**Exam in the course Diagnostic Imaging - SSY 186 & SSY185**

**Date: 2015-08-26, Wednesday, 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, maximim)
- Each question consists of multiple parts.

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# Question 1 – Magnetic Resonance Imaging (20p)

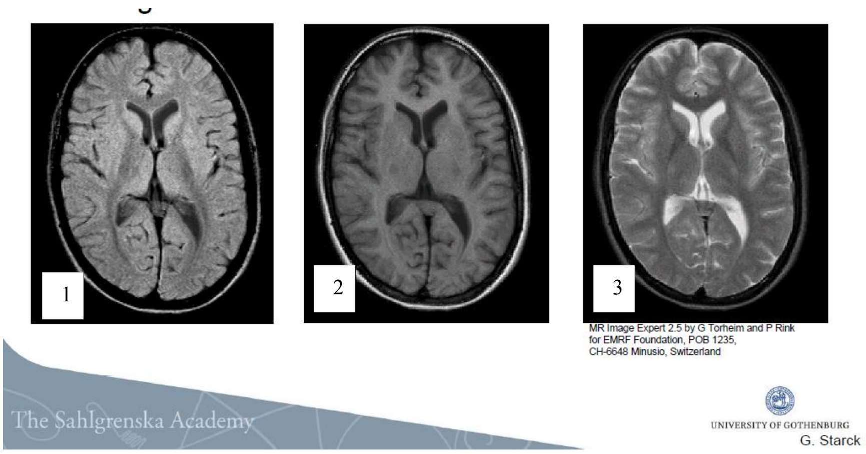
(1) Precession is important concept of NMR and MRI and the Larmor equation describes an aspect of precession in the context of magnetic resonance.

(a) What is precession and when is it present? What exactly is precessing?
(b) What is the cause of precession ?
(c) How do the Larmor equation relate to the precession?

**(5 p)**

(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



MR Image Expert 2.5 by G Torheim and P Rink
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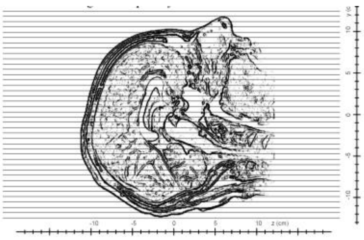
UNIVERSITY OF GOTHENBURG
G. Starck

**(5 p)**

(3) Explain the principle of slice selection (e.g. of axial slices) in MR imaging.



**(5 p)**

(4) In the context of MR we are talking about weighted and "star" signals. Explain shortly the difference between T2-weighetd MR signal, and T2* (star)-weighted MR signal.

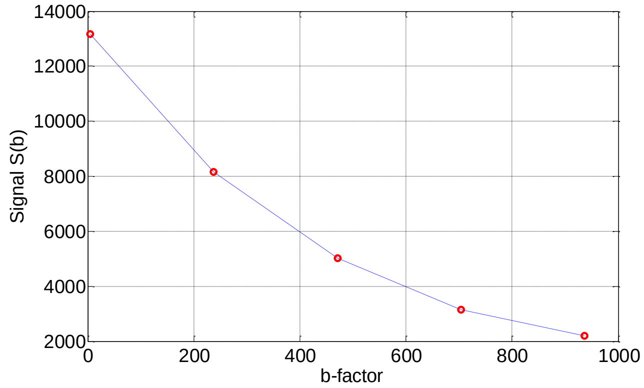
**Note:** You don't need to explain the "whole" physics behind T2 signal. Just the difference between the T2-weighted MR signal and T2*(star)-weighted MR signal.

**(5 p)**

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

(a) In a Diffusion Tensor Imaging (DTI) experiment we have measured the following points in individual pixels:

| **b-factor** $[s/mm^2]$ | **S(b)** |
|---:|---:|
| 5 | 13168 |
| 238 | 8160 |
| 471 | 5030 |
| 704 | 3140 |
| 937 | 2210 |
| ... | ... |



(1) Perform a least-square fit with a monoexponential function $S(b) = S_0 \cdot exp\,(-b \cdot D)$ for b-factors ($b$) equal 5, and 937 (i.e. using two data points). Use the logarithm of the signals to fit a linear function. $D$ stands for diffusion coefficient, $S_0$ is non-diffusion weighted signal, $S$ is diffusion weighted signal.

**(5 p)**

(2) Plot the found function (with the estimated parameters $S_0$ and $D$) in a logarithmic y-scale. What is the value of the sum of squared residuals for your solution?

**(3 p)**

(b) In an another diffusion experiment we have estimated the diffusion tensor as

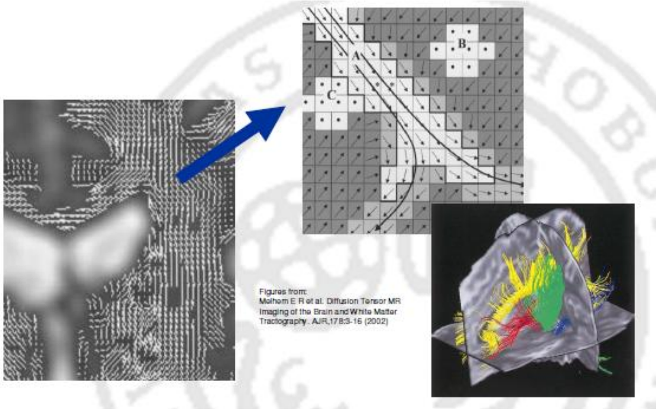
$$\boldsymbol{D} = \begin{bmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & a \end{bmatrix}$$

where $a$ stands for some value. Visualize this tensor as an ellipsoid with proper axes.
What can be said about water diffusion in such a case, is it isotropic or anisotropic?
What is the value of fractional anisotropy calculated from $\boldsymbol{D}$ ?

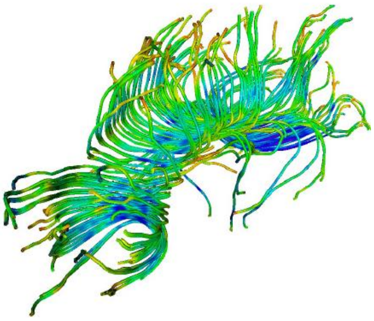
**(2p)**

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

**(5 p)**



Figures from:
Melhem E R et al. Diffusion Tensor MR Imaging of the Brain and White Matter Tractography . AJR,178:3-16 (2002)



### Brain tissue segmentation

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

|  | True class |  |  |
|---|---|---|---|
|  | 1 | 2 | 3 |
| Assigned class |  |  |  |
| 1 | 2882 | 95 | 0 |
| 2 | 37 | 6809 | 44 |
| 3 | 0 | 204 | 9436 |

Fig. Confusion matrix, class 1=CSF, class 2 = gray matter, class 3 = white matter.

Here, the matrix entries denote the number of voxels that are assigned to tissue class by the algorithm and the ground truth, respectively.

→ Calculate the performance measure called Dice index for this segmentation algorithm.
→ For which tissue does the segmentation algorithm attain the best performance?

**(5 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

Describe the main principles for generating B-mode ultrasound images. What is the main underlying principle for image generation? The scanner could be designed and operated in different ways in order to generate B-mode images. Describe the different principles.

**(5 p)**

### PET and SPECT

(a) What do PET, SPECT stand for?

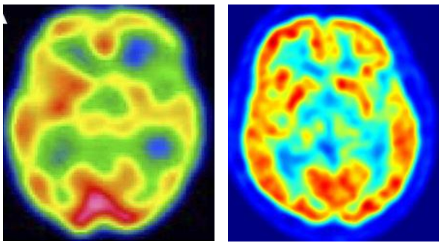
**(1 p)**

(b) Describe the main physical principles, i.e. how PET/SPECT images are generated

**(2 p)**

(c) The images below show PET and SPECT reconstructed images. What exactly do these images (intensities) represent i.e. what kind of physical property/signal?

**(2 p)**



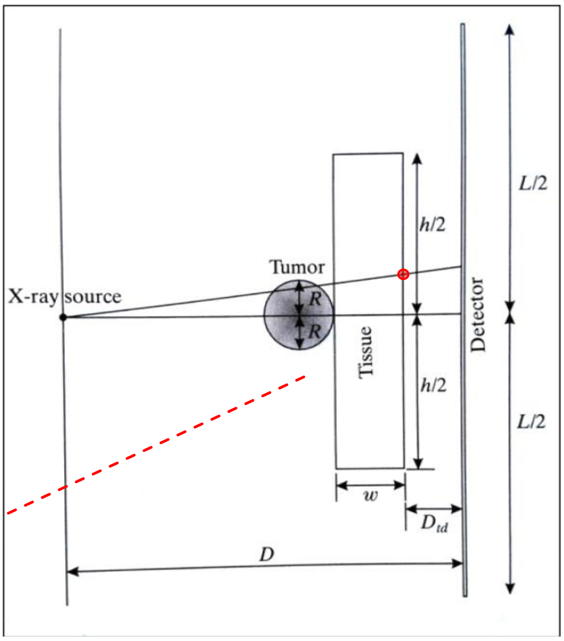
# Question 4 – Radiography/Computed Tomography (20 p)

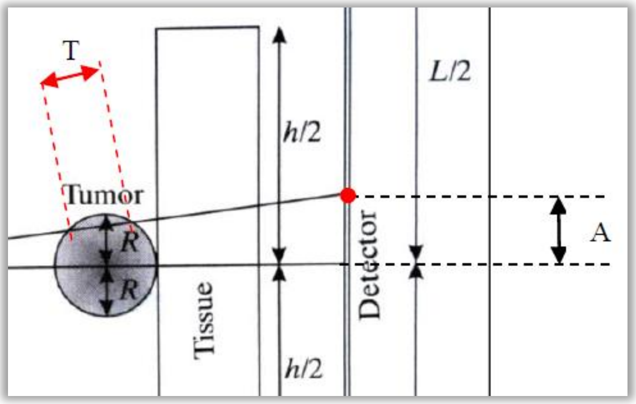
**Radiography (physics and projection)**

(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 $(keV)$ | Tissue<br>$\mu_{Tissue}$ | Tumour with Contrast Agent<br>$\mu_{Tumour}$ |
| 35 | 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 for percentage of photons that will hit that point.
Assume that the x-ray distance through the tumour is equal **T**.

**Note:** numerical calculations not needed.

**(5 p)**

(ii) Explain the Compton scattering in the context of x-rays (i.e. what is Compton scattering, the physics behind, and how does it influence the x-ray imaging).

**(5 p)**

## 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.

(5 marks)

b) In the course we have discussed the Algebraic Reconstruction Algorithm. Describe the main principle for how to formulate this imaging algorithm. Describe also different strategies for solving the imaging problem. What are the pros and cons of this approach?

(5 marks)

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

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

1. Imagine that:

    a. you have a friend that has been diagnosed with prostate cancer and needs to have invasive surgery to remove the cancerous tissue,
    b. there is a new "full range" MRI system capable of imaging at 10 μT, 100 μT, 1 mT, 10 mT, 100 mT, and 1 T (i.e. $1 \times 10^{-5, -4, -3, -2, \text{ and } -1}$ Tesla, respectively),

    and

    c. using the "full range" MR system is very expensive, so patients with prostate cancer are allowed to be imaged only 2 times before surgery.

    At which fields strengths would you recommend your friend be imaged and why? **(3 pts).**

2. A *counter indicator* is a reason a given medical procedure, practice, etc. should not be performed on a given person, e.g., alcoholism is a *counter indicator* for many medications that rely on a properly performing liver. Give two counter indicators for having a diagnostic image taken with a modern/conventional/standard MRI system that *are not* counter indicators for ulf-MRI technology?

    **(2 pts)**

**Magnetoencephalography (MEG)**

1. Why might one chose to use EEG and/or fNIRS *instead of MEG* for studies of brain activity in infants? **(1 pts)**

2. Remember that the visual alpha signal is a "cortical resting rhythm" whose magnitude (as recorded by MEG from the visual cortex) can be as much as 100× stronger when you shut your eyes. Let's assume you are doing a 2-channel MEG recording on a friend: you align sensor A over your friend's right primary visual cortex and sensor B over the left primary visual cortex. When your friend has eyes closed, the visual alpha signal is indeed 100× stronger than with open eyes *in both sensors*. You then have your friend close just one eye. How does the visual alpha signal change in *each of* the sensors? **(2 pts)**

3. Optical magnetometers are a newer class of magnetic field sensors whose sensing element is a high-temperature (300+ Celcius) gas coupled to a laser. Their magnetic field noise levels are similar to that of high-$T_c$ SQUIDs and they can be made into cells of roughly the same size as a SQUID sensor. Would you recommend attempting MEG with such a sensor technology? Why or why not? **(2 pts)**

## Tomosynthesis

(1) Why is the 3D reconstruction in digital tomosynthesis more challenging than in the conventional CT?

**(2 p)**

(2) The effective X-rays dose imparted in the (chest) tomosythesis is estimated to be:

(a) ca 10 times that of a standard digital posteroanterior and lateral radiograph chest exam
(b) ca 3 times "
(c) roughly the same "
(d) ca 10 times less "
Motivate your answer shortly.

(3) The effective X-rays dose from a chest tomosynthesis examination is:

(a) ca 3 % of an average chest CT
(b) ca 0.3% of an average chest CT
(c) ca 30% of an average chest CT
Motivate your answer shortly.

**(3 p)**

## Maximum intensity projection

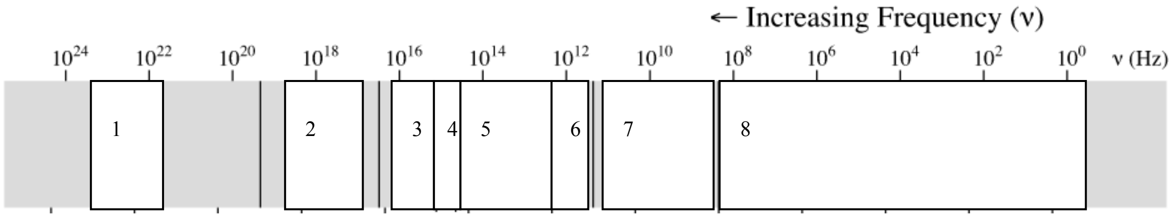
Calculate maximum intensity projection in direction of 30 degrees for the 2D image (size 3x3 pixels) below, the pixel size is 1 mm x 1 mm. The distance between pixels in the projected image should be 1 mm.

| | | |
|---|---|---|
| 7 | 8 | 9 |
| 6 | 5 | 4 |
| 1 | 2 | 3 |

**(3 p)**

## Electromagnetic spectrum

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



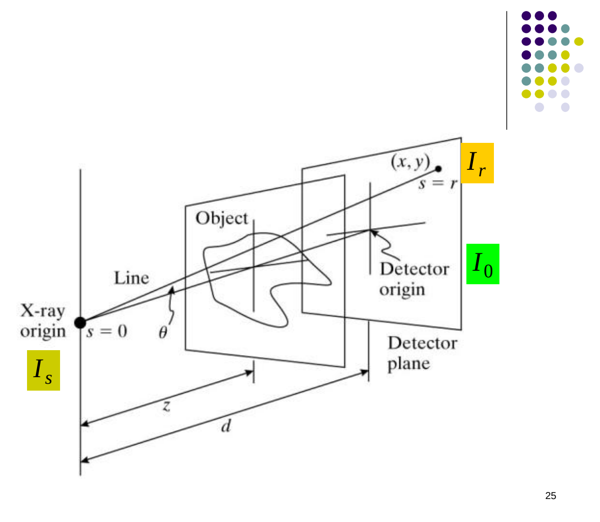
(a) radio waves
(b) ultraviolet
(c) THz
(d) gamma-rays
(e) infrared
(f) microwaves
(g) X-rays
(h) visible light

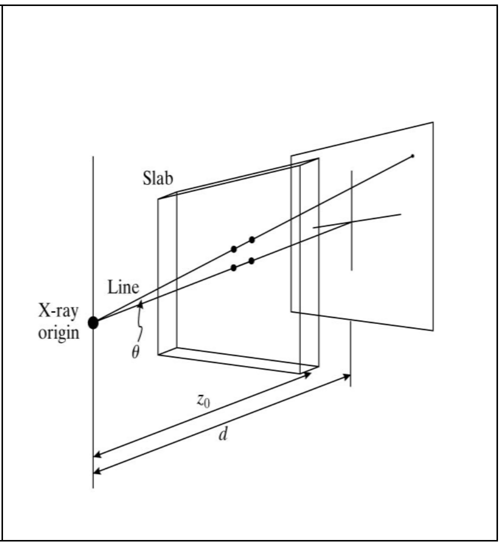
**(2p)**

**--- END (of questions)**

# 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 | $I_r(x, y) = I_0 \exp\left(-\mu \cdot L / \cos(\theta)\right)$ |

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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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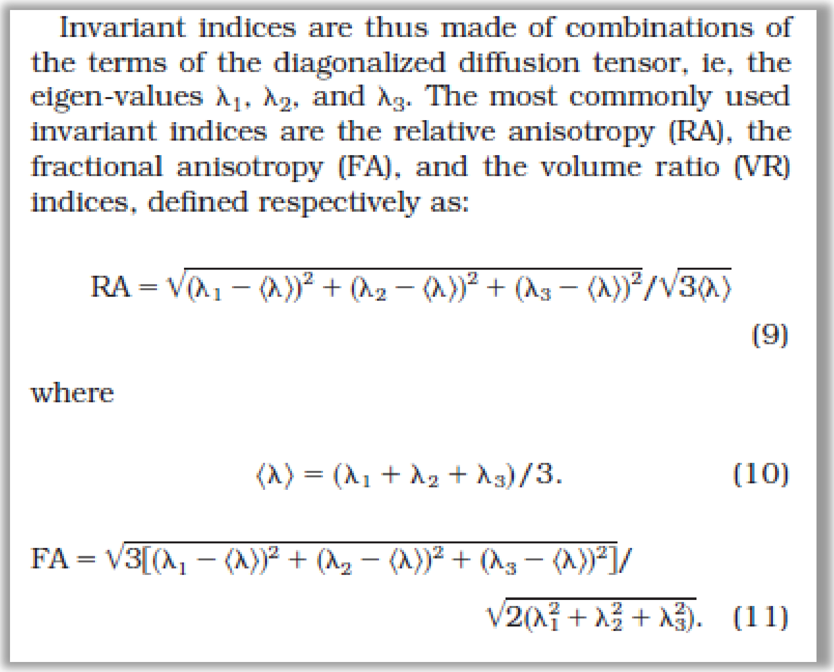
**Segmentation performance**

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):



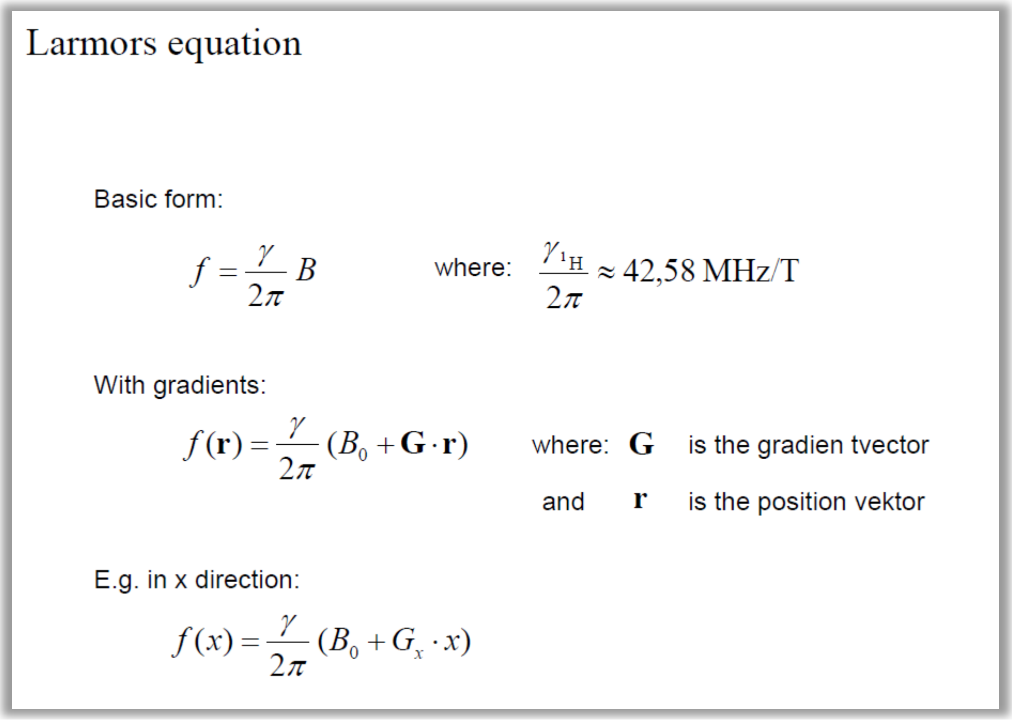
Invariant indices are thus made of combinations of the terms of the diagonalized diffusion tensor, ie, the eigen-values $\lambda_1$, $\lambda_2$, and $\lambda_3$. The most commonly used invariant indices are the relative anisotropy (RA), the fractional anisotropy (FA), and the volume ratio (VR) indices,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

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

where

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

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



Larmors equation

Basic form:

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

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:

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

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**END OF PAPER**