**Exam in the course Diagnostic Imaging - SSY186 & SSY185**

**Date: 2016-04-08, Friday, Time: 14.00-18.00**

| | |
|---|---|
| **Exam type:** | Closed book – Only the specified materials are permitted. |
| **Permitted materials:** | Calculator, dictionary, drawing materials (e.g. compass, ruler). |
| **Questions:** | Artur Chodorowski, 073-5543777<br>Andreas Fhager, 076-1257012 |
| **Exam script viewing:** | Time and place will be announced by email when the results are published. |
| **Important:** | All answers must be written in English. |

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# OBS!

- Answer all 5 (five) questions.
- Each is worth 20 marks. (5 x 20 = 100 marks, maximum)
- Each question consists of multiple parts.

## Requirements for grades:

3: ≥ 50
4: ≥ 67
5: ≥ 84
Max 100 marks.

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# Question 1 – Magnetic Resonance Imaging (20p)

(1) Resonance is important concept of MRI.

(a) Describe, what exactly is meant by **resonance** in the physical phenomenon called magnetic resonance, what is resonating in the magnetic resonance?

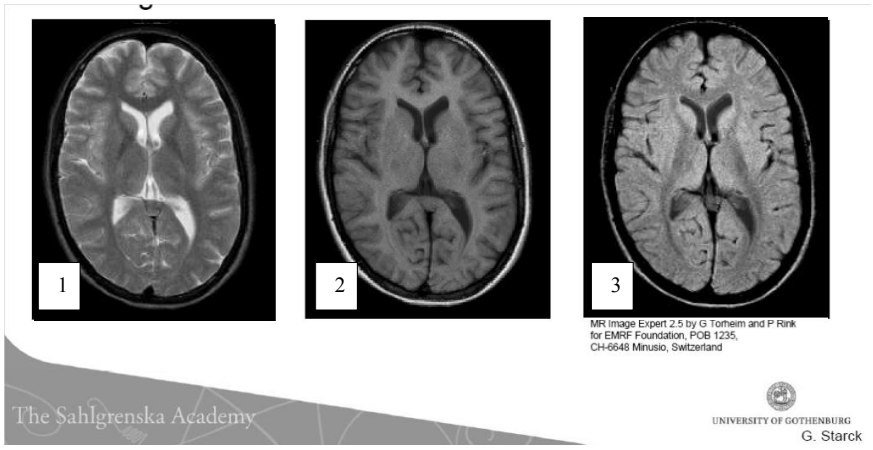
(3p)

(b) What kind of signals is used to "produce" the magnetic resonance (in the above sense, in (a))? What are the properties of these signals?

(2p)

(2) The MR images below show three different image contrasts of a slice through the skull. The task is to link each image to the correct image contrast (1-A, 2-B, etc.) and motivate shortly your choice (e.g. how different tissues look like).

(A) T1 weighted contrast
(B) T2 weighted contrast
(C) PD (proton density) weighted contrast




(5 p)

(3) Explain the concept of k-space in the context of MRI. What is k-space and how can it be used for generating MR images?

(5 p)

(4) Describe the principle of excitation and T1 and T2 relaxation for MRI. Discuss the different physical processes.

(5 p)

# Question 2 – Diffusion Tensor Imaging (DTI) and Brain Imaging (20 p)

(1) Explain what diffusion is and how it is affected by tissue microstructure

(2p)

(2)

In the second lab you used MATLAB to estimate the diffusion tensor $\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$ for each voxel in a real DTI data set. Recall that the equation for signal attenuation in direction $\mathbf{g}_i$ is given by

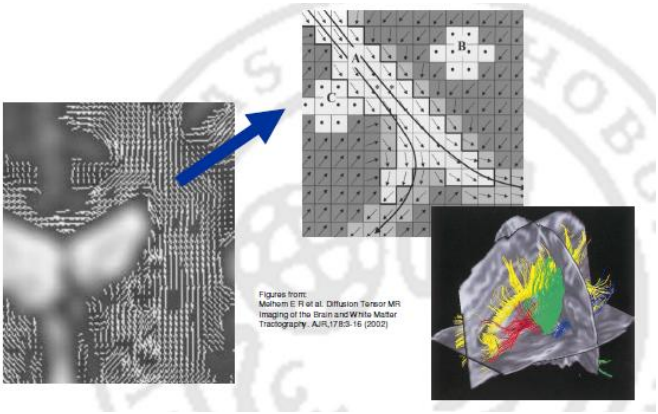
$$S_i = S_0 e^{-b\mathbf{g}_i^T \mathbf{D} \mathbf{g}_i}$$

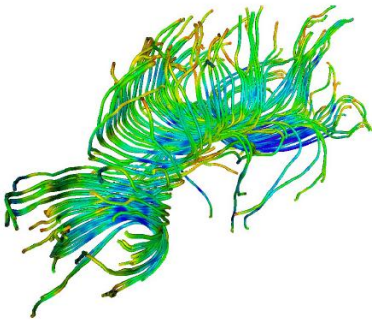
where $S_0$ is the signal intensity without diffusion weighting, and $b$ is a scalar. Explain:
(i) how **D** is estimated from this equation, and
(ii) how the main diffusion direction is estimated from **D**.

(6p)

(c) explain how DTI may be used for fibre tracking in the human brain

(2p)



**Brain tissue segmentation**

In a brain tissue segmentation algorithm (using e.g. k-means) we have obtained the following result:

| | | | | |
|---|---|---|---|---|
| | 1 | 1 | 1 | |
| 1 | 2 | 2 | 2 | 1 |
| 1 | 2 | 3 | 2 | 1 |
| 1 | 2 | 2 | 2 | 1 |
| | 1 | 1 | 1 | |

(left)

| | | | | |
|---|---|---|---|---|
| | 1 | 1 | 1 | |
| 1 | 2 | 2 | 2 | 1 |
| 1 | 3 | 3 | 3 | 1 |
| 1 | 2 | 2 | 2 | 1 |
| | 1 | 2 | 1 | |

(right)

Fig. (left) Ground truth (right) Segmented image.
Class labels, class 1=cerebrospinal fluid, class 2 = gray matter, class 3 = white matter.

→ Calculate the performance measure called Dice index for this segmentation algorithm.

→ Use the Dice index to find out for which tissue the segmentation algorithm attains the best performance.

(10 p)

# Question 3 – Microwave Tomography, Ultrasound, Nuclear Medicine (20 p)

**Microwave Tomography**

Make a comparison between the iterative reconstruction algorithm for microwave tomography we have discussed in the course and the algorithm based on the Fourier Diffraction Theorem. Make sure to address questions such as:
What assumptions and approximations are made and what are their consequences?
Design of the experimental setup?
Computation time?
Differences and Similarities in the algorithm and experimental setup? etc.

(10 p)

**Ultrasound**

With the aid of the following figures, explain what are steering, focusing, beam-forming and dynamic beam-forming. What are the advantages of using them in ultrasound imaging compared to other modalities (e.g. B-mode)?

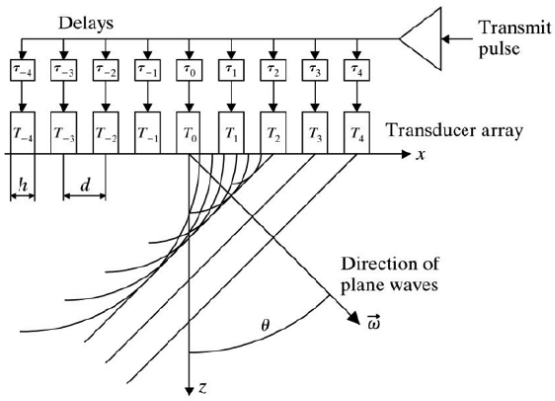



Figure 1

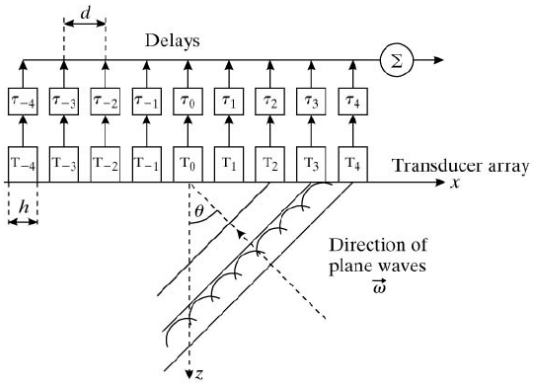
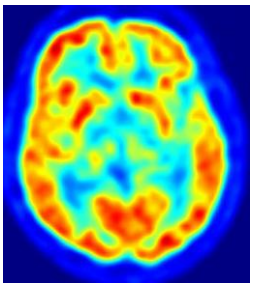



Figure 2

(5 p)

**PET and SPECT**

Describes the principles of Positron Emission Tomography (PET) in terms of tracers, data acquisition, image reconstruction and application areas.



(5p)

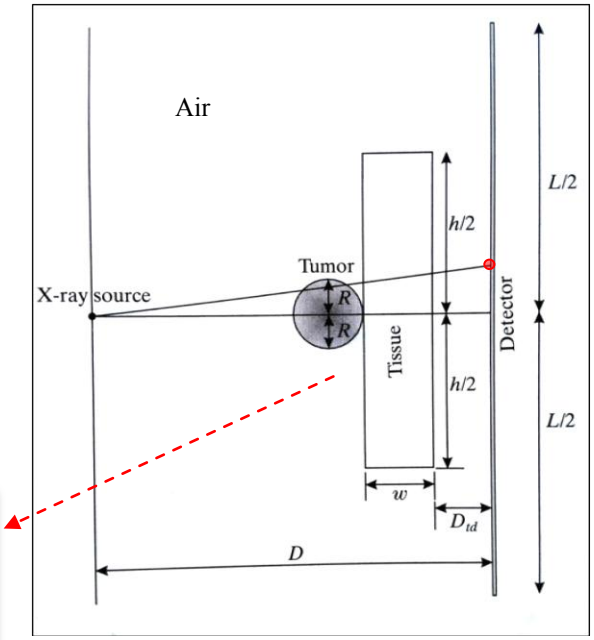
# Question 4 – Radiography/Computed Tomography (20 p)

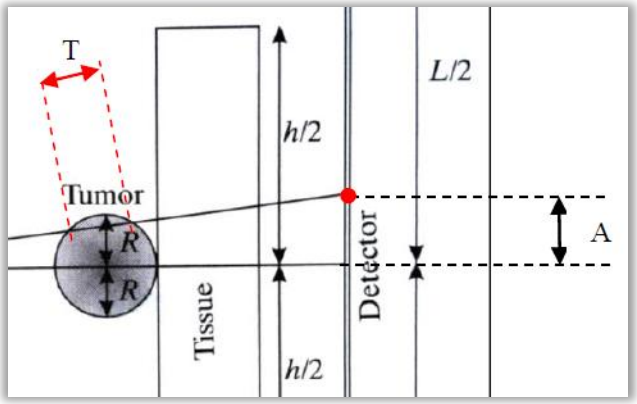
**Radiography (physics and projection)**

(a) Consider the x-ray projection radiography system shown in the figure below. Relevant dimensions in the figure are $L = 1\ m$, $D = 4\ m$, $w = 1\ cm$, $h = 3\ cm$, $R = 0.1\ cm$, and $D_{td} = 10\ cm$. **NOTE:** See the Appendix for formulae, equations, etc.

A contrast agent is used to enhance the image of the tumour. Assume a 35 $keV$ (monochromatic) x-ray source and the linear attenuation coefficients given in the table below.

| | $\mu$ - Linear Attenuation Coefficient ($cm^{-1}$) | | |
|---|---|---|---|
| Energy ($keV$) | Air $\mu_{Air}$ | Tissue $\mu_{Tissue}$ | Tumour with Contrast Agent $\mu_{Tumour}$ |
| 35 | 0.01 | 1 | 10 |




(i) Assume that x-ray photons pass through the system in a straight line (from x-ray source to the point at distance **A** from the centre of the detector, see the Figures). Find the expression and calculate the percentage of photons that will hit that point. Assume that the x-ray distance through the tumour is equal **T**.

**Note:** numerical calculations give 2 pts.

(8+2=10 pts)

**Computed Tomography**

(a) Describe in detail the principle for the Filtered Back Projection algorithm. Describe with words (use pictures or flowcharts if you need) the different steps that are necessary in order to reconstruct the image, originating from the projection data, i.e. the sinogram.

(3pts)

(b) Demonstrate Back Projection algorithm (with NO filtering) by reconstructing the image below from TWO projections only (horizontal and vertical). You should show the projection images, back-projection images and the final reconstructed image. Describe with words the images you drawn/computed.

| | | | | |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 1 | 0 | 0 |
| 0 | 0 | 1 | 0 | 0 |
| 0 | 1 | 1 | 1 | 0 |
| 0 | 0 | 0 | 0 | 0 |

Fig. The original image. The pixel values (0 and 1) represent the linear attenuation coefficient ($1\ cm^{-1}$).

(4 pts)

(c) List and briefly describe as many sources of errors/artifacts in CT-imaging that you can.

(3pts)

# Question 5 – Future / Other Modalities (20 p)

**Ultra-low field MRI (ulf-MRI)**

1. Ultra-low field MRI relies on superconducting quantum interference device (SQUID) technology. The "quantum" in SQUID comes from the fact that (pick one):
    a. When the sensor is cooled below its critical temperature, Tc, the charges pair up, form Cooper pairs that are bosonic, and thereby collapse into the same quantum state.
    b. The interfering voltage potentials between the poles of the device lead to quantized Josephson radiation emitted from them.
    c. The superconducting current that can flow through the device is quantized in terms of the charge quantum.
    d. The magnetic flux that can penetrate the device's loop is quantized in terms of the flux quantum.
    e. (a) and (c)
    f. (a) and (d)
    g. None of the above

    (EASY 1 pt)
2. Give 2 reasons why the military might be interested in ultra-low field MRI (as opposed to conventional MRI). (MODERATE 2 pts)
3. Why isn't standard/conventional MRI performed with (low- or high-Tc) SQUID sensors. In other words, why are standard "antennas" (normal conducting coils) good enough for MRI performed at 1+ (one or more than one) tesla? (HARD 2 pts)

**Magnetoencephalography (MEG)**

The power signal-to-noise ratio is defined as a function of the signal magnitude, $S$, and the magnitude of the noise, $N$, as follows:

$$SNR = \frac{S^2}{N^2}$$

*Assumption 1: Low-Tc SQUIDs have roughly 10× lower noise magnitude as compared to high-Tc.*

*Assumption 2: The signal magnitude is constant/the same for low- and high-Tc SQUIDs.*

1. How much worse is the power signal-to-noise ratio for a high-Tc as compared to a low-Tc SQUID under both *Assumption 1* and *Assumption 2*? (EASY 1 pt)
2. Why is *Assumption 1* above important/relevant in terms of MEG with high-Tc vs low-Tc SQUIDs? (MODERATE 2 pt)
3. Why is *Assumption 2* above important/relevant in terms of MEG with high-Tc vs low-Tc SQUIDs? In other words, why bother with high-Tc SQUID-based MEG? (HARD 2 pts)

**fMRI - functional MRI**

(1) What is functional MRI? What it can be used for?
(2) What is BOLD and how is it used in the context of functional MRI ?

(4p)

**Maximum intensity projection**

A Maximum Intensity Projection (MIP) is a volume rendering method for 3D data. Compute the maximum intensity projection of the volume below in the three planes: coronal, sagittal and axial. The volume is a cube of 3 x 3 x 3 voxels. The integer values correspond to voxel intensity values, the voxel in the cube's center has intensity value equal 3 (see Figure below). It consists of the following layers:

| | | |
|---|---|---|
| 7 | 8 | 9 |
| 1 | 5 | 4 |
| 3 | 5 | 3 |

| | | |
|---|---|---|
| 7 | 9 | 9 |
| 6 | 3 | 4 |
| 1 | 2 | 3 |

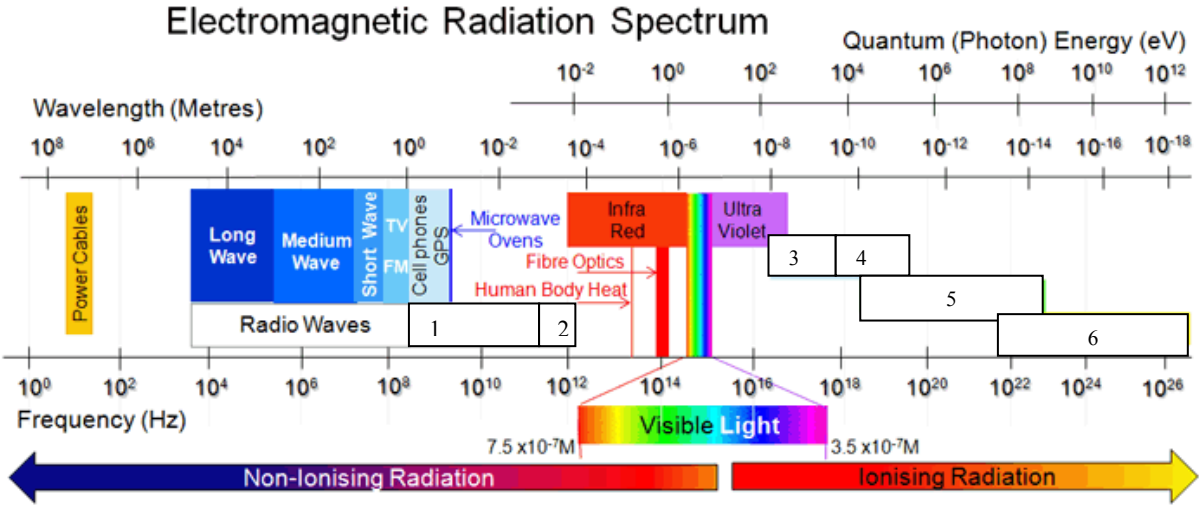
| | | |
|---|---|---|
| 7 | 4 | 2 |
| 1 | 5 | 4 |
| 1 | 2 | 3 |

Fig. Layer #1 Layer #2 Layer #3

(4 p)

**Electromagnetic spectrum**

The figure below shows the electromagnetic spectrum and the names of different bands are listed below the figure. Your task is to match the band with its name, e.g. 1-a, 2-b, ...

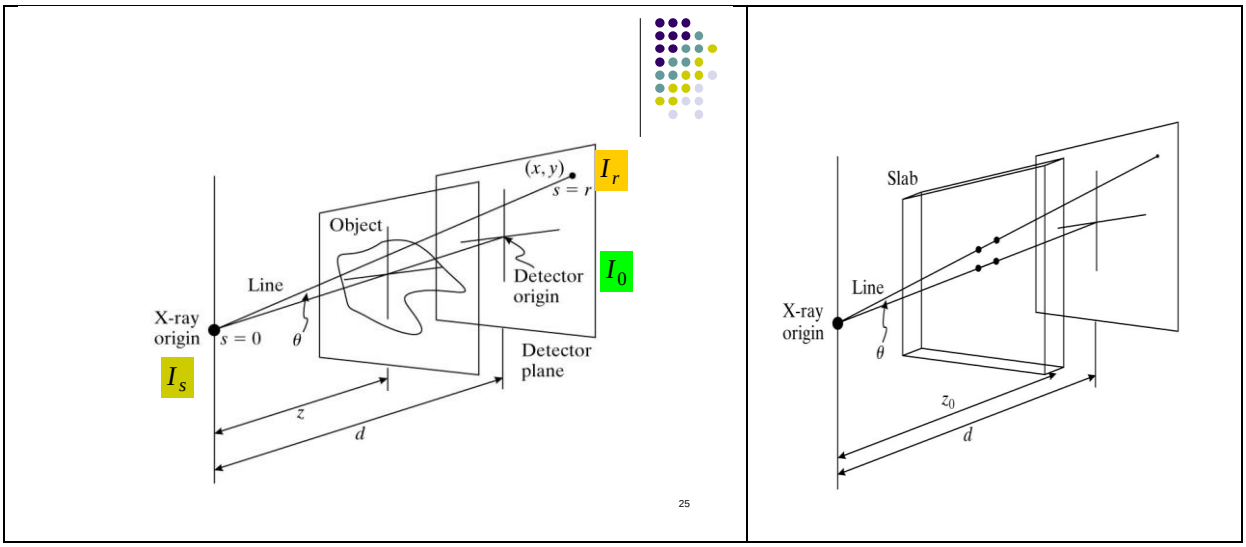



(a) hard x-rays
(b) soft x-rays
(c) THz waves
(d) cosmic rays
(e) microwaves
(f) gamma rays

(2p)

# APPENDIX – formulae

## Geometric effects associated with x-ray image formation




where
$I_0$ - beam intensity at the origin of the detector
$I_r$ - beam intensity at distance $r$ from the origin of the detector
$d$ - distance between the x-ray origin and the detector plane
$r$ - distance between the x-ray origin and the detector point (x,y)
$L$ - slab thickness
$\mu$ - a constant linear attenuation coefficient

| | |
|---|---|
| Inverse Square Law | $I_r(x,y) = I_0 \frac{d^2}{r^2} = I_0 \cos^2(\theta)$ |
| Obliquity | $I_r(x,y) = I_0 \cos(\theta)$ |
| Path Length | $I_r(x,y) = I_0 \exp(-\mu \cdot L/\cos(\theta))$ |

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The fundamental photon attenuation law for the monoenergetic case:

$$I_{out} = I_{in} \exp(-\mu \cdot \Delta x)$$

where $I_{in}$ is the intensity of the incident beam, $\Delta x$ is the thickness of the slab of material, $I_{out}$ is the beam intensity after passing through the slab, and $\mu$ is a constant linear attenuation coefficient.
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**Segmentation performance**

The Dice index/score is equal $2V_{ae}/(V_a + V_e)$, where $V_{ae}$ denotes the number of voxels that are assigned to tissue by both the automated algorithm the ground truth, $V_a$ and $V_e$ denote the number of voxels assigned to tissue by the algorithm and the ground truth, respectively.
The Jaccard index ($J$) is related to Dice index ($D$) by $J = D/(2 - D)$.

**Scalar DTI invariants**

from (Le Bihan, 2001):

Invariant indices are thus made of combinations of the terms of the diagonalized diffusion tensor, ie, the eigen-values $\lambda_1$, $\lambda_2$, and $\lambda_3$. The most commonly used invariant indices are the relative anisotropy (RA), the fractional anisotropy (FA), and the volume ratio (VR) indices, defined respectively as:

$$RA = \sqrt{(\lambda_1 - \langle\lambda\rangle)^2 + (\lambda_2 - \langle\lambda\rangle)^2 + (\lambda_3 - \langle\lambda\rangle)^2}/\sqrt{3}\langle\lambda\rangle \quad (9)$$

where

$$\langle\lambda\rangle = (\lambda_1 + \lambda_2 + \lambda_3)/3. \quad (10)$$

$$FA = \sqrt{3[(\lambda_1 - \langle\lambda\rangle)^2 + (\lambda_2 - \langle\lambda\rangle)^2 + (\lambda_3 - \langle\lambda\rangle)^2]}/\sqrt{2(\lambda_1^2 + \lambda_2^2 + \lambda_3^2)}. \quad (11)$$

## Larmors equation

Basic form:

$$f = \frac{\gamma}{2\pi} B \qquad \text{where:} \quad \frac{\gamma_{^1\mathrm{H}}}{2\pi} \approx 42{,}58\ \mathrm{MHz/T}$$

With gradients:

$$f(\mathbf{r}) = \frac{\gamma}{2\pi}(B_0 + \mathbf{G}\cdot\mathbf{r})$$

where: $\mathbf{G}$ is the gradien tvector

and $\mathbf{r}$ is the position vektor

E.g. in x direction:

$$f(x) = \frac{\gamma}{2\pi}(B_0 + G_x \cdot x)$$

**END OF PAPER**