Imperial College London
BSc/MSci EXAMINATION June 2008

This paper is also taken for the relevant Examination for the Associateship

Medical MRI and Ultrasound

For Third Year Physics Students
Tuesday 3rd June 2008: 10.00 to 12.00

Answer THREE questions.
All questions carry equal marks.
Marks shown on this paper are indicative of those the Examiners anticipate assigning.

General Instructions

Write your CANDIDATE NUMBER clearly on each of the THREE answer books provided.

If an electronic calculator is used, write its serial number in the box at the top right hand corner of the front cover of each answer book.

USE ONE ANSWER BOOK FOR EACH QUESTION

Enter the number of each question attempted in the horizontal box on the front cover of its corresponding answer book.

Hand in THREE answer books even if they have not all been used.

You are reminded that the Examiners attach great importance to legibility, accuracy and clarity of expression.
1. A spin system consisting of protons contained within the human body is placed into a uniform static magnetic field of 3.0T.

(i) Calculate the mean ratio of the spin populations on the two energy states. Comment on the implications of this for MRI

\[ \gamma = 42.58 \times 10^6 \text{ Hz/T} \]
\[ h = 6.6 \times 10^{-34} \text{ J-s} \]
\[ k = 1.38 \times 10^{-23} \text{ J/K} \]  

[7 marks]

(ii) Starting with Planck’s law calculate the frequency and wavelength of electromagnetic radiation required to induce coherent transitions between these two energy states. In what part of the EM spectrum does this lie? 

[3 marks]

(iii) Comment on the following statement with reference to MRI and the results of (ii) : “In imaging techniques the resolution is ultimately limited by the wavelength of the interrogating radiation”

[5 marks]

(iv) The spin system described is exposed to a pulse of electromagnetic radiation at its resonant frequency and the subsequent nmr signal collected as a free induction decay (there is no spatial encoding). This experiment is repeated 5 times varying the length of the pulse in approximately equally space increments starting at zero length (no pulse) and ending with a pulse that induces an inversion of the net magnetisation sketch the magnitude of the frequency spectrum of the received signal for each of the 5 pulses and explain why they look as they do. What might be the use of such an experiment?

[5 marks]

[TOTAL 20 marks]
2. A new contrast agent has been developed which accumulates in lesions in the Liver and results in a reduced T2 in these areas. Identifying these lesions is clinically important. The liver is generally difficult to image due to the high iron content and hence very short T2*. The liver also moves during respiration.

(i) Suggest a suitable pulse sequence for use with this contrast agent justifying your reasons. [3 marks]

(ii) Draw a schematic of this pulse sequence. The diagram should show the activity of all gradients along with the RF activity and the activation of the receiver all as a function of time. All elements of the schematic should be labelled, the purpose of each element stated and a brief explanation of how it serves this purpose given. [8 marks]

(iii) Explain how repetition time (TR) and echo time (TE) affect contrast in MR images. [4 marks]

(iv) The contrast agent results in a 50% reduction in T2 in lesions. The T2 of normal tissue is 10ms and lesion without contrast agent 12ms. Assuming a simple spin echo sequence is used, calculate the optimal TE to maximum contrast between normal and tissue and lesion after contrast administration. [5 marks]

[TOTAL 20 marks]
3. Consider two spin packets, the first moving along the x axis of an MR scanner at constant velocity and the second stationary. These experience, in two separate MRI experiments the gradient waveforms played out in time shown in figure 1 and 2.

(i) In experiment 1 and 2 what is the net phase accumulated by the stationary spin packet? [2 marks]

(ii) Consider the moving spin packet: Express the packet’s location as a function of time using a Taylor series expansion, using this derive an expression for the phase accumulated by the moving spins in each experiment and calculate the net phase at the end of each experiment. [8 marks]

Figure 1

Figure 2

(iii) Calculate the velocity range over which the gradients in figure 1 encode unique values of phase. What happens if a spin packet is moving at a velocity outside this range. [2 marks]

(iv) A 3rd spin packet is moving from an initial position x with an initial velocity v with a constant acceleration a. How would one go about calculating the accumulated phase for
each of these gradients. (You do not need to calculate it). Which of figure 1 or 2 would
me most appropriate to quantitatively measure acceleration – why?

[2 marks]

(v) In ultrasound quantitative measurement of velocity can also be achieved. Compare MR
velocity encoding and pulsed ultrasound velocity encoding with specific reference to
the physics of this encoding, the time taken for the measurement and the limitations of
each measurement

[6 marks]

[TOTAL 20 marks]
4. Ultrasound Transducers and Image formation

(i) Outline the steps required to generate a standard B-mode ultrasound image. [4 marks]

(ii) Two transducers have the same centre frequency but one has double the frequency bandwidth of the other, which one should give the better axial resolution, explain why? [2 marks]

(iii) Derive the thickness of the matching layer on the surface of an ultrasound transducer. [5 marks]

(iv) Explain the purpose of this layer and describe the other key components of a multi-element ultrasound transducer. [3 marks]

(v) Explain the balance between sensitivity and resolution inherent in ultrasound transducer design. [2 marks]

(vi) Calculate the thickness of the active elements in a 256 element linear array 5 MHz ultrasound transducer made from PZT (NOTE: speed of sound in PZT = 4350 m/s). State the maximum lateral separation of the individual elements in the array and explain what would happen if this distance is exceeded. Explain your reasoning throughout. [4 marks]

[TOTAL 20 marks]
5.

(i) Derive the expected Doppler shift from a scatterer moving within an ultrasound field.

(ii) Describe how the directional Doppler shift is estimated using a simple continuous wave ultrasound device.

(iii) What effects does using pulsed ultrasound have on this process?

(iv) Blood is flowing with a peak velocity of 0.1 m/s in large blood vessel. The angle of the vessel to the skin is 45° and the blood is flowing away from the transducer. If a 3 MHz ultrasound probe is used, what would the measured Doppler shift frequency be? (Assume the speed of sound = 1540 m/s) [2 marks]

(v) If a pulsed Doppler mode is used what is the minimum pulse repetition frequency that could be used, explain why?

(vi) What is the largest depth within a patient for which the flow in this vessel could be accurately imaged using pulsed Doppler?

(vii) Explain the differences in the acquisition, processing and information provided by colour Doppler, power Doppler, and spectral Doppler modes.

[TOTAL 20 marks]
(i) Describe the key factors determining the temporal and spatial resolution of an ultrasound scan. Take care to explain the differences between the resolutions in each of the three spatial dimensions.

[5 marks]

(ii) Calculate the maximum useful penetration depth from which an ultrasound image can be formed given the following system parameters: The centre frequency of the 256 element ultrasound transducer is 5 MHz, the attenuation coefficient of tissue is 0.5 dB/cm/MHz, the speed of sound in tissue to be 1540 m/s. The system has a maximum output pressure amplitude of 2 MPa and incoming signals must have amplitudes above 100 Pa to be detectable above the system noise. The pressure reflection coefficient of strongest reflectors in the scan in this case is 0.01. Determine the maximum frame rate for this scan. Show your reasoning to get full marks.

[5 marks]

(iii) To extract the maximum signal possible from an MRI experiment we require as short a possible echo time and as long as possible repeat time. Why in practise do we rarely acquire data under these conditions.

[5 marks]

(iv) For the following list state how each affects the signal to noise ratio in an MR acquisition:
   - Main magnet field strength
   - Gradient strength
   - Voxel size
   - Coil sensitivity
   - Parallel Imaging acceleration factor

[5 marks]

[TOTAL 20 marks]