HETERONUCLEAR IMAGING

BioE-594 Advanced MRI

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Topics to be Discussed:

- What is heteronuclear imaging.
- Comparing the hardware of MRI and heteronuclear imaging.
- Clinical applications of heteronuclear imaging.
- Sodium Imaging.
- Carbon Imaging.
- Oxygen Imaging.

What is heteronuclear imaging?

Heteronuclear imaging

- It is a Non-proton imaging such as ^{23}Na imaging, ^{13}C imaging, ^{31}P imaging, ^{19}F imaging, ^{17}O imaging; operating between 6 and 300 MHz.
- Hardware for the heteronuclear imaging differs from that of the proton imaging.

Comparing the hardware of MRI and a non-proton imaging method

Main hardware of MRI

- Magnet
  - establishes the B_0 field to align the spins.
- Gradients
  - Within the **magnet** are the **gradient coils** for producing variations in B_0 in the X, Y, and Z directions to make a localization of the received data possible.
- RF coils
  - Within the gradient coils are the **radio frequency coil**s used to excite the nuclei fall into two main categories;
    - » surface coils and volume coils.
  - The RF coil also detects the signal emitted from the spins within the object being imaged.
- Analog to digital converter
  - The analog to digital converter converts the received analog raw data into digital values.

Why is the hardware different for heteronuclear imaging?

Natural abundances of some nuclei studied by MRI

Isotope	Natural Abundance
^{1}H	99.985%
^{12}C	98.9%
^{13}C	1.1%
^{14}N	99.63%
^{15}N	0.37%
^{16}O	99.9%
^{17}O	0.04%
^{31}P	100%

- Due to the low natural abundance in biological tissues, the non-proton signals usually lead to low spatial resolution, low SNR, and long acquisition times compared to conventional proton imaging.
- For non-proton imaging RF volume coils are more privilege to provide better homogeneity of the field than the surface coils .
- Double resonant coils are used for high SNR and field homogeneity.
- Non-proton Imaging benefits from high magnetic field achieving images of high SNR.

Clinical Applications of heteronuclear imaging

- ^{23}Na imaging is used for examining the dysfunction of the NA-K pump in the cells of different parts of the body, assessment of the sodium content in the tissue.
- ^{17}O imaging is used for the estimation of cerebral blood flow, oxygen consumption in organs.
- ^{13}C imaging is used for examining fatty tissues in the different organs of the body.

Sodium Imaging

- In comparison to ^1H (γH = 42.57 MHz/T, I = 1/2) in ^{23}Na (γNa = 11.26 MHz/T, I = 3/2), sensitivity is low.
- The ^{23}Na nucleus has spin 3/2 and possesses an electric quadrupole moment.
- For this reason, relaxation times T1 and T2 of ^{23}Na are shorter than those of ^1H.

Nucleus	Gyromagnetic ratio γ (MHz/T)	T_1 (ms)	T_2 (ms)
^1H	42.5	900	50
^{23}Na	11.2	33	0.5 – 13

- So gradient echo techniques are generally used.

Sodium Imaging to find the distribution of the brine in muscle (done by Jean–Pierre, Soraya)

- Materials and methods that were used:
  - Superconducting magnet of 9.4 T was used, operating at 105.8 MHz for ^{23}Na.
  - Gradient echo pulse sequence was chosen for its short echo time, because ^{23}Na is a quadrupolar nucleus, T2 time is very short i.e. 10ms.
  - The spins are refocused using a gradient-echo by reversing the sign of the slice selection gradient .
  - TE was 4.7ms and TR was 10ms.

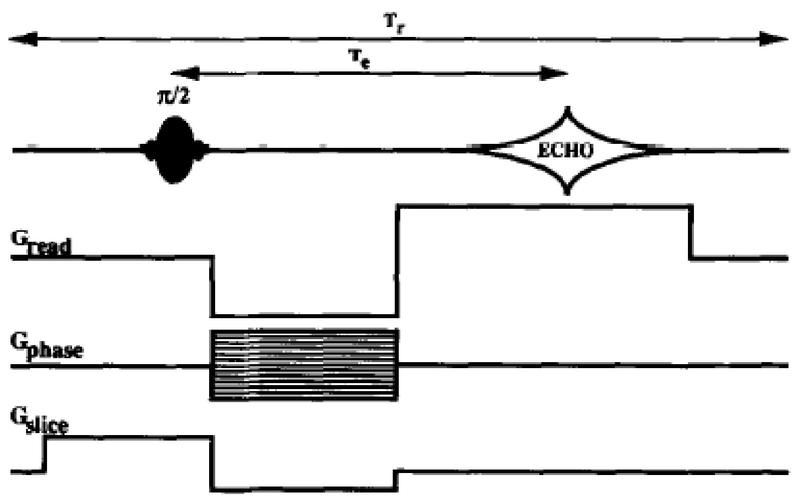


Fig. 1. RF and gradient pulse sequence used for sodium imaging.

Results

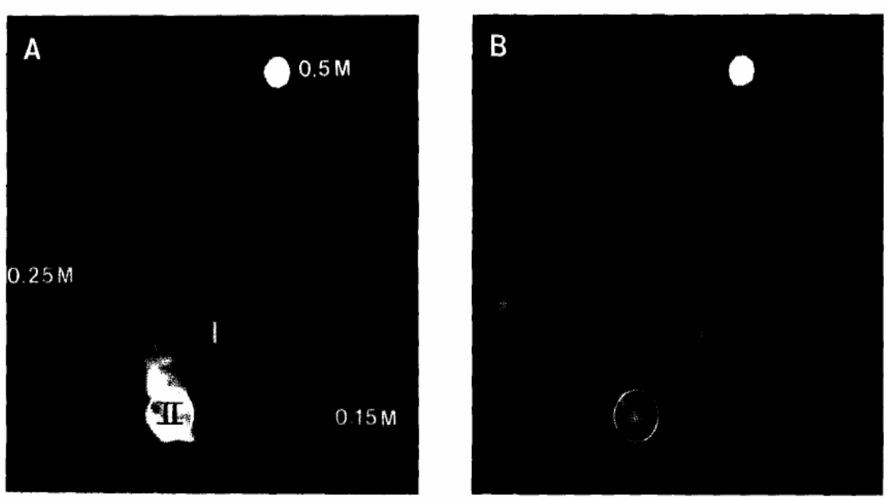


Fig. 2. Sodium image of rabbit muscle obtained with gradient-echo sequence. The brightest signal corresponds to the highest concentration of Na^+. Surrounding spots are images of tubes containing different NaCl concentration (0.5 M; 0.25 M, 0.15 M). (A) Immediately after arterial injection of brine (5 M NaCl); and (B) 6 hr after injection.

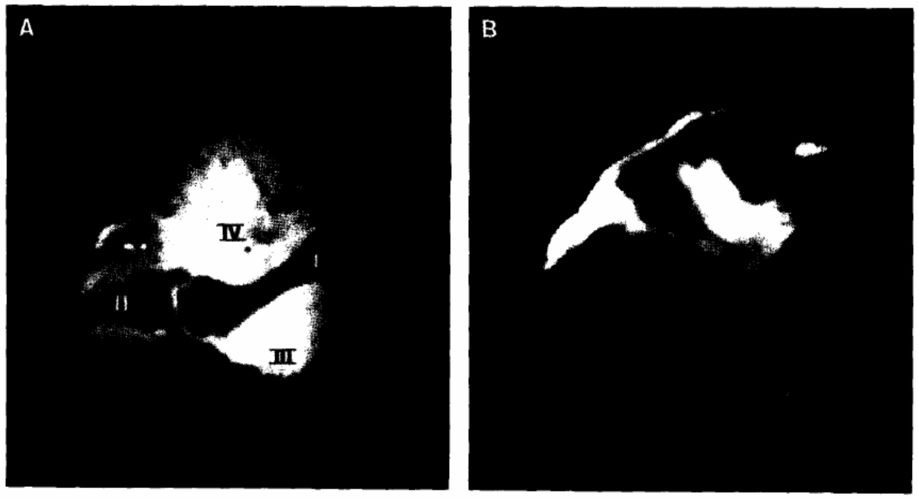


Fig. 4. Image of piglet ham. Two images from a complete 3D gradient-echo data set are shown; they correspond to the same slice. Experimental parameters given in text. (A) Proton image. (I) = femur; (II) = Tibia; (III) = muscle *vastus lateralis*; (IV) = muscle *semimembranosus*; (V) = muscle *semitendinosus*. (B) Sodium image. Very high contrast observed from patch in ham core.

Sodium 3-D MRI of the human torso using a volume coil (by Günter Steidle, Hansjörg Graf and Fritz Schick)

Theoretical considerations:

- The SNR in an MR image depends on conditions as coil geometry, density of the nuclei, T1, and T2, type of the imaging sequence, voxel size and readout bandwidth

$$\Delta v = N/T_s$$

T_s is the readout time and *N* the number of sampling points.

- Decreasing readout bandwidth leads to significant noise reduction
- The reduction of noise can be done by decreasing bandwidth by the condition $T_s < T2^*$.

- As described by Parrish, spoiled gradient echo (GRE) sequences are suitable for sodium imaging.
- TE was chosen long enough to avoid image artifacts.
- For a spoiled GRE sequence the signal amplitude is given by

$$M = M_0 \cdot \sin\alpha \frac{(1 - E1)}{(1 - E1 \cdot \cos\alpha)} e^{-TE/T2*},\ E1 = e^{-TR/T1},\ E2 = e^{-TR/T2},$$

-(1)

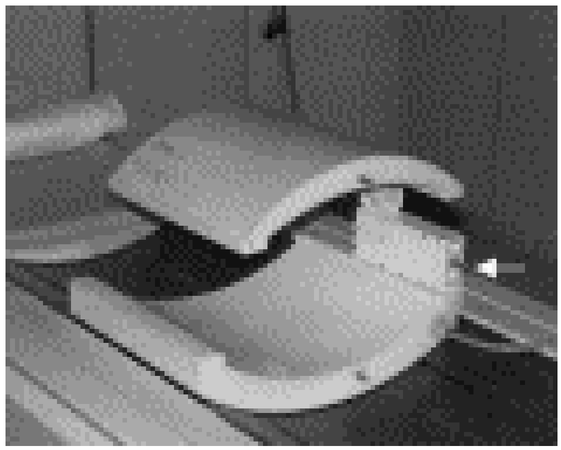
where $M0$ is the equilibrium magnetization and α the flip angle. For TR and TE kept fixed, M is maximal at the Ernst angle

$$\alpha Ernst = \arccos(E1). \qquad \text{-(2)}$$

Hardware of Sodium MRI scanner

- All measurements were performed on a **1.5 Tesla** whole body system (Vision, Siemens AG, Erlangen, Germany).
- For transmit and receive at the Larmor frequency of sodium a **custom-made volume coil** (Fraunhofer-Institut für Medizintechnik, St. Ingbert, Germany) was used.
- It consists of two opposing loops each having a diameter of **27 cm** and being slightly curved for a better fit to a human torso's shape.
- Automatic shimming was performed.

Photograph of the volume coil for sodium imaging of the human torso.



Results

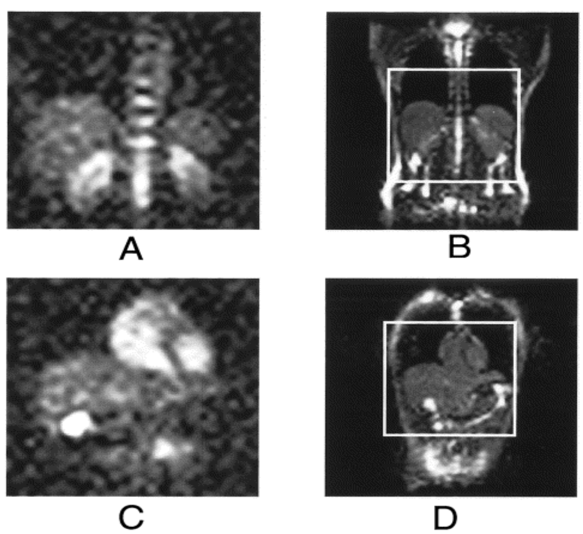


Figure: A and C, Two coronal sodium images TA = 12.7 min, in-plane resolution 8.75 mm × 8.75 mm (resulting voxel size: 1.15 cm3). (B,D) 1H images

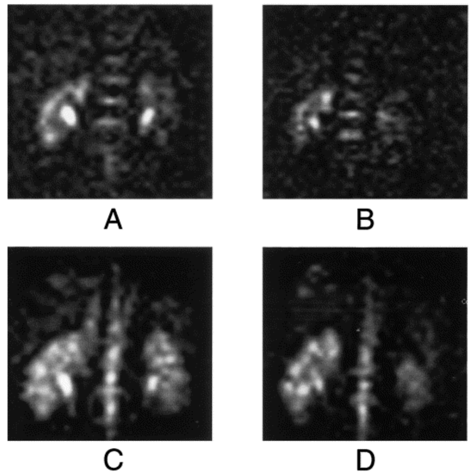


Figure: Sodium Coronal images of the kidneys of a 37-year-old male. A,C Kidneys in a dehydrated state after 12 h without drinking. (B,D) Kidneys in the rehydrated state, 20 min after drinking 20 ml water per kg body weight. A distinct alteration of sodium content is clearly visible for the volunteer in both, the images of the single slice.

Multinuclear magnetic resonance imaging technique-simultaneous proton and sodium imaging (by S.W Lee and S.K Hilal)

- System configuration:
  - The existing 1.5T whole body MRI was modified to perform simultaneous imaging protons and sodium.
  - Two RF coils is placed tuned to 64MHz(protons) and 17MHz(sodium).
    - Body sized ring resonator coil(50 cm in diameter) was used for protons.
    - Head sized saddle-shaped coil(30 cm in diameter) was used for sodium.

Modified MRI system to perform simultaneous imaging

- 3 switches: to multiplex the 2 RF frequencies.
- 2 set of amplifiers in the receiving channels due to different gain requirements and to avoid SNR degradations.

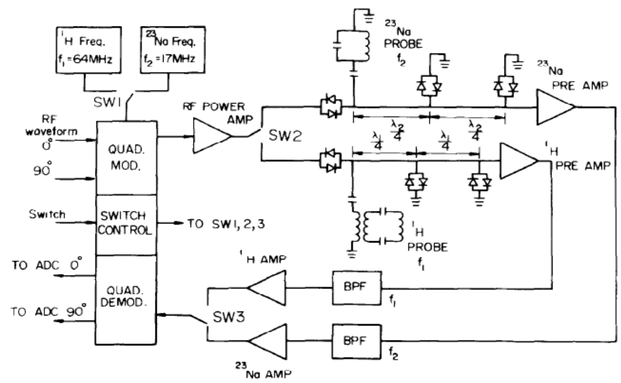


Fig. 1. Block diagram of the RF system for simultaneous multinuclear experiment.

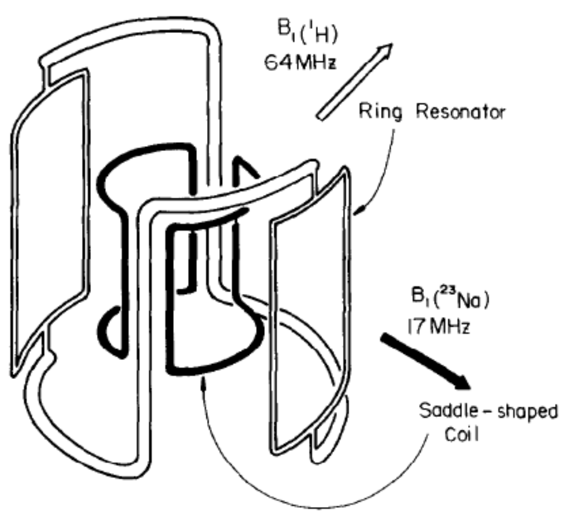


Figure: Arrangement of RF probes

Imaging and results

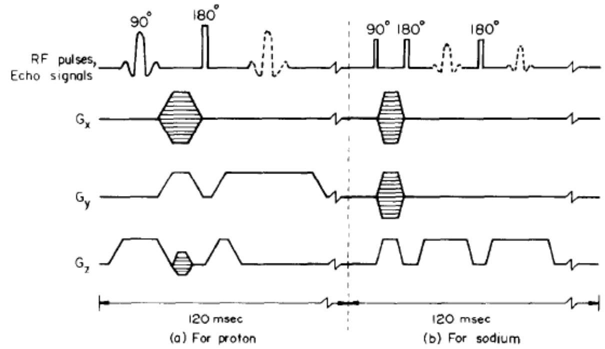


Fig. 3. Pulse sequence diagram for (a) proton and (b) sodium imaging.

3D Fourier imaging method, TE for proton imaging is 38msec,for sodium imaging TE1=14msec,TE2=28msec

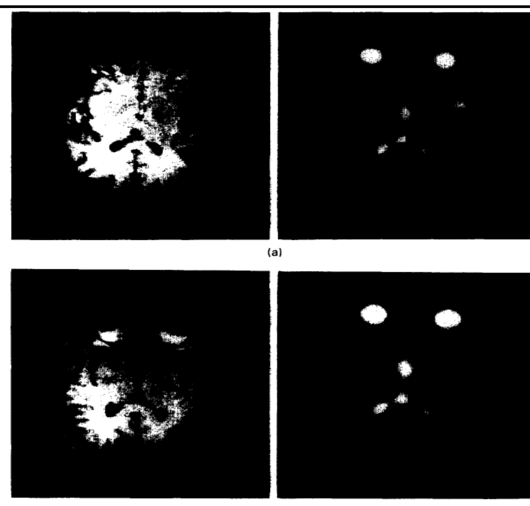


Figure: Images of volunteer’s head, proton images (left), sodium images (right)

Carbon-13 MRI of a Human Arm (by Siemens medical Technologies limited, Japan)

- To examine the carbon-13 image of $–CH_2-$ chains of the fatty tissues in the human arm.
- The MR machine used was 2T.
- The coil used was Slotted-tube resonator which produces a high current.

- STR consists of two ring conductors of copper coil of 0.1mm in thickness mounted on an acrylic resin tube of 110 mm in outer diameter 2a.
- Width of the ring is W which is 30mm,length of vertical conductors are 2l, 80mm.
- The coil is tuned for resonance at 21.4 MHz (carbon-13) at 2T.

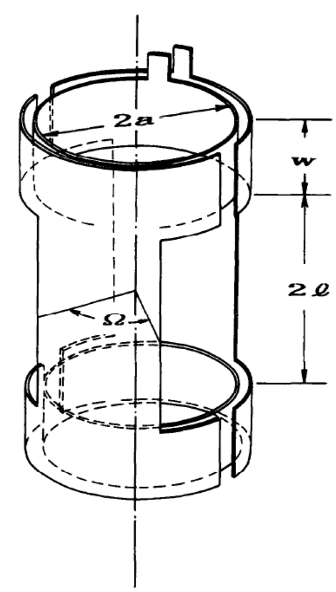


Fig. 1. The STR consisting of two foil rings, two vertical H-shaped conductors with a subtended angle of Ω and isolation sheets (not shown).

Imaging and Results

- The machine frequency was set to acquire the $-CH_2-$.
- A saturation recovery image sequence was used.
- The signals were acquired at FOV=60cm*60cm, matrix =128*128, d=8cm,TE=6msec, TR=200msec, acquisition time of Ts=6msec.
- Total imaging time was 30 min.

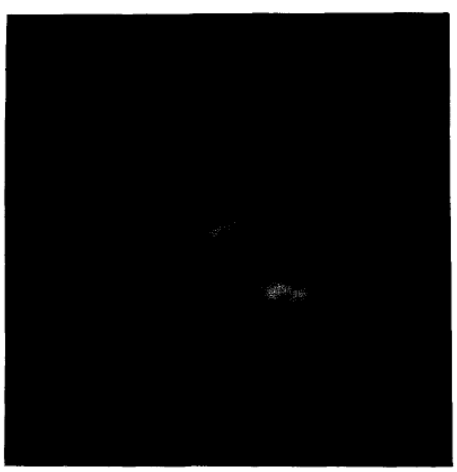


Fig. 2. The naturally abundant carbon-13 $-CH_2-$ image of a human right upper arm obtained at 2 T.

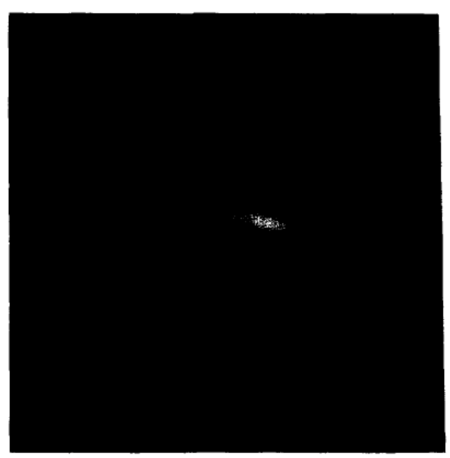


Fig. 3. The proton $-CH_2-$ chemical shift image of a human right upper arm obtained at 2 T.

In vivo Oxygen-17 MRI for the estimation of cerebral blood and oxygen consumption (by Toshiyuki Arai, Shin-ichi and Hiroko Mori)

- ^{17}O is a quadrupolar nucleus with a spin quantum number of 5/2, very less gyromagnetic ratio, and natural abundance of 0.037%.
- In vivo ^{17}O MR will give the blood flow and oxygen consumption in the body.
- The examination was done on rabbits.

- Material and methods:
  - A MR machine of 2T, with a surface coil(3.5 cm in diameter) tuned to both the ^{1}H(85.6MHz) and ^{17}O(11.6 MHz).
  - For the measurement of cerebral blood flow, a 1ml saline with 20% enriched H_2O was injected into the internal carotid artery of a rabbit.
  - For the measurement of cerebral oxygen consumption 40% O_2 gas was delivered to rabbit.

Imaging and results

- Acquisition parameters were used with one pulse sequence of 20KHz sweep width, repetition time of 13.8msec.

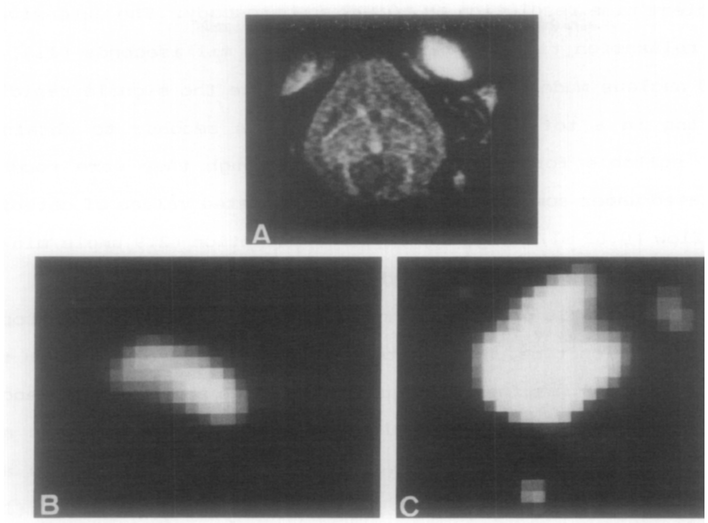


Figure 4. The coronal NMR images of rabbit brain at 2.0 Tesla
A) The 256 X 256 ^{1}H NMR image showing the anatomical level from which the ^{17}O NMR signals were obtained
B) The 32 X 32 ^{17}O NMR image obtained before the intravenous injection of $H_2^{17}O$.
C) The 32 X 32 ^{17}O NMR image obtained after the intravenous injection of $H_2^{17}O$.

References

- Sodium 3-D MRI of the human torso using a volume coil by Günter Steidle, Hansjörg Graf and Fritz Schick.
- 23 Na magnetic resonance imaging, distribution of Brine in Muscle by jean-Pierre, Soraya Benderbous.
- A multinuclear magnetic resonance imaging technique-simultaneous proton and sodium imaging by S. W. Lee, S.K. Hilal.
- Carbon-13 MRi of a Human Arm- Norio Iriguchi and Jun Hasegawa.
- Invivo oxygen-17 MRI for the estimation of cerebral blood flow and oxygen consumption- Toshiyuki Arai, Shin-ichi and Hiroko Mori.