UNIVERSITY OF SOUTHAMPTON PHYS2007W1

SEMESTER 2 EXAMINATION 2014-2015

MEDICAL PHYSICS

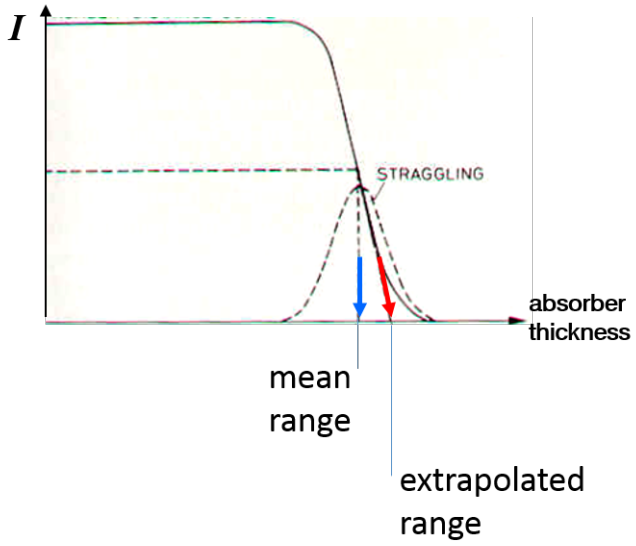
Duration: 120 MINS (2 hours)

This paper contains 10 questions.

Model answers and outline marking scheme

Section A

A1. With the aid of a suitable diagram, define the terms *mean range*, *extrapolated range*, and *straggling* for heavy charged particles. [4]



[1/2] *for shape of curve,* **[1/2]** *for axis labels*
mean range: inflection point of the curve (maximum of the derivative) **[1]**
extrapolated range: take tangent line at the inflection point and extend it to where it intersects the x-axis **[1]**
straggling: difference between the two **[1]**
(bookwork)

A2. Briefly explain the differences between *absorbed dose*, *equivalent dose*, and *effective dose*. Your answer should indicate the appropriate units for each case. [3]

absorbed dose: physical quantity equal to the amount of energy deposited per unit mass of absorber material; measured in gray (Gy) **[1]**
equivalent dose: a measure of the biological effectiveness of a given dose of radiation that takes into account the different biological effects of different types of radiation; equal to the absorbed dose multiplied by a radiation weighting factor w_R*; measured in sievert (Sv)* **[1]**
effective dose: also a measure of the biological effectiveness of a given dose, but which takes into account the differing radiosensitivity of different types

of tissue; equal to the absorbed or equivalent dose multiplied by a tissue weighting factor w_T; measured in sievert (Sv) **[1]**
(bookwork)

A3. Briefly explain how $^{99}\mathrm{Tc}^{m}$ meets three key requirements of radioisotopes for use in nuclear medicine. [3]

Looking for three of the following:
Half-life of 6 hours is sufficient to be practical for imaging, yet short enough to avoid unnecessary dose **[1]**
Emits a single gamma ray of 140 keV: has sufficient energy to escape body, reduces scatter, and allows for simpler rejection of photons that do scatter **[1]**
Emits gamma rays only, with no high-LET (beta, alpha) associated particles, which minimises patient dose not contributing to the image formation process. **[1]**
Can be incorporated into a huge number of biologically active compounds to maximise the number/variety of possible studies. **[1]**
Could also award **[1/2]** *for less important aspects (eg toxicity) up to max of 3 marks*
(bookwork)

A4. Explain the meaning of *image contrast* and how it is quantified. [4]

Contrast is the ability to distinguish adjacent levels of intensity within an image, in other words how visible a feature is compared to a background of a similar level **[1]**. *This can be affected by the size of the feature* **[1/2]** *and the noise levels of the image* **[1/2]**.

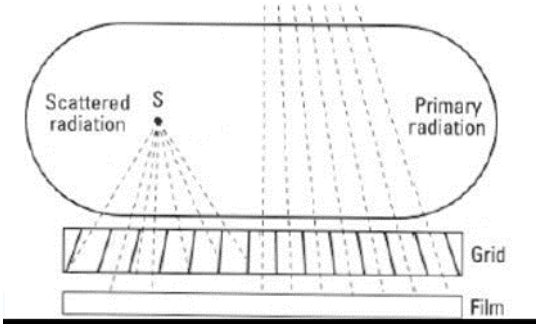
Contrast is quantified as the difference between two intensity levels e.g. $C = I_1 - I_2$ **[1]**, *or sometimes normalised against some reference level:* $C = \frac{I_1 - I_2}{I_{ref}}$ **[1]**.
(bookwork)

A5. What purpose does a grid serve in radiography? Draw an example of a focused

TURN OVER

grid which illustrates your answer. [4]

A grid serves to reduce scatter reaching the detector thereby increasing image quality and is also known as an anti-scatter grid. [2]



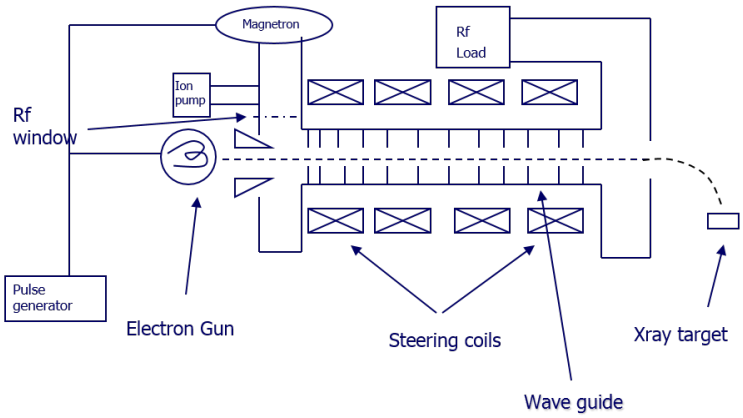
Drawing must show how the grid is composed of alternately radio-transparent and opaque strips and how scattered radiation is preferentially removed and prevented from reaching the detector. [2]
(bookwork)

A6. Describe how protons interact with a magnetic field to create two spin states. [2]

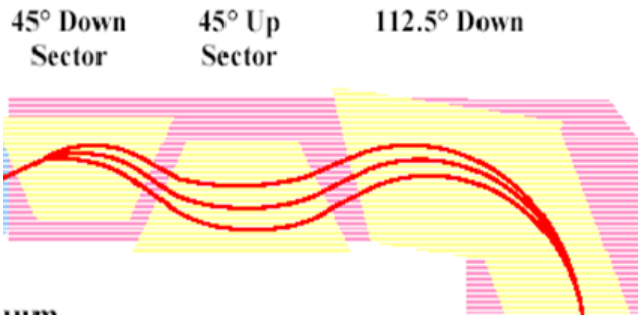
Protons possess both positive charge and intrinsic spin $I = 1/2$ and these give rise to a magnetic dipole moment in the presence of a magnetic field. **[1]**
As a result of this, the protons (or spins) have $2I + 1$ orientations in a magnetic field (i.e. two), spin up and spin down. Spin up has a lower energy level and spin down has a higher energy level with slightly more spins aligned with the field (spin up) than against it (spin down). **[1]**
(bookwork)

Section B

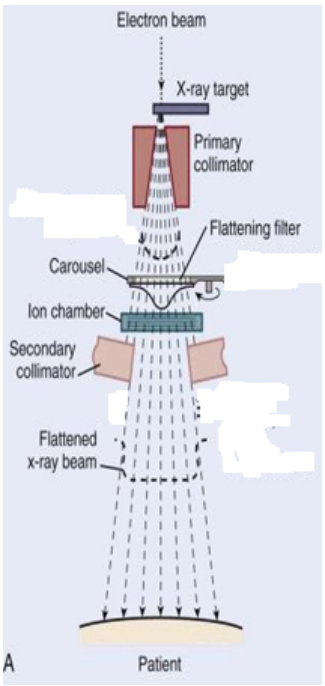
B1. (a) With the aid of a block diagram, describe how MV photons are generated and delivered by a medical linear accelerator (LINAC). [11]



Accelerator



Bending magnet



Delivery head

(i) Electron Gun. **[1/2]** *Heated filament releases electrons by Thermionic emission.* **[1/2]**

(ii) Magnetron **[1/2]** *Generates RF wave* **[1/2]**

(iii) Pulse Generator **[1/2]** *- Synchronises the electrons with the RF wave* **[1/2]**

(iv) Waveguide **[1/2]** *Cylindrical structure in which electrons are accelerated by the action of an electric field produced by the interaction of RF wave with the waveguide.* **[1/2]**

(v) Steering coils **[1/2]** *Maintain the path of the electrons within the wave guide to counter the effects of gravitational and electromagnetic fields on the electrons trajectory* **[1/2]**

(vi) Transmission Target **[1/2]** *Photons produced by Bremstrahlung through interaction of electrons with Tungsten transmission target.* **[1/2]**

(vii) Bending Magnet **[1/2]** *Steers the electrons to the target and reduces spread of electron energies.* **[1/2]**

(viii) Primary Collimator **[1/2]** *Determines the maximum size of useful beam and attenuates unwanted leakage and scattered radiation from the treatment head.* **[1/2]**

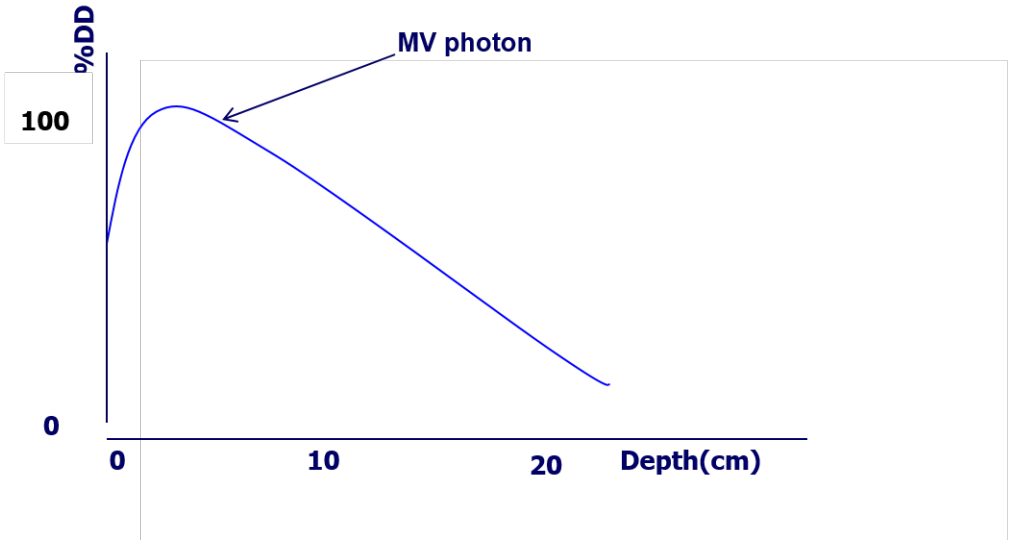
(ix) Flattening Filter **[1/2]** *Preferentially attenuates the centre of the photon beam to flatten the naturally forward peaked shape of the lateral distribution to give a uniform beam incident on the patient.* **[1/2]**

(x) Ion Chamber **[1/2]** *- Monitors the intensity and relative fluence of the radiation field. Used to control the duration of patient exposure and hence delivered dose.* **[1/2]**

(xi) Collimator **[1/2]** *- Shapes the radiation beam* **[1/2]**

(bookwork)

(b) With the aid of a diagram, describe the depth dose curve for an MV photon beam. Include in your answer a discussion of the dominant interactions between photons and tissue. What are the main clinical advantages of using an MV photon beam instead of a kV X-ray beam for treatment? [5]



[1]

Percentage Depth Dose = ratio expressed as a percentage of absorbed dose at any point in a phantom to the absorbed dose on the beam central axis at the depth of maximum dose **[1/2]**

Main interactions between MV Photons and tissue are Photo electric effect , Compton Scattering and Pair production **[1]**. *Compton Effect is the dominant interaction at clinical MV energies.***[1/2]**

There is a build up region at the surface due to the forward scattering of electrons giving an increasing contribution to absorbed dose until electronic equilibrium is achieved. From depth of dose maximum the dose falls off due to effects of inverse square law and attenuation of the beam. **[1]**

Clinical advantages of MV (i) skin sparing **[1/2]** *(ii) more penetrating so suitable for treating deeper tumours* **[1/2]**
(bookwork)

TURN OVER

(c) A patient is planned to receive a total dose of 40 Gy in 20 fractions with MV photons. If the clinician decided that they wanted to deliver the dose in n=10 fractions instead, calculate the dose per fraction d that must be delivered in order to have the same biological effect on the tumour, given that

$$EQD_2 = \frac{nd(d + \alpha/\beta)}{(2 + \alpha/\beta)}$$

and $\alpha/\beta = 10$ for the tumour. [2]

What might be the disadvantages of this change? [2]

$10 \times d(d + 10)/(2 + 10) = 40$ **[1/2]**

$10d^2 + 100d - 480 = 0$ **[1/2]**

$d = \frac{-100 + \sqrt{100^2 - (4 \times 10 \times (-480))}}{2 \times 10}$ **[1/2]**

$d = 3.54$ *Gy* **[1/2]**

The doses will only be biologically equivalent if delivered over the same overall treatment time. **[1]** *Surrounding normal tissue is likely to have a lower* α/β **[1/2]** *and therefore although the relative biological effect on the tumour is maintained the biological effect on normal tissue may be increased for the new regime* **[1/2]**.

(similar to problem worked in lecture)

B2. Positron Emission Tomography (PET) is increasingly utilised in diagnostic imaging, particularly for oncology applications.

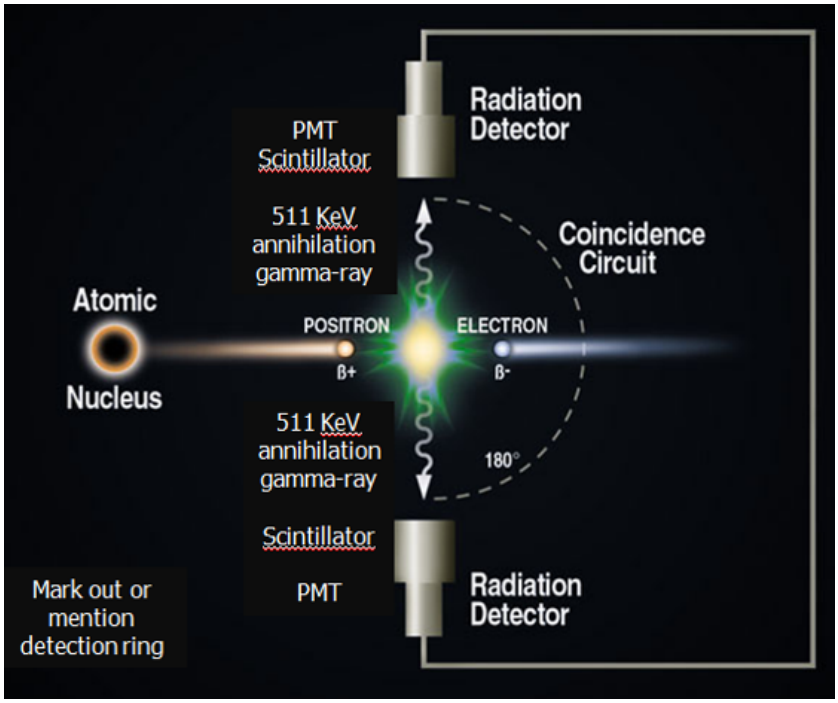
(a) PET offers functional information with unrivalled sensitivity. Briefly discuss two other aspects of PET imaging that make it particularly attractive as a functional (molecular) imaging modality. [4]

Two from:

- *Quantification is inherent in PET detection (unlike SPECT)* **[2]**
- *Positron-emitting biological tracers are readily available (e.g.15-O, 11-C, 13-N, 18-FDG for Glucose)* **[2]**
- *Offers improved spatial resolution (¡4mm) cf SPECT (∼15mm)* **[2]**

(bookwork)

(b) Sketch a line diagram of the principal components of a PET detector system. [5]



One mark for correctly marking each of the following:

- *Scintillation-based radiation detector*

TURN OVER

- *marked at 180 degrees apart*
- *PMT or photodiode based convert / amplifier*
- *coincidence circuit*
- *Forming 360 degree detector ring*

(bookwork)

(c) Explain why 2-D PET scanning was used historically, but is not required for modern detector systems. How was 2-D PET scanning achieved? What advantage do modern 3-D systems have compared to earlier 2-D systems? [5]

Traditional approach has been to use 2-D PET scanning for clinical applications so as to:

- *Limit number of events* **[1/2]**
- *Simpler to reconstruct data* **[1/2]**

Not required for modern system due to

- *Faster scintillator* **[1/2]**
- *Faster (lower dead-time) electronics* **[1/2]**

(able to deal with higher count rate)

Achieved using lead septa between each ring of block detectors to limit acceptance angle. **[1]**

Significant increase in sensitivity **[1]**, *reducing dose to patient or scan time* **[1]**

(bookwork)

(d) For more than a decade, PET imaging systems have been combined with other imaging modalities, producing dual-modality systems. What are two of the key advantages to obtaining X-ray computed tomography (CT) data concurrently with PET images? [3]

Improved quantification of PET data using CT for attenuation and scatter correction **[2]**
Localisation of functional PET data with anatomical CT data **[1]**
(bookwork)

(e) Time of Flight (ToF) PET has the potential to deliver improved image contrast, potentially improving lesion detection. For a timing window of $\Delta t = 0.5$ ns, what is the theoretical event localisation distance Δx? Which component limits ToF performance in current systems? [3]

$\Delta x = c\Delta t/2$ *where* $\Delta t = 0.5$ *ns is the timing resolution.*
Localisation is $\sim$*7.5 cm* **[2]**
(similar problem done in lecture)

The scintillator is the limiting component **[1]** *[only useful with very fast scintillators (clinical systems currently using Lutetium yttrium orthosilicate (LYSO))]*
(bookwork)

TURN OVER

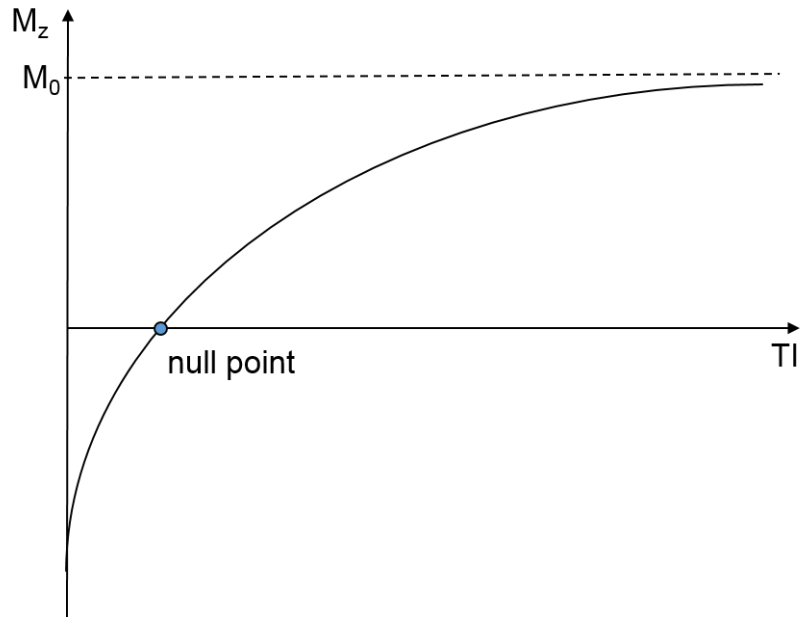
B3. (a) The equation that describes signal intensity in an inversion recovery pulse sequence is

$$M_z = M_0[1 - 2\exp(-TI/T_1)].$$

Sketch the signal intensity as a function of TI and, making use of your sketch, explain the terms in this equation. What is the significance of the point at which $M_z = 0$? [3]

In a fluid attenuated inversion recovery (FLAIR) pulse sequence, calculate the inversion time used to null signal from cerebrospinal fluid (CSF), assuming $T_{1CSF} = 3600$ ms. [3]

Briefly explain why fat has a shorter T_1 time than CSF. [3]



[1] *mark for sketch*

[1/2] *marks for each defined term:*

M_0 maximum or net magnetization

TI inversion time of the sequence

T_1 T_1 relaxation time of the substance of interest

If a $90°$ pulse is applied at the inversion time TI, i.e. at which $M_z = 0$ for a particular substance with a particular T_1, the signal from this substance will be eliminated from the image. **[1/2]**

(similar problem done in lectures)

To null signal from CSF, calculate the time at which $M_z = 0$, so:

$$\begin{aligned} 1 - 2\exp(-TI/T_1) &= 0 \qquad [\mathbf{1}] \\ 2\exp(-TI/T_1) &= 1 \\ \exp(-TI/T_1) &= \frac{1}{2} \\ -TI/T_1 &= \ln\frac{1}{2} \\ -TI/T_1 &= -0.693 \\ TI &= 0.693 \times 3600 \\ &= 2494\text{ms} \qquad [\mathbf{2}] \end{aligned}$$

Full marks also awarded for knowing that $TI = \ln(2)T_1$ and hence $TI = 2494\text{ms}$. (similar problem done in lectures)

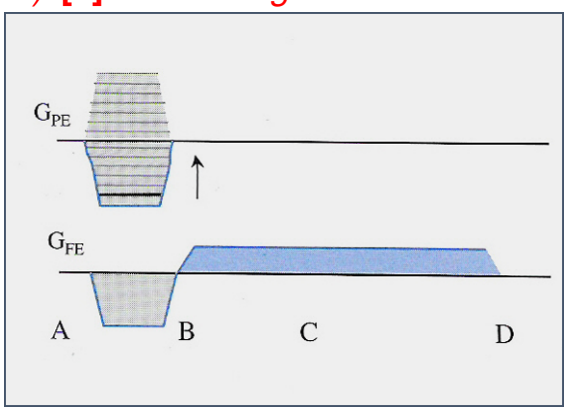
Fat has a shorter T_1 time than CSF as fat is a heavy molecule and moves more slowly (at a frequency closer to the Larmor frequency) **[1]**. *Energy is removed most efficiently and this results in a short T_1* **[1]**. *CSF is more liquid, so molecules have high frequency movement, so it is less easy to remove energy, which results in a long T_1* **[1]**. *(bookwork)*

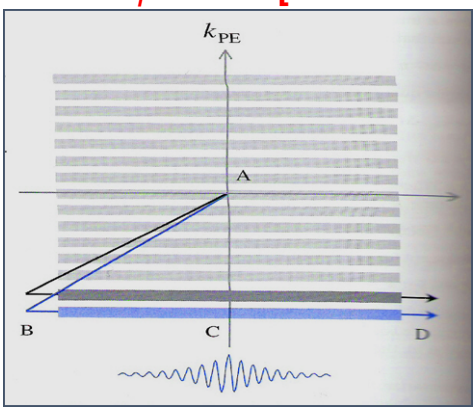
(b) Provide a description of k-space (as applied to MRI) and describe how phase and frequency encoding gradients are used to fill k-space (include diagrams). [8]

Raw MRI signals are stored in k-space (spatial frequency space) **[1/2]** *and this is the Fourier Transform of the real MR image* **[1/2]**. *MRI signals which contain all the spatial frequency information to fully encode and reconstruct an image are deposited within k-space* **[1]**. *During an MRI acquisition, each time the phase encoding gradient is applied, a different spatial frequency in the image is sampled* **[1/2]**. *Therefore, to fully sample all spatial frequencies in the MR image, the phase encoding gradient must be applied many times* **[1/2]**. *Frequency and phase encoding gradients trace out a trajectory in k-space, i.e. to ensure that it is fully filled and*

TURN OVER

all spatial frequencies are sampled **[1]**. *The application of the first phase encoding gradient moves data acquisition to the bottom of k-space (i.e. corresponding to the spatial frequency encoded by that phase encoding gradient). During frequency encoding, the MRI signal is sampled and the data stored in that line of k-space. The next application of the phase encoding gradient moves data acquisition to another line of k-space and data is stored in this line during frequency encoding. This continues until all lines of k-space are filled (i.e. all spatial frequencies have been sampled)* **[2]**. *The diagrams below illustrate this process* **[1 mark for each]**





(bookwork)

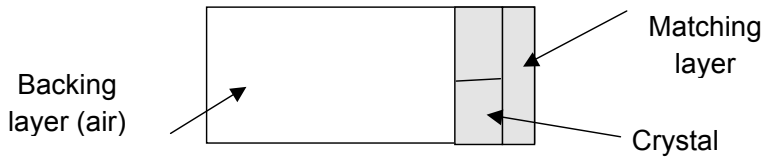
(c) Calculate the acquisition time (in minutes and seconds) of a spin echo pulse sequence if the repetition time $TR = 500$ ms, the echo time $TE = 40$ ms, the flip angle = $90°$, a 256 x 256 matrix image is acquired and the number of signal averages (NSA) = 2. [3]

Acquisition time

$$TA = TR \times NPE \times NSA \quad [2]$$
$$= 500 \times 256 \times 2$$
$$= 256000 \text{ ms}$$
$$= 256 \text{ s}$$
$$= 4 \text{ minutes } 16 \text{ seconds} \quad [1]$$

(new problem)

B4. (a) With the aid of a diagram, describe the function of the components of a simple continuous wave Doppler ultrasound transducer. Explain how the sizes of the critical components are optimised. [4]



[1/2] *for each component,* **[1/2]** *for its function,* **[1/2]** *for size (where relevant):*

(i)Piezo-electric crystal, split for receive/transmit, $\lambda/2$ thick
(ii) Matching layer, to match impedance, $\lambda/4$ thick
(iii) backing layer, eg air to reflect ultrasound
(bookwork)

(b) Show that for a sound wave of frequency f, incident normally on a reflector moving in the same direction at a velocity v, the change in frequency of the reflected wave, Δf, is given by:

$$\frac{\Delta f}{f} = -\frac{2v}{v_s}$$

(assume that v is much less than the speed of sound $v_s = 1540$ m/s in tissue) [8]

For a moving reflector, there are two frequency shifts to take into account. The transducer emits at frequency f. The reflector, moving away from the source at velocity v, sees a frequency

$$f' = f\left(1 - \frac{v}{v_2}\right). \qquad [2]$$

The reflected wave has frequency f' but since the reflector (the 'source') is moving away at v, the wave received at the transducer (the 'observer')

TURN OVER

has frequency

$$f'' = \frac{f'}{1 + \frac{v}{v_s}}. \qquad [2]$$

The total change in frequency is

$$\begin{aligned} \frac{\Delta f}{f} &= \frac{f'' - f}{f} \\ &= \frac{v_s - v}{v_s + v} - 1 \\ &= \frac{-2v}{v_s + v}. \qquad [2] \end{aligned}$$

But $v \ll v_s$ *so*

$$\frac{\Delta f}{f} \approx \frac{-2v}{v_s}. \qquad [2]$$

[alternative correct derivations will be accepted]
(bookwork)

(c) If a continuous wave ultrasound system has a transducer that operates at a frequency of 6 MHz, what Doppler shift frequency would be observed from blood cells that are moving away from the transducer at a velocity of 2 m/s? (assume the blood cells move along the ultrasound axis) [2]

appropriate parameters for calculation are:

f *=6 MHz,* v*=2 m/s,* v_s *= 1540 m/s*

hence $\Delta f = -2 \times 6 \times 10^6 \times 2/1540 = -15.6$ kHz

[1/2] *for rearranging equation,* **[1/2]** *for correct parameters and* **[1]** *for final answer,* **[1/2]** *deduction for failing to indicate reduction of frequency*
(similar problem worked in lectures)

(d) If the transducer described above is replaced with a pulsed Doppler transducer operating at the same frequency, *by deriving an appropriate expression*, calculate the maximum velocity of blood that can be accurately measured if the distance to the target blood cells of interest is 5 cm. [6]

The maximum resolvable frequency shift (Nyquist limit) is

$$|\Delta f_{max}| = \frac{PRF}{2} \qquad [\mathbf{1}]$$

where PRF is the pulse repetition frequency.

From (b),

$$\frac{\Delta f}{f} = \frac{-2v}{v_s} \qquad [\mathbf{1}]$$

so

$$\begin{aligned} |\Delta f_{max}| &= \frac{2v_{max}f}{v_s} = \frac{PRF}{2} \\ v_{max} &= \frac{PRF v_s}{4f}. \end{aligned}$$

The PRF is related to the penetration depth D by

$$PRF = \frac{v_s}{2D}. \qquad [\mathbf{1}]$$

Hence

$$\begin{aligned} v_{max} &= \frac{(v_s/2D)v_s}{4f} \\ &= \frac{v_s^2}{8fD} \qquad [\mathbf{1}] \end{aligned}$$

*Taking v_s = 1540 m/s, f = 6 MHz, D = 5 cm (**[1]** for correct parameters):*

$$V_{max} = \frac{1540^2}{8 \times (6 \times 10^6) \times 0.05} = 0.988\text{m/s}$$

[1] *for correct answer with units*

(Derivation done in lectures)

END OF PAPER