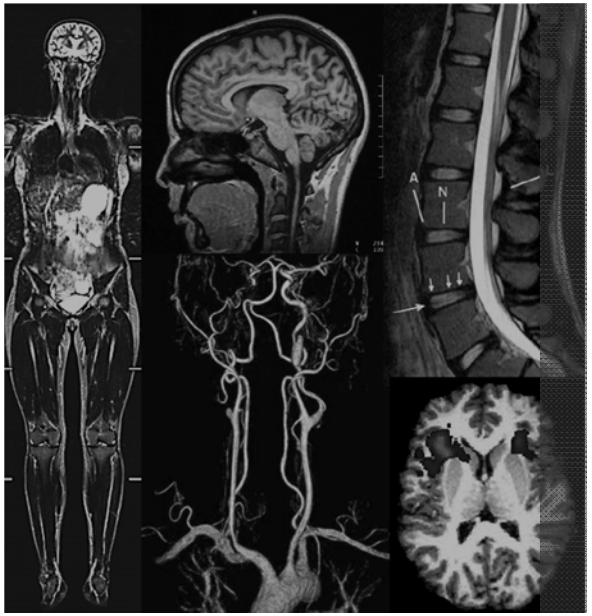
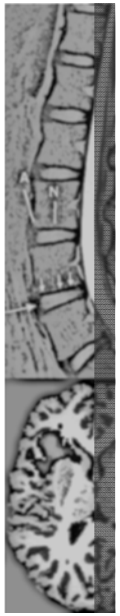


血管攝影與對比劑
A Course of MRI

盧家鋒 助理教授
國立陽明大學 物理治療暨輔助科技學系
alvin4016@ym.edu.tw



本週課程內容-MR Angiography (MRA)

- 非對比劑增強MRA(Unenhanced MRA)
  - Time-of-flight (TOF) angiography
  - Phase-contrast (PC) angiography
- 對比劑增強MRA(Contrast-enhanced MRA)
- 腦血流灌注(Brain MR perfusion imaging)

- References

  - Magnetic Resonance Angiography: Principles and Applications, Carr et al, 2012 by Springer
  - Magnetic Resonance Angiography: Techniques, Indications and Practical Applications, Schneider et al, 2005 by Springer

非對比劑與對比劑增強MRA

Unenhanced and Contrast-enhanced MRA

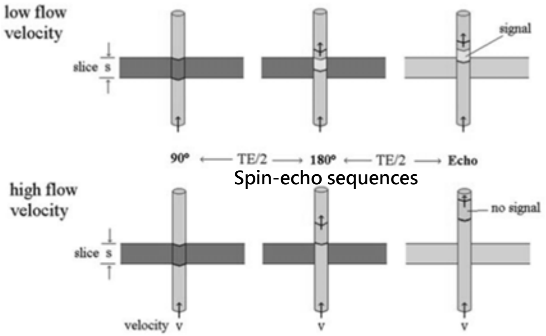
Unenhanced MRA

- Rely solely on flow effects (the movement of blood)

- Amplitude effects
  - Blood flowing into or out of a chosen slice has a different **longitudinal magnetization** compared to stationary spins.
  - Depend on the duration of stay (time-of-flight) in the slice
- Phase effects
  - Blood flowing along the direction of a magnetic field gradient changes its **transverse magnetization** compared to stationary spins.

Outflow-related signal loss

- Washout effect, $v \geq \frac{s}{TE/2}$ → T2 flow void

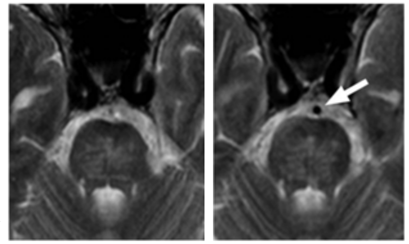


Blood flowing within the imaging plane are not affected by this phenomenon.

Outflow-related signal loss

- $v \geq \frac{s}{TE/2}$ → flow void
- The intensity of the vascular signal declines with
  - Decreasing slice thickness, s
  - Increasing echo time, TE
  - Increasing flow velocity, v

thrombosis After thrombolysis



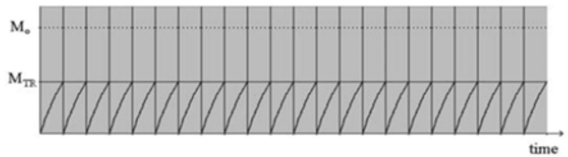
Axial T2W SE image
Basilar artery

Outflow-related signal loss

- Only observed for SE sequences and is most pronouced on T2-weighted imaging (longer TE).
- The washout effect does not occur in GRE techniques.
  - Only one RF pulse

Inflow-related signal enhancement

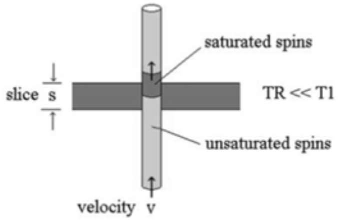
- With short TR (TR≪T1) of GRE sequence, the spin signals can be saturated.



- Spins outside the excited slice are not influenced by the RF pulses, and therefore are fully relaxed.
- Flowing blood gives rise to higher signal intensity relative to that of the saturated spins in the stationary tissue.

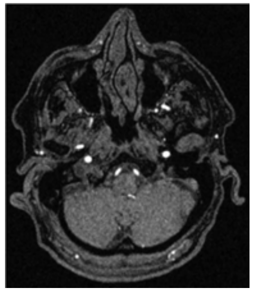
Inflow-related signal enhancement

- $v > \frac{s}{TR}$ → flow enhancement
  - Replace the vessel spins by unsaturated spins in the time interval TR
- The signal intensity of flowing blood increases with
  - Decreasing slice thickness, s
  - Increasing flow velocity, v
  - Increasing TR
    (Signal of stationary tissue ↑)



Inflow-related signal enhancement

- The inflow effect occurs both with SE and GRE sequences.
- However, the competing washout effect in SE tends to overbalance the inflow effect at higher flow velocities, leading to decreased flow signal.
- **TOF angiography**
  - GRE sequences
  - Bright-blood images
  - Endogenous contrast agent



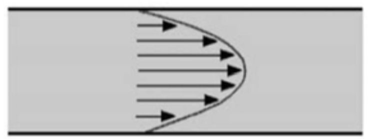
Bright vessels
Gray/black background

TOF Angiography

- Spoiled GRE sequences
  - No washout phenomenon
  - Short TR (<40 msec) to efficiently saturate stationary tissues
  - Short TE (< 5 msec) to reduce spin dephasing
  - Short acquisition time to acquire 3D datasets
  - Flow conpensation
- TOF techniques can be divided into 3 groups
  - Sequential 2D multi-slice method
  - 3D single-slab method
  - 3D multi-slab method

Flow compensation gradients

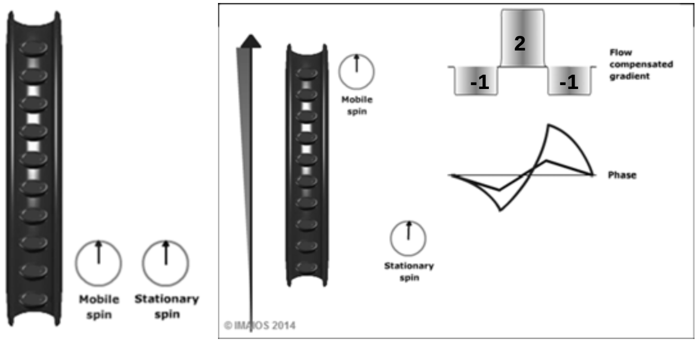
- Laminar flow with a parabolic flow profile
  - An increased velocity from the border towards the center.
  - Intravoxel dephasing of spins with different velocities



- TOF employs additional gradients on the slice-selection and frequency-encoding directions to refocus unwanted phase accumulations.

Flow compensation gradients

- Avoid dephasing in flows at constant velocity



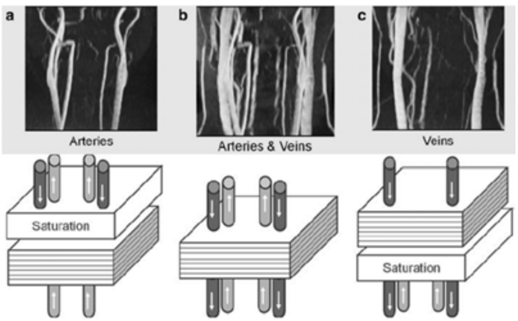
http://www.imaios.com/en/e-Courses/e-MRI/MR-Angiography-Flow-imaging/flow-compensation

Sequential 2D technique

- Larger flip angle (30º~70º)
- Thicker slice thickness (2~3 mm) to achieve better SNR
- Best suited for imaging vessels that are straight and perpendicular to the slices.
  - Carotid arteries or vessels in the lower extremities.
- It is necessary to synchronize the acquisition of data to the cardiac cycle (ECG gating).

Spatial saturation pulse

- Superior saturation pulses are used suppress the signal from veins above the heart, and arteries below the heart
- Inferior saturation pulses are used to suppress the signal from arteries above the heart and veins below the heart

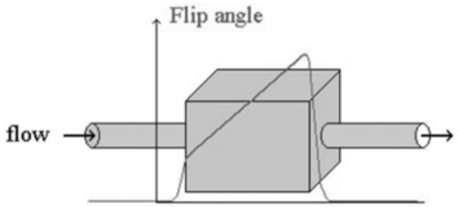


3D TOF MRA

- Smaller voxels (<1 mm), isotropic voxels, shorter TE, and higher SNR
- Because a slab is imaged, a small flip angle (<30º) must be used so the signal from blood that remains in the slab does not become too saturated.
- A small flip angle also leads to preserve undesirable signal from stationary tissues.

TONE flip angle adjustment

- Tilted, Optimized, None-saturating Excitation (TONE)
- The flip angle is varied linearly in the slice direction, beginning with small values at the entry side and ending with high values at the exit side of the volume.

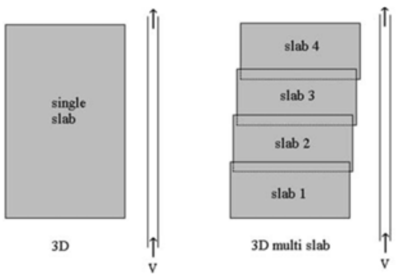


3D TOF MRA

- The extent of saturation depends on the length of time in which the blood stays inside the volume.
  - Slow flow vessels ➔ signals diminish even for a short cover distance
  - Fast flow vessels ➔ signals remain visible for a greater cover distance
- The maximum slab/volume thickness should be kept as small as possible.
  - Just matched to the size of the vessel region of interest
- Larger vessel sections ➔ 3D multi-slab technique

3D multi-slab method

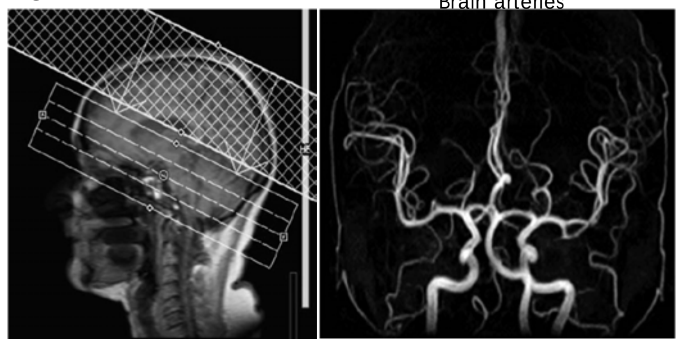
- Retains the advantages of 3D TOF and also has reduced saturation effects like 2D TOF
- Multiple overlapping thin slab acquisition (MOTSA) (4~6 cm)
  - 20-30% overlapping
- Longer acquisition time



3D multi-slab method

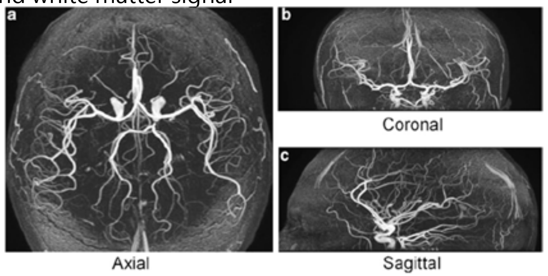
- Presaturation slab above the imaging volume suppresses the signal of venous flow.

Brain arteries



Background-blood contrast

- Magnetization transfer contrast (MTC)
- MTC can further suppress background signal.
  - Reduction of gray and white matter signal by 15-40%
  - But not in blood
- Fat suppression



TOF Angiography

Table 3. Comparison of 2D TOF and 3D TOF angiography

2D TOF	3D TOF
Strong inflow effect, minimal saturation	
• sensitive even to slow flow (veins)	More saturation effects
• sensitive to rather fast flow (arteries)	
Relatively poor signal-to-noise ratio	High signal-to-noise ratio
Short scan times	Poor background suppression
Relatively thick slices	
• suitable for large vessels	Thin slices, allows isotropic voxels
• suitable for small vessels	
Poor in-plane flow sensitivity	
• for straight, unidirectional flow	Better than 2D TOF for tortuous vessels
Long echo times	Short echo times, less dephasing
Step artifacts at the vessel wall	Smoother vessel walls

TOF Angiography

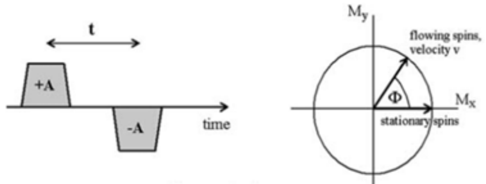
- Vein: slow flow
- Artery: fast flow

Table 4. Options to improve TOF angiography

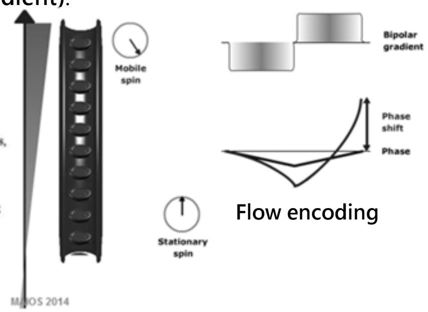
Orientation of slices or volume perpendicular to flow direction
2D for slow flow, 3D for fast flow
3D multi-slab for larger vessel sections
Spatial presaturation to isolate arteries and veins
Use of minimum TE reduces signal loss due to spin dephasing
TONE pulse reduces saturation effects in 3D TOF
Magnetization transfer (MTC) and fat suppression improve vessel contrast

Phase effects

- Phase effects concern the transverse magnetization.
- Apply a pair of gradients with identical strength and duration but opposite sign **(bipolar flow-encoding gradient)**.
- Stationary spins ➔ zero net phase shift
- Flowing spins ➔ a non-zeros phase shift



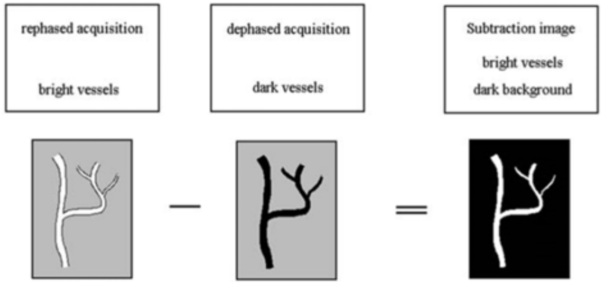
Phase shift $\Phi = \gamma \cdot A \cdot t \cdot v$



http://www.imaios.com/en/e-Courses/e-MRI/MR-Angiography-Flow-imaging/phase-contrast-mra

Magnitude contrast method

- Acquire two datasets
  - Flow-rephased images: flow compensation, bright-blood image
  - Flow-dephased images: strong flow-sensitive bipolar gradients, velocity-dependent phase shifts, dark-blood image.



Phase contrast method

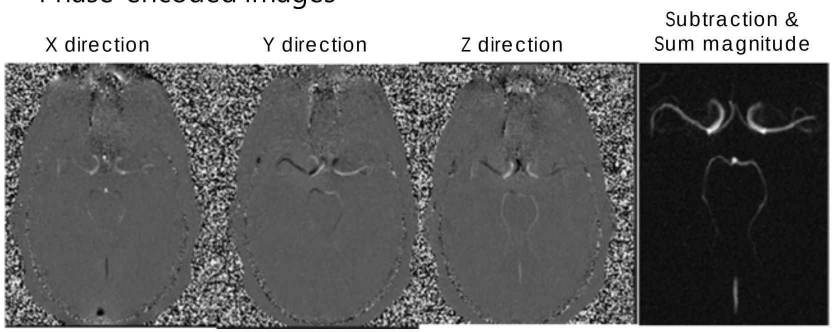
- Acquire two datasets
  - Flow-rephased images (S1): flow compensation, bright-blood image
  - Flow-dephased images (S2): flow-sensitive bipolar gradients, velocity-dependent phase shifts, dark-blood image.
- The flow-sensitive gradient is weak enough to avoid complete phase dispersion arising from the velocity distribution of the spins.
- Complex subtraction (S1-S2) ➔ the difference vector ΔS

Phase contrast method

- A direct quantitative measure of the velocity of the flowing blood
- No restriction on image orientation (not dependent on infow effects)
- Velocity encoding (VENC)
  - The velocities between –VENC and +VENC are encoded by the phase shifts between -180^o and +180^o.
  - The flow velocity exceeded the VENC value ➔ aliasing
- General velocity
  - Arterial flow 40~60 cm/s
  - Venous flow 20~30 cm/s

Phase contrast MRA

- Phase-encoded images



Phase contrast MRA

Table 6. Options for improving phase contrast MRA

Adapting flow sensitivity (venc) to maximum flow velocity
Encoding different flow velocities (multivenc) or different flow directions
Contrast agent improves flow signal
2D acquisition provides one *single* projection within a short acquisition time,
3D acquisition permits MIP postprocessing
ECG triggering can be applied in cases of pulsatile flow
Presaturation pulses can separate arteries and veins

Table 7. Flow velocities in some large vessels (according to Siemens application manual Magnetom Vision)

Vessel	Flow velocity (cm/s)
Ascending aorta	50 – 100
Descending aorta	100
Aortic stenosis	150 – 500
Aortic valve insufficiency	150 – 200
Common carotid artery	60 – 80
Carotid artery stenosis	100 – 500
Middle cerebral artery	60
Basilar artery	40 – 50
Femoral artery	60 – 80
Popliteal artery	35 – 40
Vena cava	5 – 40
Portal vein	5 – 10

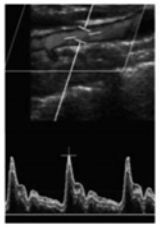
TOF vs. phase contrast MRA

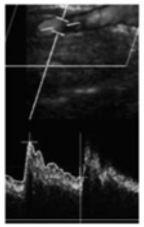
Table 9. Benefits and limitations of TOF and phase contrast MRA

	TOF-MRA	Phase contrast MRA
Advantages	Simple to implement, robust	No saturation effects
	High spatial resolution	Excellent background suppression
	Shorter acquisition time (in 3D)	Enables quantitative flow measurement
Disadvantages	Reduced sensitivity to slow flow	Prior knowledge about flow rates required
	Restrictions to size and orientation of the imaging volume	Very long acquisition times for 3D techniques
	Short T1 tissue may be mistaken for flowing blood	Susceptible to phase errors

Limitations

- Highly sensitive to motion artifacts ➔ ECG gating
  - Heart beats and breathing


ECA


ICA


MCA

MCA is less pulsatile.

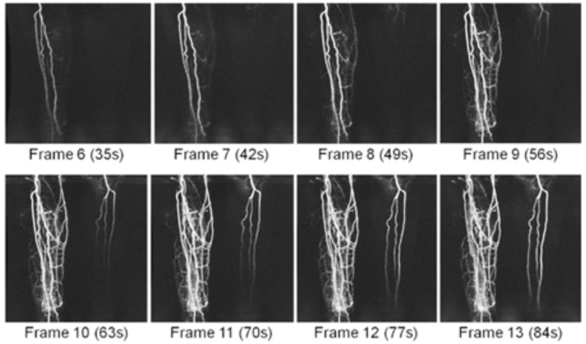
ECA: external carotid artery
ICA: internal carotid artery
MCA: middle cerebral artery

Contrast-enhanced MRA

- Avoidance of blood signal saturation
- Better turbulent flow imaging
- Injection a contrast material intravenously (IV) to selectively shorten the T1 of the blood ➔ brighter signal in T1W images.
- Gadolinium-chelate (Gd) contrast agents
  - Seven unpaired electrons ➔ paramagnetic, shorten T1 and T2
  - Injection rate: 0.5~4.0 ml/s
  - Injection volume: 0.1~0.3 mmol/kg body weight, typically 20~40 ml
  - Computer-controlled power injector
  - Examine the patient's renal function before scanning!

Contrast-enhanced MRA

- 3D, RF-spoiled, fast gradient-echo imaging sequences ➔ T1W images (FSPGR, FLASH, or T1 FFE)



Mask subtraction

Applications areas of MRA

Table 8. Application areas of MRA techniques

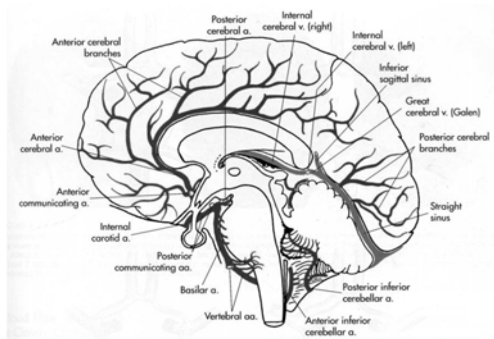
	3D-TOF	2D-TOF	3D-PC	2D-PC	Magnitude contrast	CE MRA
Intracranial:						
- Arteries	***		*			*
- Veins	*	***	**	*		*
Carotids	**	**				***
Peripheral vessels		**			*	***

*** method of choice; ** second-best alternative or for additional information; * working technique, but with sub-optimal results
TOF MRA: Time-of-Flight MRA; PC MRA: Phase Contrast MRA; CE MRA: Contrast Enhanced MRA

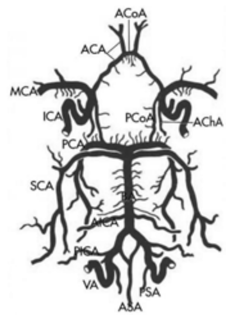
腦血流灌注

Brain MR perfusion imaging

Blood supply of the brain

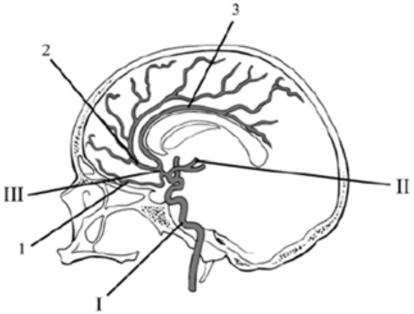


Circle of Willis



J. Nolte. The human brain- an introduction to its functional anatomy, 5th (2002)

Arterial system



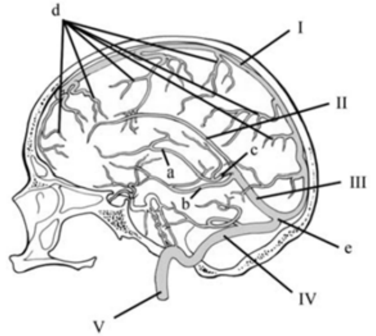
I Internal carotid artery (ICA)
II Middle cerebral artery (MCA)
III Anterior cerebral artery (ACA)

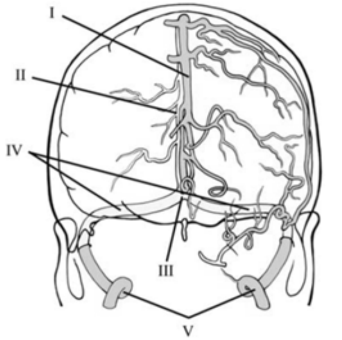
1 Medial frontobasal artery
2 Callosomarginal artery
3 Pericallosal artery

I Vertebral artery (VA)
II Basilary artery (BA)
III Posterior cerebral artery (PCA)
IV Anterior spinal artery

a Inferior posterior cerebellar artery
b Inferior anterior cerebellar artery
c Superior cerebellar artery
d Temporooccipital arteries
e Medial occipital arteries

Venous system



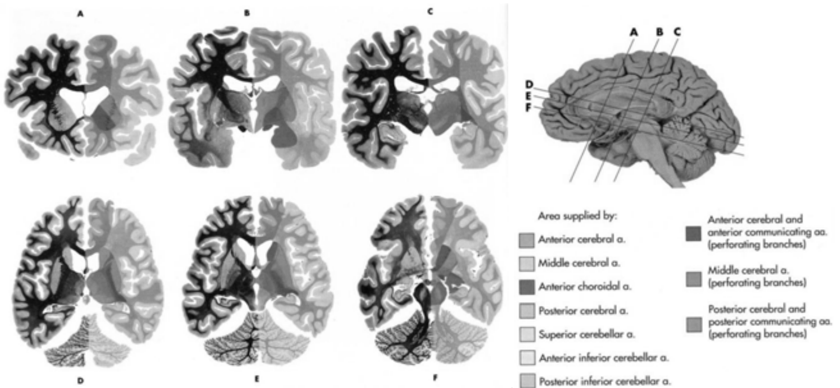


I Superior sagittal sinus (SSS)
II Inferior sagittal sinus (ISS)
III Sagittal sinus (SS)
IV Transverse sinus (TS)
V Sigmoid sinus

a Internal cerebral vein (ICV)
b Basal vein (BV)
c Vein of Galen (VG)
d Superior cerebral veins
e Sinus confluence (SC)

I Superior sagittal sinus (SSS)
II Inferior sagittal sinus (ISS)
III Sinus confluence (SC)
IV Transverse sinus (TS)
V Sigmoid sinus

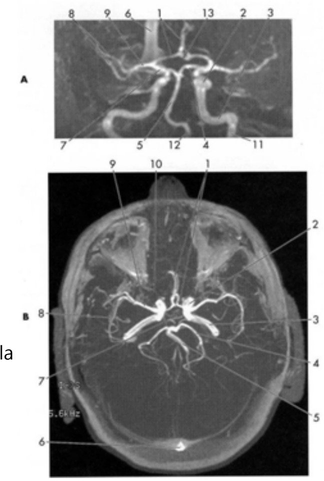
Vascular Territories



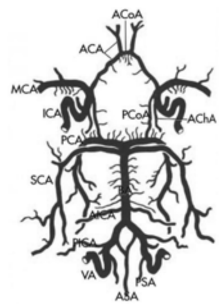
J. Nolte. The human brain- an introduction to its functional anatomy, 5th (2002)

TOF MRA

11. Internal carotid a. (ICA)
   2. Cavernous sinus part
   3. Temporal bone part
1. Anterior cerebral a. (ACA)
4. Posterior cerebral a. (PCA)
13. Anterior communicating a. (ACoA)
7. Posterior communicating a. (PCoA)
9. Middle cerebral a. (MCA)
8. Branch on the surface of the insula
12. Vertebral a. (VA)
5. Basilar a. (BA)
6. Superior sagittal sinus
10. ophthalmic a.



Circle of Willis

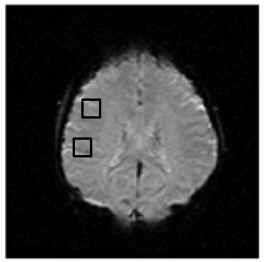


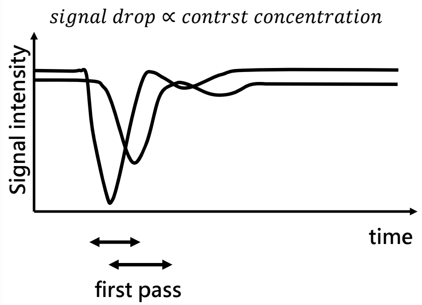
Brain perfusion imaging

- The information on the capillary microcirculation of tissue
- Quantitative measurements
  - Blood volume
  - Blood flow
  - Temporal data (transit time and time to peak)
- Two major techniques
  - Dynamic-susceptibility-contrast (DSC) MRI
  - Arterial spin labeling (ASL) MRI

DSC MRI

- **bolus tracking** of Gd-DTPA contrast agent, reduce T2 and T2* relaxation time





DSC MRI

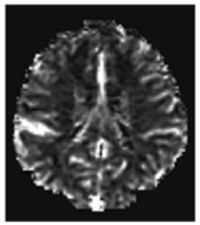
- T2-weigthed SE-EPI: specific to the micro-vascular compartment
- T2*-weighted GRE-EPI: also take into account larger vessels

- Post-preprocessing
  - Extract the first pass signal (gamma-fitting) and remove the recirculation signal
  - Define the arterial input function (AIF)
  - Deconvolution of tissue concentration-time curves by the AIF

Hemodynamic maps

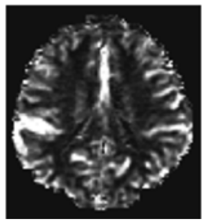
Cerebral blood volume

$$rCBV = \frac{\int_{first\ pass} c_t(t)dt}{\int_{first\ pass} c_a(t)dt}$$



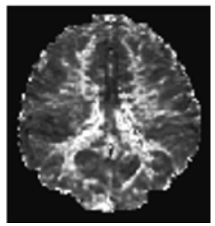
Cerebral blood flow

$$C_t(t) = rCBF \cdot Ca(t) \otimes R(t)$$

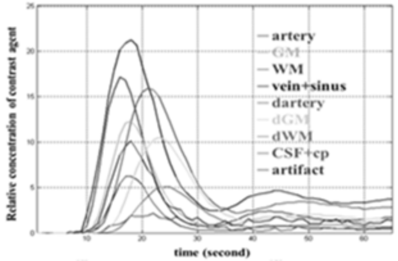


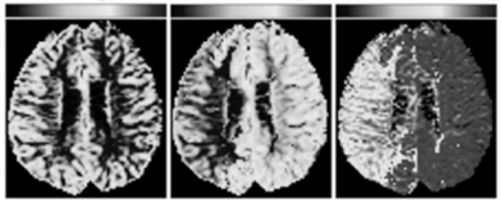
Mean transit time

$$MTT = \frac{rCBV}{rCBF}$$



Tissue Classification





99% stenosis of right internal carotid artery

- *Wu et al,* Magnetic Resonance in Medicine, 57:181-191, 2007.
- *Lu el al,* PLoS One, 8(7): e68986, 2013.

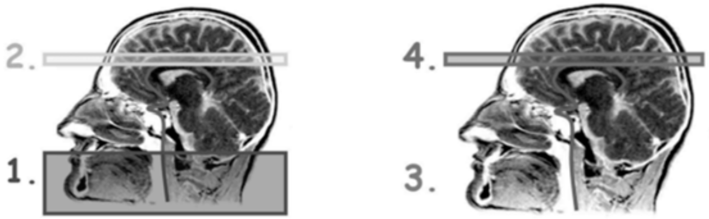
ASL MRI

- Arterial spin labeling uses arterial blood water as an endogenous contrast agent.
- Blood is "tagged" or magnetically inverted which changes its magnetic properties and its effect on MR signal.
- Create paramagnetic tracer to suppress MR signal wherever arterial blood is delivered.
- Can be used to quantify CBF (cerebral blood flow) in arterioles and capillaries.

http://www.usc.edu/programs/neuroscience/private/mona_journal_club/David_Clewett_powerpoint.pdf

Principles of ASL

1. Tag inflowing arterial blood by magnetic inversion
2. Acquire the tag image
3. Repeat scanning without tag
4. Acquire the control image

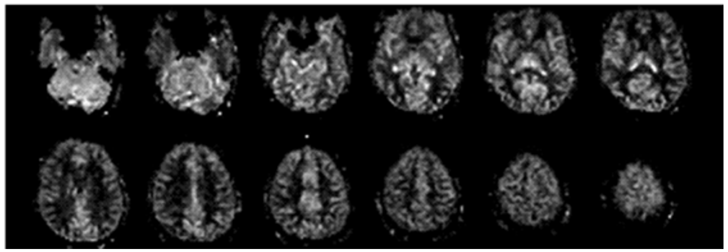


$$\boldsymbol{4(control\ image) - 2(tag\ image)\ \propto CBF}$$

http://www.usc.edu/programs/neuroscience/private/mona_journal_club/David_Clewett_powerpoint.pdf

ASL CBF map

- Pulsed Arterial Spin Labeling (PASL)
  - A volume of blood is labeled upstream of the region of interest by a short RF pulse
- Continuous Arterial Spin Labeling (CASL)
  - Increase the delivered RF energy
  - Two sets of transmitter and receiver coils



THE END

alvin4016@ym.edu.tw