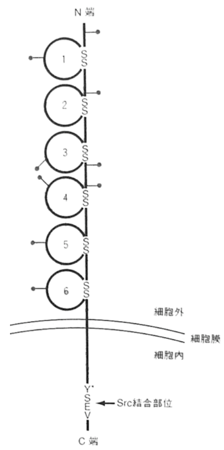

Fig 1 Schematic drawing of flow/share stress receptor, PECAM-1

Usual berry aneurysms were born at the bifurcation of arteries. These aneurysms were made by damage of vessel wall by blood flow with co-existing congenital maldevelopment of the vessel wall. Possibly because of error while apostosis while embryo to develop brain arteries, buds of aneurysm can exist at the bifurcations. There are other types of aneurysms. Arteriovenous malformation is a rare disease. Direct connection of arteries to the veins. So, high flow is produced at the shunt. At the proximal arteries, flow related aneurysms are produced. By treatment of AVM (Shunt flow), the flow related aneurysms can be disappeared.

2.1.2 Arteriovenous malformation (AVM)

As described above, AVMs (Fig 4) are arteriovenous shunts having very complex vascular structure. They consist of feeding arteries, nidus (bird nest; elongated abnormal vessels around the shunts) and draining veins. AVM has really complex vascular structure. Possible flow related aneurysms, varix or arterial flow steal. Shunt flow itself has clinical risk. At the same time, venous hypertension is really the problem. Cerebral blood flow can be disturbed by the venous hypertension. Medical doctors have believed AVMs have "sump" effect to aspirate flow from normal circulation to the shunts. Getting three dimensional structure and flow pattern must be really difficult to obtain. AVM also has risk of rupture. Moreover in some cases of AVM, patients suffer epilepsy because of brain damage and/or ischemia around the shunt. Total removal with/without embolization or radiosurgery is the standard treatment. And if the AVM is too large or too risky for direct attack, conservative partial embolization is done to control epilepsy. If CFD will be able to point out the effective points and/or the risky point to embolize, it must be very helpful to control AVMs.

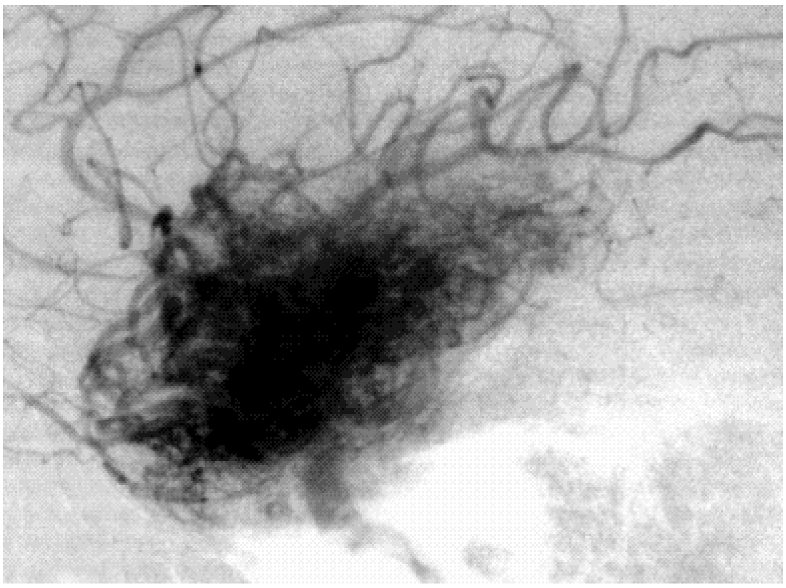

Fig 4 Digital subtraction angiography of the left temporal lobe arteriovenous malformation (artrial phase)

2.1.3. Dural arteriovenous fistulae (d AVF)

D AVF (Fig 5) is the other interesting disease. This lesion also can be made artifical venous

hypertension experimentally. Venous hypertension can possibly open the possible shunt structure.
These kind of shunt disease is interesting from the point of CFD. Biological factor may more important roles

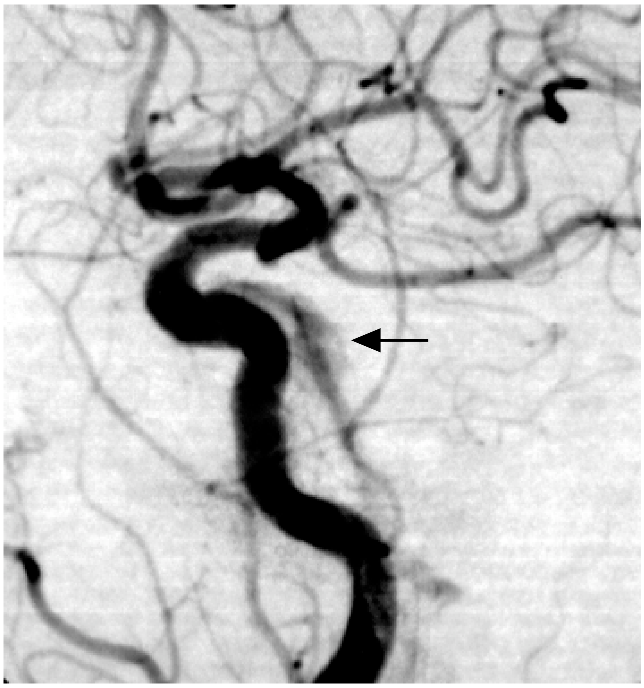

Fig 5 DSA of dural arteriovenous fistula. Shunt flow from the internal carotid artery to the cavernous sinus (arrow)

2.1.4. Syringomyelia
Syringomyelia had been a very rare disease before magnetic resonance imaging. It is a chronic disease of the spinal cord characterized by the presence of fluid-filled cavities and leading to spasticity and sensory disturbances at the shoulder. The most common reason is Chiari malformation; One of the largest space of cerebrospinal fluid (cisterna magna) is occupied by herniated neural structure (cerebellar tonsile Fig 6)). In normal pattern, jet flow of cerebrospinal fluid can enter the cisterna magna and decrease it kinetic energy. In Chiari malformation, the cistern is occupied by tonsile. So, the jet flow goes to the central canal of the spinal cord and let the central canal enlarge. So patient suffers sensory disturbance and spasticity.
This disease can be treated surgically. By removing posterior fossa bone, alternative space of cisterna magna can be made. By this operation, symptoms improve and the syrinx also disappear. This is a really interesting example that fluid dynamics affects neurological diseases.

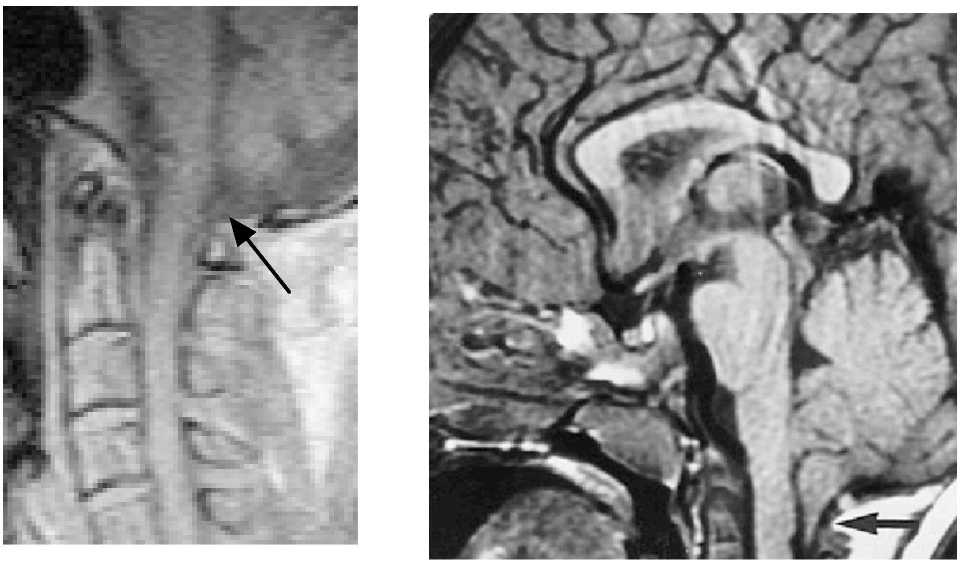

Fig 6 MR imaging (T1 WI) Sagittal slice
Left side is normal(rather atrophic) image and right is Chiari Malformation.
Cisterna magna is occupyed by neural structure in the right

2.1.5. Dissecting aneurysms

Dissection of arterial wall (dissecting aneurysm) is famous at the aorta. And such dissection can occur at brain circulation, carotid artery and vertebral artery or intracranial arteries, too. Recently, it is reported that painless dissection possible occurs from aorta to carotid artery and causes cerebral infarction. This kind of dissection can be treated by metallic stents, to place expandable metallic tube to push the dissected wall to the proper wall. However, if the dissection has re-entry, stent occlude the re-entry and let occupy more space in the true lumen by increasing false lumen. If painless dissection, brain angiography can not detect the entry or re-entry so stents may be placed to get larger vascular lumen to improve brain circulation. Then stent can occlude re-entry and progress dissection to worsen the dissection or lead dissection to proximal side to occlude the orifice of coronary artery. Dissection can progress passing blood flow line. If dissection from aorta to carotis can be locate some proper direction of carotis, further examination can be done before treatment.

2.1.6. Ischemic disease

The patient population of ischemic disease is very large, larger than suffering hemorrhagic diseases. Ischemia can occur from several reasons. One is embolic source from hart because of some kinds of arrhthmia (Af, arterial fibrillation). The other is stenosis at the brain circulation. In case of Af, blood can be static at the left atrium and produce thrombus. By paroximal Af or by some other reasons, such debris go to left ventricle, then to the systemic circulation and occlude some vessels. CFD for heart having Af can prove production of thrombi. In the case of stenosis, CFD can play more important role. Surgical indication for stenosis is decided whether the stenosis affects brain circulation or not. At present, cerebral blood flow is imaged by microscope method using radioisotope labelled tracers. If CFD can give same information, it must be helpful to decide indication and surgical procedures.

2.1.7. Hemiparesis

By natural course of brain vascular accident, neural structure is destroyed. Such patients suffers proper neurological deficits. Hypertension disease braked pyramidal tract. So patients suffers hemiparesis; weakness at the arm and leg opposite to the site of accident. At present we have no way to re-connect the destructed neural fibers. Muscles can be moved not only by the commands from nerves. Muscles can be moved by electrical stimulation, too. Functional electrical stimulation (FES) is a method to move paralyzed muscle by electrical stimulation. By analysis of normal human walking, excellent program to give walking to such patients.

2.2. Neurosurgical treatment method and biomechanics

In neurosurgery, craniotomy, endovascular procedure and radiosurgery are the triad. Craniotmy is the legacy and fundamental technique. opeing skull and dissect the fissure to approach the lesions. Emdovascular technique is the recently developping techique to approach the lesion from iside the vascula rlumen. Gamma knife is the representative techinique in radiosurgery. in radiosurgery, large dose of radiation is gicen with minimal damge to the mormal structure.

2.2.1. Coil embolization of aneurysms

Coil embolization is the alternative way for treatment of cerebral aneurysms. As described above, this can be done by placing microcatheter in the aneurysm and deposit fragile platinum coils in the lumen. The microcatheter was advanced to the aneurysm lumen under fluoroscopic guide and through the catheter, detachable coil (GDC, Fig 7) was place in the aneurysm lumen. Guglielmi detachable coil, which releases coil by electrolysis, is the commercially available coil for aneurysms.

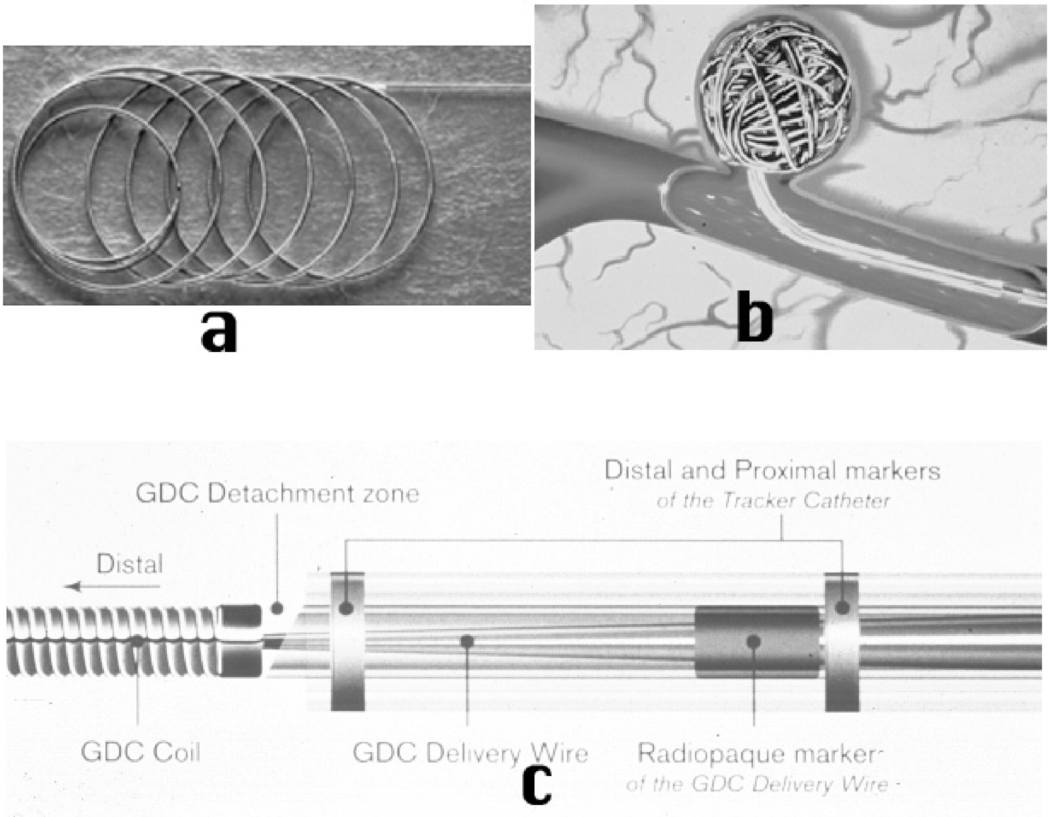

Fig 7 GDC system
a: GDC coil having helical shape, b: shcematic drawing of coil embolization for aneurysm and c: GDC detach zone. Coil itself is mounted at teh tip of stainless steel coil pusher. When all of the coil pushed out from the catheter, the detach zone is destroyed by electrolysis. (See colour page)

When the coils fit well with the aneurysm, the coils detached from the pusher by electrolysis (Fig 8). Then additional coils are placed until no more coils can be placed. If the coil does not fit well, it can be retrieved before detachment.

GDC treatment is really less invasive but have some risks. One of the risks is coil compaction (fig 9). The coils are designed very soft and fragile to avoid aneurysm rupture while pushing the coils.

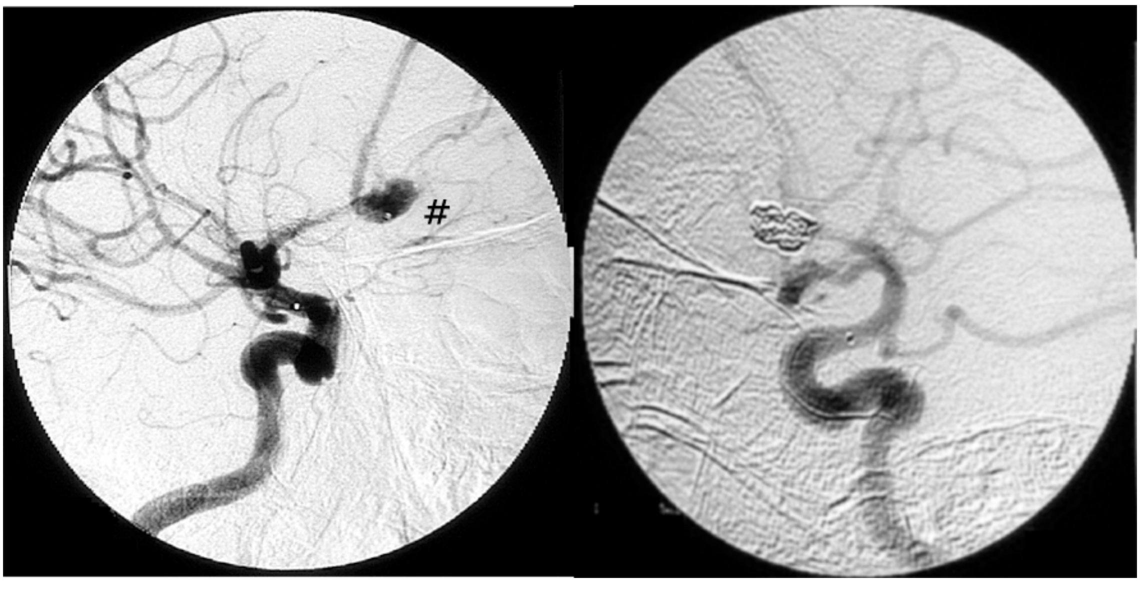

Fig 8 Anterior communicating aneruysm (#) before embolizxation and after embolization.
Radiopaque GDC coils were depositted in the aneurysm lujmen and the aeurysm was not visualized

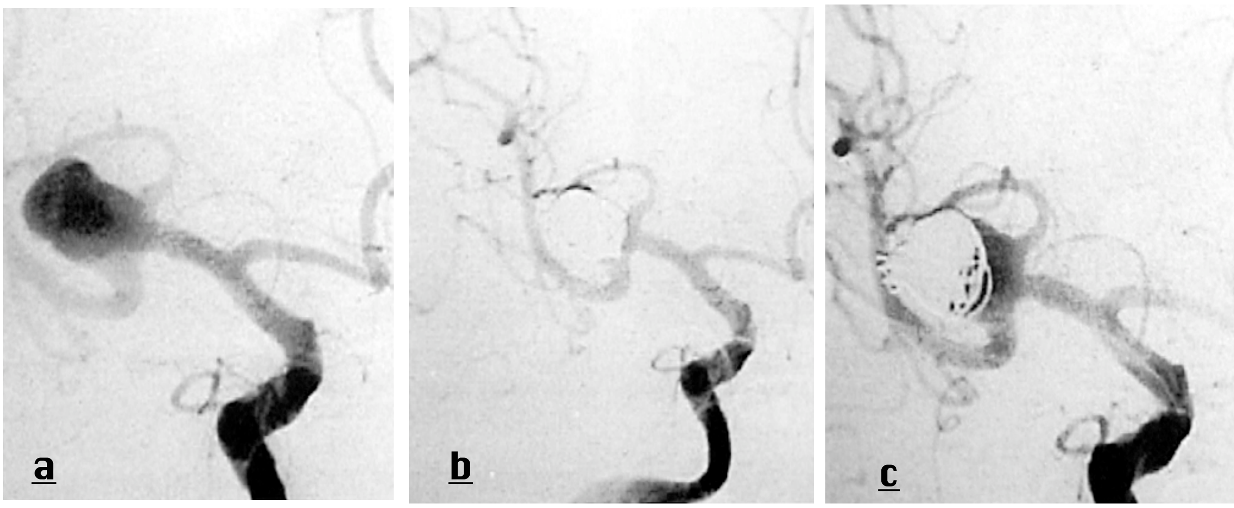

Fig 9 Coil conpaction
a: Right middle cerebral aneurysm before embolization, b: just after embolization and c: follow up DSA showing compaction
The coils are deformed and the areusrysm lumen re-apprear.

Softness of the coils are effective to prevent rupture of the aneurysm and at the same time, have risk of deformity after treatment. Even aneurysm lumen look as if packed enough, after long follow up observation, the coil-mass can be deformed and the aneurysm lumen can re-open. This phenomenon called coil comapction. Blood flow can deforms the coil.
Coil system at present is designed to have three degrees of rigidity; standard, soft and ultrasoft. In each rigidity, we have various size of helix from two to 30 mm. The rigidity of 10 mm helix coil and 2 mm coil is same. So larger diameter coil can be softer comparing smaller ones. If each diameter coil has proper rigidity, the risk of compaction can be decreased. This kind of modification of coils can improve the result of detachable coil treatment.
At present, place coils as much as possible (dens packing) the only possible way to avoid coil compaction. When more than about 30 % of aneurysm lumen is packed (volume embolization ratio, VER), coil compaction will be rare. Using various of coils from standard to ultrasoft coil series, the lumen can be packed enough.
Having soft and ultrasoft coil, to pack residual small lumen and increase VER. At the endstage of embolization, all of two cm GDC can not place in the residual lumen. Variable detachable system is the other solution.
Alternative way to prevent compaction is bioactive coils. At first, PVA (polyvinyl alcohol) rod was placed in the GDC coil and stained in the rod some biological mediators to induce inflammation to have scar in the lumen. Coating of coil is also another resolution.
The other is hydrogel coil. After releasing coil in blood (fluid) the polymer absorb water and increase its volume to decrease risk of coil compaction.

2.2.2. Flow pattern modification and aneurysm

Direct attack such as coil embolization and clipping is the standard technique to cure standard aneurysms. Direct attack is effective but has risk of rupture. In case of giant aneurysms, parent artery occlusion is an effective treatment. If flow in the aneurysm decreases enough to induce clotting, there might be possibility to induce spontaneous thrombosis in the aneurysm. If it is possible, there is possibility to cure aneurysm without direct attack. Modification of parent artery is possible using open surgery and endovascular surgery. CFD simulation must be essential for this concept.

2.2.3. Catheter manipulation

Intravascular procedure looks simple, having only two dimension of freedom, push and pull of catheter/guide wire and rotate or twist the guide wire.

Intravascular surgery is base on progress of microcatheter, fluoroscopy (imaging system) and embolic materials. We have two catheter systems. One is over the wire technique (including monorail system) and flow guided technique (including detachable balloon technique). Flow guided system is less invasive but not easy to operate. Recent treatments are performed by over-the-wire dominantly. By over-the-wire technique, rigid (of course, having gentle and soft tip) steerable guide wire was passed through the delicate microcatheter. Advancing the guide wire through the vascular lumen then microcahteter follows the wire. At the branch of blood vessels, the route was selected by the curve at the tip of wire (Fig 10). Of course we can rotate the tip of the wire for selection. We must understand if push the wire with curve the wire do not go to the direction of curve. The wire goes straight even if curved tip. Movement of guide wire is affected by curve of wire, friction between vessel wall. The motion of microcatheter is affected by guide wire, shape of catheter itself, friction and gap between wire and catheter. Compression or shortening catheter by the friction between vessel wall is a big problem, too.

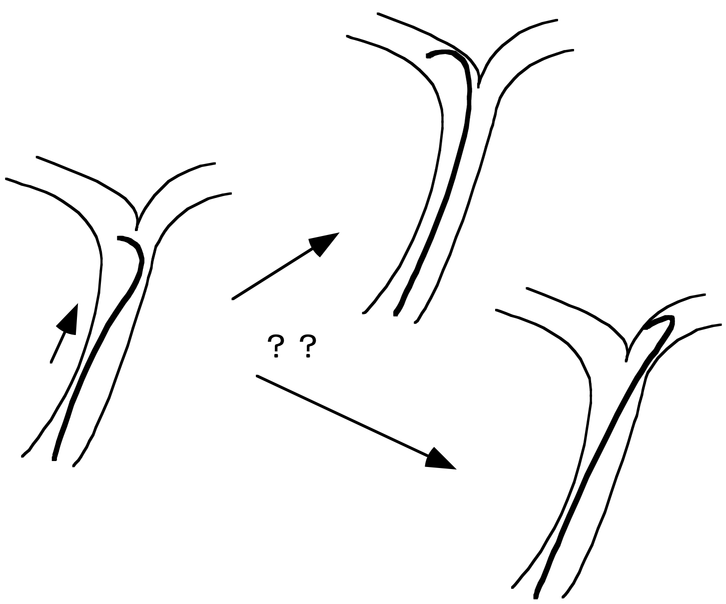

Fig 10 movent of guide wire
When advancing the curved guide wire at tthe bifurcation, the wire goes to the right or left?
Even with the cureve, the tip possible goes to both side.

If we have simulator for these procedure, training using patient's own vessels will be possible as vascular structure itself can be obtained by 3D imaging modalities, already. And remote or robotic surgery can be achieved. If robotics joins to catheter manipulation, operator can feed enhanced force-feedback fro the catheter, dangerous manipulation can be stopped by computer and extremely fine manipulation can be possible. And an expert operator can treat a very difficult operation at the remote site. So safety of the procedure can be increased.

2.2.4. Carotid endoarterctomy (CEA)

CEA (Fig 11) is a surgical treatment for sclerotic carotid artery stenosis at the carotid artery at the

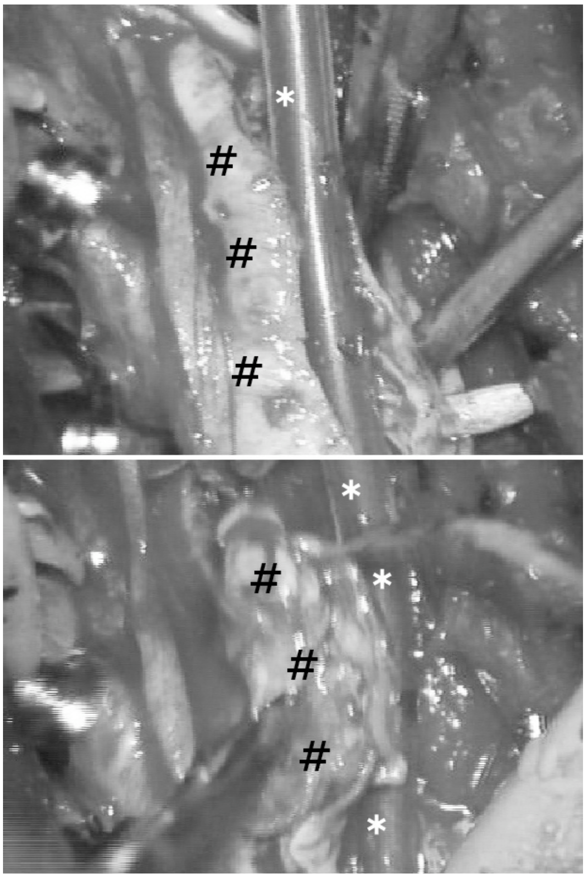

Fig 11 CEA
Intraoperative view of CEA
is the atheromatous plaque and * is the shunt tube passing blood to the distalside, to the brain while operation.
(see colour page)

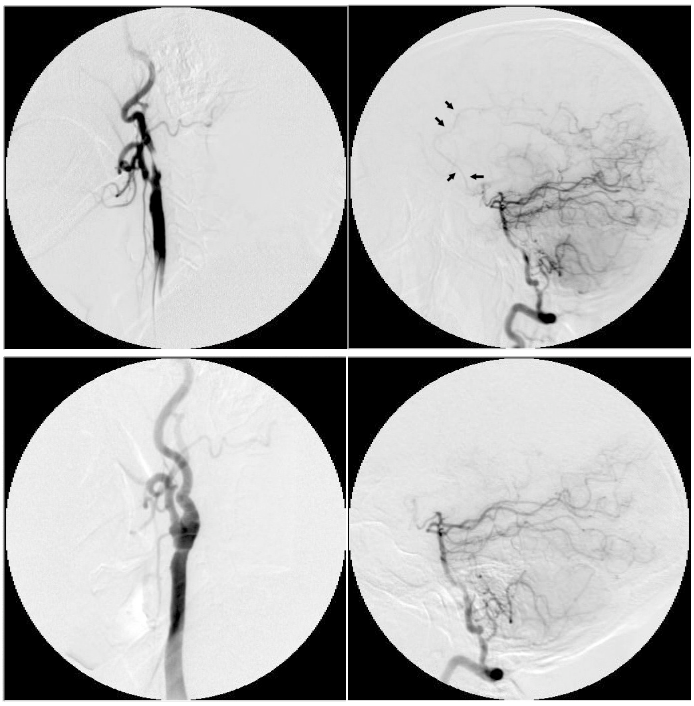

Fig 12 DSA before (upper) and after (lower) CEA
Left carotid (left side) stenosis was released by surgery.
By levt vertebral angiography, anterior cerebra artery (arrows) was visualized before operation and dispappear after surgery.
Before surgery, purfusion pressure from the internal carotid artery was disturbed by the stenosis to splly the the anterior cerebral artery from the vertebro-basilar system. After CEA, the perfusion pressure was recovered to supply anterior cerebral artery from the internal caroti artery.
(See colur page)

neck, especially at its bifurcation. The indication is hemodynamic compromise (fig 12) or production of emboli at the stenosis. Carotid artery at this level has large caliber, about 10 mm or more. Three dimensional structure by computer tomography can be easily obtained and the boundary condition also easy because Doppler sonography can examined.

2.2.5. STA MCA anastomosis

STA (superficial temporal artery) is an artery supplying scalp. MCA (middle cerebral artery) is the largest brain artery supplying about half cerebrum. MCA runs beneath STA separated by skull. On opening skull just under the STA, MCA is easily found and possible to anastomose(Fig 13). This

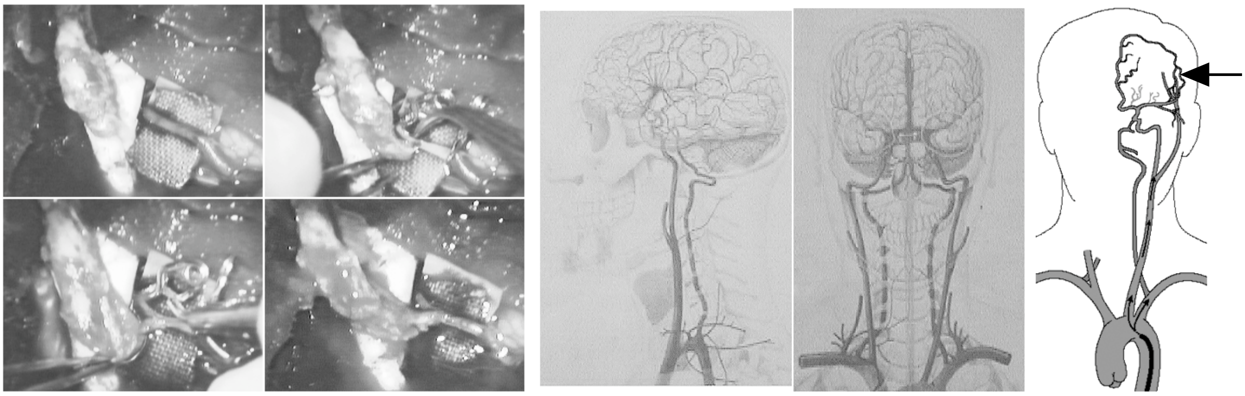

Fig 13 STA-MCA anastomosis
Right: intraoperative view and left schematic drawing of cerebral arteries
STA-MCA anastomosis was place at teh site of arrow. (See colour page)

anastomosis technique has been used as a surgery for brain ischemia. STA MCA anastomosis can be performed not only toward occlusive state but also toward stenotic lesions. If stenotic lesion has two blood supply, one is from proximal side, the other from distal side, how will the stenosis change? This may be interesting simulation for CFD.

2.2.6. Stent treatment and thrombosis

Stent is a material to make new vessel wall from inside the vascular lumen to treat stenotic lesion. The balloon can expand by its own elasticity (self expandable) or balloon expansion (balloon expandable).

Generally, stents are made from metallic materials. One is coil stents which was made from knitted filaments. The other is so called tubular stent made from thin wall metallic tube cut with LASER etc.

After stent placement, antiplatelet therapy is kept to prevent coagulation at the stents. In cases using coils stents may need more effective one even both are made from the same materials. This may possibly different from fine flow pattern around the implanted stents. CDF should be helpful to decide ideal antiplatelet or anticoagulating therapy after sent deploy.

2.2.7. Craniotomy

Craniotomy is a legacy modality in neurosurgical field. There are a lot of possible approaches. Brain must NOT be destroyed by approach. Brain must be treated very gently. With rough manipulation, brain can be damaged easily. Dissection of large brain fissure is the usual approach to the lesion and if needed, minimal brain dissection is essential for brain surgery. This is a big difference from abdominal or thoracic surgeries. In craniotomy various body positions such as supine, lateral or prone, are used. However, what is the best approach? Positioning can also damage patients if not ideal. If having virtual human body with bone, muscle and nervous system, if having such data from individuals, ideal safe position can be decided.

3. Conclusion

Biomechamics has a lot of merits for neurosurgical field, of course , not only in neurosurgical filed but also all of surgical and medical field. In neurosurgical field, computational biomechanics can solve problems from etiology of diseases to risk management of lethal diseases. Classical craniotomy also needs biomachanical assistance to decide ideal surgical approach. Medical imaging techniques needs more accuracy and more resolution. Based on biomechanics, remote surgery, robotics operation and tailor made medicine will be realized.