Appearance of flowing blood

- Flow effects can be attributed to
  - Time of flight (TOF) effects, $M_z$
  - Motion-induced phase changes (phase contrast), $M_{xy}$
- TOF effects
  - Signal loss (high-velocity signal loss or TOF loss)
  - Signal gain (flow-related enhancement, FRE)

High-velocity signal loss

- For spin echo (SE) imaging
  - Slice-selective refocusing RF
  - If $v \geq \Delta z / (TE/2) \rightarrow$ flow void

\[ I \propto (1 - v/(2\Delta z/TE)) \]
Flow-related enhancement (FRE)

- In GRE
- Also called entry phenomenon
- The fresh inflowing blood that enters the first slice is totally unsaturated (by last RF excitation)
- If \( v \geq \Delta z / TR \) → maximal signal
- \( I \propto I_0 + v(TR/\Delta z) \)

MR Angiography

- Unenhanced MRA
  - TOF (time of flight) MRA
  - PC (phase contrast) MRA
- Contrast-enhanced MRA
  - IV injection of gadolinium

Unenhanced MRA

- Rely solely on flow effects (the movement of blood)
- Amplitude effects (TOF)
  - 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 (Phase contrast)
  - Blood flowing along the direction of a magnetic field gradient changes its transverse magnetization compared to stationary spins.

Flow-related signal enhancement

- The FRE occurs both with SE and GRE sequences.
- However, the competing TOF loss in SE tends to overbalance the FRE 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 TOF loss 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 compensation (refocus unwanted phase accumulations)

- TOF techniques can be divided into 3 groups
  - Sequential 2D multi-slice method
  - 3D single-slab method
  - 3D multi-slab method

Sequential 2D technique

- Larger flip angle (30°–70°)
- 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).

Saturation effects in 2D acquisition

- When...
  - (2D acq.) Flowing blood travels within (rather than through) a slice
  - (3D acq.) blood travels though a thick imaging volume (or slab)
- The gradual loss of longitudinal magnetization caused by repeated excitation radio frequency (RF) pulses.
  - the distal/in-plane portion of a vessel not to be displayed.

In-Plane Saturation Artifact

- When vessels travel within plane, their blood may become saturated like stationary tissues, resulting in decreased signal.
3D multi-slab method

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

Spatial saturation pulse

- Superior saturation pulses are used to 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.

Comparison between 2D and 3D TOF

<table>
<thead>
<tr>
<th></th>
<th>2D-TOF MRA</th>
<th>3D-TOF MRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Faster scanning</td>
<td>Higher SNR because signal is acquired from a larger volume</td>
</tr>
<tr>
<td></td>
<td>Maximized FRE because each slice is an entry slice</td>
<td>Improved spatial resolution</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>In plane saturation effects</td>
<td>More susceptible to saturation effects</td>
</tr>
<tr>
<td></td>
<td>Less sensitive to slow flow</td>
<td></td>
</tr>
</tbody>
</table>

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
Magnitude contrast method

• Acquire two datasets
  - Flow-rephased images: flow compensation, bright-blood image

Phase contrast method

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

Phase contrast MRA

• Phase-encoded images
  - X direction
  - Y direction
  - Z direction
  - Subtraction & Sum magnitude

Aliasing

• Aliased velocity = VENC – actual velocity
• May apply two different VENCs—a small VENC and a large VENC in the same FOV

VENC =150 cm/sec  VENC =300 cm/sec

The root of aorta
(in a patient with aortic stenosis)
**TOF vs. phase contrast MRA**

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

**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)

**TOF-MRA vs CE-MRA**

Carotid bifurcations, detection of ulcer

[Images of TOF-MRA and CE-MRA with subtraction features]

CE-MRA

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Rapid technique</th>
<th>Resistant to dephasing (e.g. from turbulent flow)</th>
<th>Large FOV with good resolution</th>
<th>Excellent SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disadvantages</td>
<td>Dependent on timing (venous contamination may occur)</td>
<td>Require intravenous injection for administration of gadolinium</td>
<td>No directional information</td>
<td></td>
</tr>
</tbody>
</table>

MOTSA (reducing saturation effects)
- Multiple Overlapping Thin-Slab Acquisition
  - Extracting the central slices of each slab and discard the peripheral slices (which are more affected by saturation effects).

MOTSA imaging
- Left parietal lobe AVM
- Carotid arteries

TONE (reducing saturation effects)
- The flip angle $\alpha$ is increased progressively as the flowing spins move into the imaging volume by using increasing RF pulses.
- Increasing $\alpha$ counteracts saturation effects of slowly flowing blood in deeper slices.
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

Maximum Intensity Projection (MIP)

MRA Clinical Applications

<table>
<thead>
<tr>
<th>Technique</th>
<th>Clinical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D-TOF</td>
<td>Carotid and vertebral arteries in the neck.</td>
</tr>
<tr>
<td>MRA</td>
<td>Venous structures (due to slow flow)</td>
</tr>
<tr>
<td>3D-TOF</td>
<td>Intracranial vessels (circle of Willis)</td>
</tr>
<tr>
<td>MRA</td>
<td>Intracranial vascular malformations and aneurysms</td>
</tr>
<tr>
<td>2D-PC MRA</td>
<td>Portal vein</td>
</tr>
<tr>
<td></td>
<td>CSF flow study</td>
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<tr>
<td></td>
<td>Localizer for determining YDCI (velocity encoding)</td>
</tr>
<tr>
<td>3D-PC MRA</td>
<td>Intracranial vasculature</td>
</tr>
<tr>
<td></td>
<td>Intracranial vascular malformations and aneurysms</td>
</tr>
<tr>
<td>3D-CE MRA</td>
<td>Carotid and vertebral arteries of the neck</td>
</tr>
<tr>
<td></td>
<td>Aortic arch, renal arteries, and upper or lower extremity</td>
</tr>
<tr>
<td></td>
<td>runoff</td>
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</tbody>
</table>
THE END

alvin4016@ym.edu.tw