Fall 2022 Medical Physics Qualifying Exam
for Advancement to Candidacy
Part 1
August 26, 2022
11:30-13:45 PDT

If you are in the PhD in astronomy or PhD in physics programs, stop! This is the Medical Physics version of the exam.

Do not write your name on your exam papers. Instead, write your student number on each page. This will allow us to grade the exams anonymously. We'll match your name with your student number after we finish grading.

This portion of the exam has 3 questions. Answer all three of the questions.

You have 2.25 hours to complete 3 questions.

You are allowed to use your own formula sheet, and a handheld, non-graphing calculator.

Question 1 – External Beam Radiation Therapy (40pts)

Part 1: Radiation beam characteristics

For each of the questions below, select the appropriate response(s) and provide a physical explanation for your answer. You may use sketches to help illustrate your answers.

a) With reference to a megavoltage **X-ray** beam incident on a water phantom,

Under conditions of normal beam incidence :

(i) (4 marks) the percent surface dose (relative to the maximum dose):

☐ increases ☐ decreases

with increasing beam energy because:

(ii) (3 marks) The mean energy of the photon beam

☐ increases ☐ decreases

with depth in the phantom because:

(iii) (3 marks) The percent depth dose

☐ increases ☐ decreases

as the field size increases because:

(iv) (3 marks) For beams with identical energy spectra, and with identical secondary and tertiary collimation, the percent depth dose

☐ increases ☐ decreases

more rapidly with depth than the TMR because:

(v) (3 marks) The penumbra of a 25 MV beam is

☐ narrower ☐ wider

than the penumbra of a 6 MV beam because:

Under conditions of oblique beam incidence:

(vi) (4 marks) the depth of maximum dose (d_m)

☐ increases ☐ decreases

and the surface dose

☐ increases ☐ decreases

relative to a normally incident beam because:

b) With reference to a megavoltage **electron** beam incident on a water phantom,

Under conditions of normal incidence:

(i) (3 marks) The mean energy of the electrons

☐ increases ☐ decreases

with depth in the phantom because:

(ii) (3 marks) The percent surface dose (relative to the maximum dose)

☐ increases ☐ decreases

with increasing beam energy because:

Part 2: Photon beam therapy

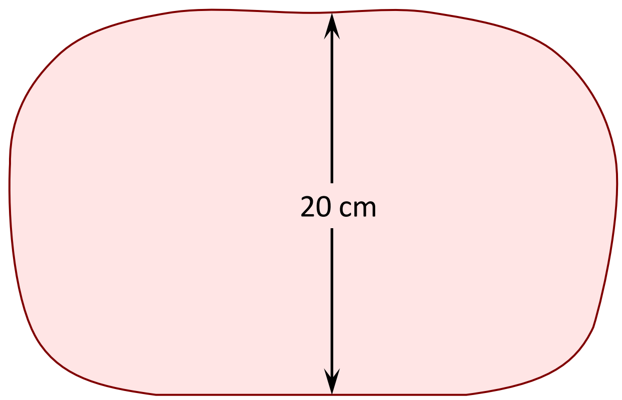
A patient with a pelvic tumour is to be treated using a three field technique with a 15 MV linac X-ray beam (isocentric set-up). A dose of 200 cGy/fraction is prescribed to the isocentre. The MU are determined using an isocentric dose calculation formalism with normalization depth at d_m (depth of maximum dose) and machine output =1.000 cGy/MU for a 10 cm $\times$10 cm field at d_m (isocentric set-up). The treatment plan parameters are listed in the table below. There is no customized field shaping in the form of blocks or MLC.

a) (8 marks) Fill in the missing information. (Note: collimator settings are provided with respect to the patient coordinate system).

Field #		**1**	**2**	**3**
Isocentric beam weight		1.00	0.75	0.75
dose delivered to isocentre				
gantry angle		0°	270°	90°
collimator setting, r_c	*axial*	15 cm	10 cm	
	longitudinal	15 cm	15 cm	
dynamic (virtual) wedge angle		no wedge	45°	
SSD		92 cm	84 cm	
equivalent square field size, r_d		15 cm		
TMR(d, r_d)		0.922		

S_c (r_c)	1.020	1.006
S_p (r_d)		1.005
wedge factor, WF	n/a	0.807
MU	84.0	97.7

b) (4 marks) On the figure below (axial view of patient in plane of isocentre), sketch the beam arrangement for the plan, including the approximate location of the central beam axes, field borders, and isocenter, as well as the orientation of the wedges.

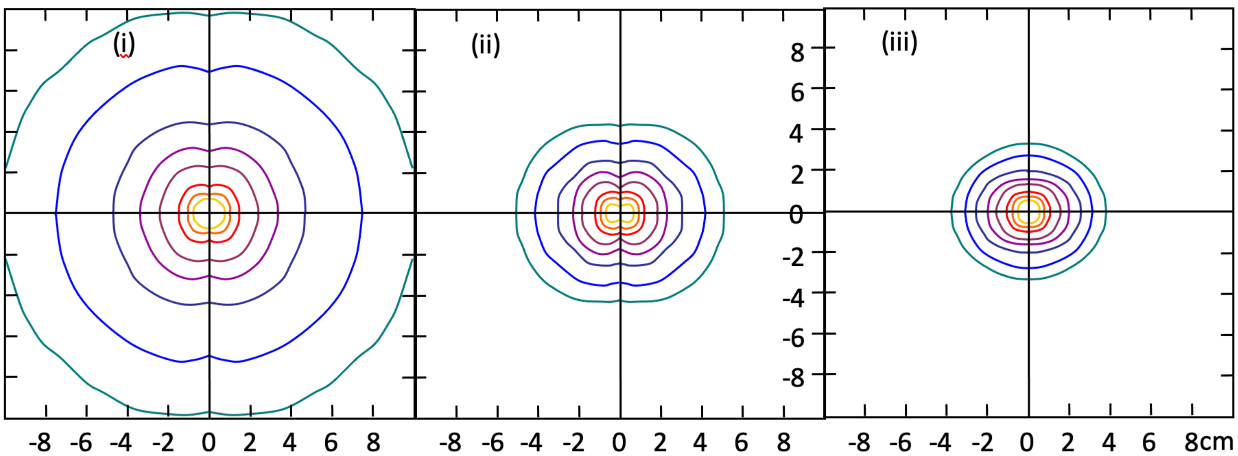


c) (2 marks) What is the main purpose of the wedges in this beam arrangement?

Question 2 - Brachytherapy

a) (3 marks) Of the following choices, which corresponds to each of the 3 isodose distributions [(i)-(iii)] illustrated below?

- LDR Cs-137 tube source
- LDR I-125 seed
- LDR Pd-103 seed
- LDR Ir-192 seed
- HDR Ir-192 source



Isodose curves produced in water by various linear brachytherapy sources, shown in a plane passing through the long axis of the source. All of the sources have S_K= 100 μGy m²/hr. The isodose lines represent, starting from the outside, dose rates of 1, 2, 5, 10, 20, 50, 100, and 200 cGy/hr.

b) (1 mark) What is the orientation of the long axis of the sources in the above figures?

c) (1 mark) What is S_K?

d) (13 marks) With the help of a labeled sketch of the geometry that forms the basis of the TG43 dose calculation formalism, name and briefly describe the dosimetric parameters that are required, in addition to S_K, to produce the above isodose distributions using this dose calculation formalism. Use the notation introduced in the TG43 update published in 2004. For each parameter, be sure to indicate (i) how it is defined relative to the TG43 geometry and (ii) the principal physical phenomenon or process that it characterizes.

e) (2 marks) Consider a prostate brachytherapy implant with Pd-103 seeds. Of the parameters listed in part (d), which has the greatest effect on the dose distribution within the clinical target volume? Provide a brief explanation for your answer.

f) Consider an eye plaque containing twelve Pd-103 seeds (all with the same S_K) arranged in two concentric polygons as shown in the figure. Using the geometric information provided in the figure (it may be assumed that the eye and its layers are perfect spheres, and that the plaque conforms to the outer eye), as well as the TG-43 data provided for the Pd-103 seeds:

(i) (11 marks) Determine the initial S_K (at t=0) required to deliver 80 Gy to the prescription point (P) at the apex of the PTV, if the plaque is left in place for exactly 6 days. You may assume that the plaque material is water-equivalent.

(ii) (6 marks) Determine the dose to point A.

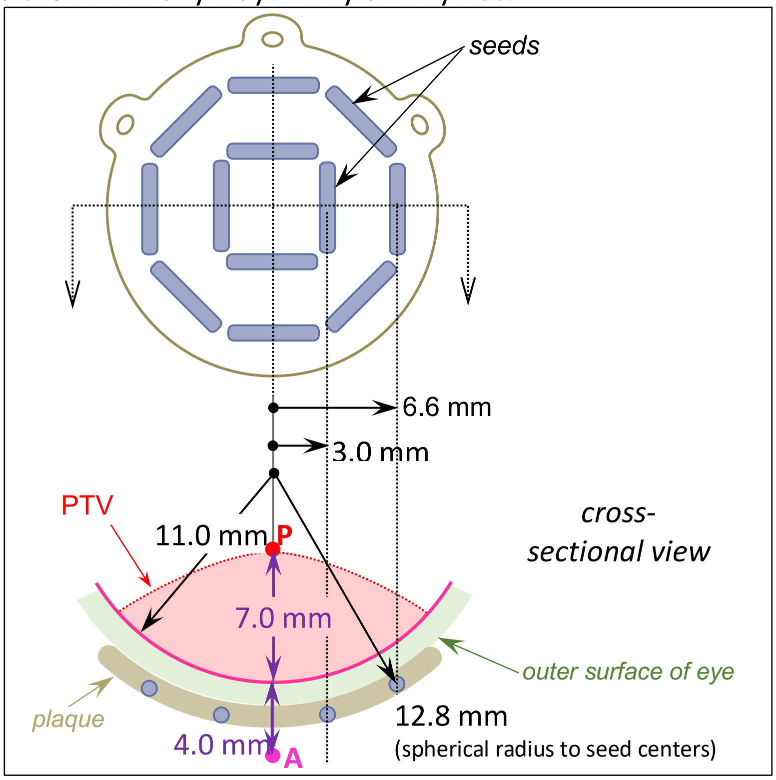
(iii) (3 marks) Without changing any of the treatment plan parameters (e.g. seed geometry, S_K, treatment duration), what could feasibly be done to reduce the dose to point A? Would this affect the dose to the PTV in any way? Why or why not?

Λ = 0.686 cGy hr^{-1} U^{-1}

$T_{1/2}$ = 16.991 days

active length = 3.5 mm

r (cm)	$g_L(r)$
0.3	1.3800
0.4	1.3600
0.5	1.3000
0.6	1.2400
0.7	1.1800
0.8	1.1200
0.9	1.0600
1.0	1.0000
1.1	0.9498
1.2	0.8996
1.3	0.8494
1.4	0.7992



$F(r,\theta)$	θ (deg)									
***r* (cm)**	**0.0**	**10.0**	**20.0**	**30.0**	**40.0**	**50.0**	**60.0**	**70.0**	**80.0**	**90.0**
0.25	0.619	0.284	0.496	0.775	0.917	0.945	0.976	0.981	0.992	1.000
0.50	0.694	0.496	0.442	0.586	0.734	0.837	0.906	0.929	0.955	1.000
0.75	0.601	0.495	0.486	0.585	0.726	0.831	0.907	0.954	0.959	1.000
1.00	0.541	0.487	0.501	0.593	0.727	0.834	0.912	0.964	0.972	1.000
1.50	0.534	0.496	0.524	0.613	0.739	0.844	0.922	0.977	0.995	1.000

Period 1: Question 3

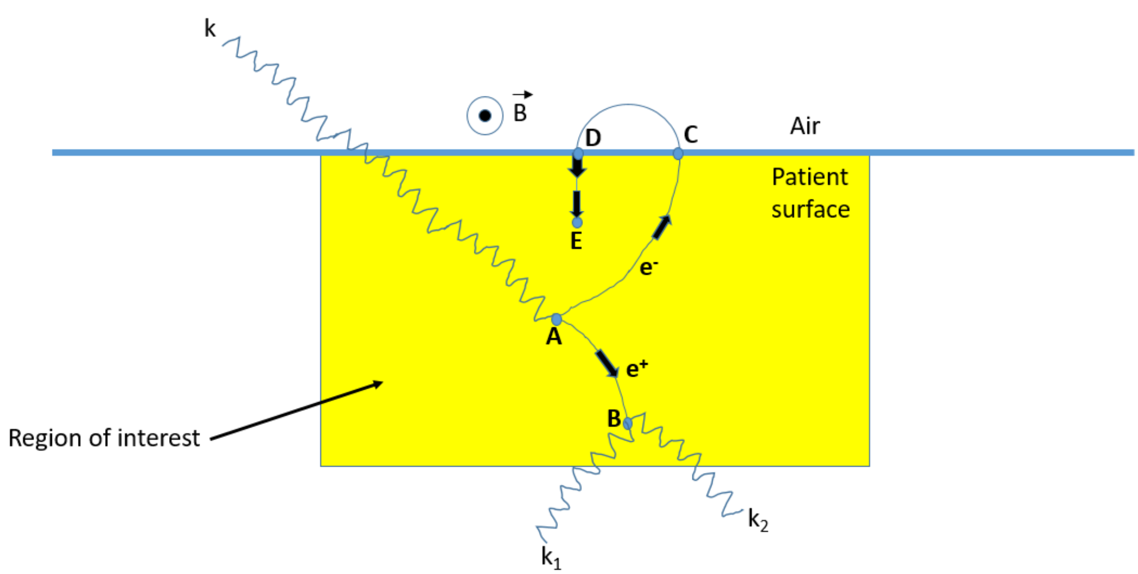
A patient receives radiation therapy on a Magnetic Resonance Linear Accelerator (MR Linac). For this purpose, a photon beam is delivered in the presence of a magnetic field **B** with an intensity of 1.0 T.

The figure below shows a small region of interest close to the interface between the patient surface and air. The magnetic field is perpendicular to the plane of the figure.

A photon *k*, with an energy of 9.022 MeV, enters the region of interest and undergoes pair production at point A. Assume that the electron and the positron acquire equal kinetic energies.

The positron expends half of its initial kinetic energy before undergoing annihilation in flight at point B, where it gives rise to two photons (k_1 and k_2) that leave the region without further interaction.

The electron loses 2.978 MeV of its energy through many local interactions along its path from point A to point C, where it leaves the patient volume (perpendicular to both the patient surface and the magnetic field). However, due to the 'return effect' of the magnetic field, it re-enters the patient at point D and eventually loses all of its remaining kinetic energy on the path from D to E.



Period 1: Question 3

Questions:

1.) Calculate the combined energy carried away from this region by photons k_1 and k_2. (10 Marks)

2.) In reference to the ICRU definitions of fundamental dosimetric quantities, calculate the *energy transferred*, the *net energy transferred* and the *energy imparted* to the region of interest? (10 Marks)

3.) Assuming that there are no electron interactions in air, calculate the distance from C to D. (Treat the problem relativistically, i.e. considering that the kinetic energy of the electron is the difference between the total energy and the rest energy.) (10 Marks)

4.) In the continuous slow-down approximation, estimate the path length from D to E. (10 Marks)

Useful information:

Conversion factor from MeV to J	1 MeV = 1.602 x 10^{-13} J
Rest energy of electron	0.511 MeV
Speed of light	3 x10^{8} m/s
Charge of electron	1.602 x 10^{-19} C
Rest mass of electron	9.1 x 10^{-31} Kg

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Do not write your name on your exam papers. Instead, write your student number on each page. This will allow us to grade the exams anonymously. We'll match your name with your student number after we finish grading.

This portion of the exam has 5 questions. Answer both the first and second question as well as one of the three last 'elective' questions. Do not submit answers to more than 3 questions—if you do, only the first 3 of the questions you attempt will be graded. If you attempt a question and then decide you don't want to it count, clearly cross it out and write "don't grade".

You have 2.25 hours to complete 3 questions.

You are allowed to use your own formula sheet, and a handheld, non-graphing calculator.

Period 2: Question 1 – you must answer this question

Question 1 (40marks)

Part A: What are the biological effects of ionizing radiation? In diagnostic imaging, which effects are more likely and why?

Part B: How can the dose to the patient be managed/reduced in mammography? Why is dose reduction important in this modality?

Part C: Describe in detail the different types of interactions that occur when an electron beam interacts with a tungsten target. Draw the resulting distribution of x-rays produced.

Period 2: Question 2 – you must answer this question

Question 2: (40marks)

Part A:

A regular lung cancer treatment schedule prescribes a total dose of 70 Gy in 25 fractions. The oncologist wants to reduce the number of delivered fractions to 11 (hypofractionation).

i) What dose should be used for each of the 11 fractions so that similar tumour control is achieved? Assume $\alpha/\beta = 9$ Gy for the tumour and ignore repopulation.

ii) How would your result change (qualitatively) if repopulation was a concern and why?

Part B:

The alpha/beta ratio is a useful parameter in a commonly used model describing radiation damage to tissue. One method to determining this parameter is to use data from clinical trials of different dose-fractionation schedules that show equal effect on the tissue of interest. One such set of trials is the following:

Trial A: 25 fractions of a total dose of 50Gy (i.e. 2Gy per fraction)
Trial B: 35 fractions of a total dose of 55 Gy (i.e. 1.571 Gy per fraction)
And
Trial C: 22 fractions of a total dose of 48.4Gy (i.e. 2.2 Gy per fraction)

Determine a numerical value of the alpha/beta ratio for the tissue that received a similar amount of damage in these three different trials A, B, and C.

Period 2: Question: Biomedical Optics Elective – chose ONE of the elective questions

Electives Question Biomed Optics (40marks)

Diagnosis:

Optical coherence tomography (OCT) and confocal microscopy are two promising diagnostic imaging tools for realizing "optical biopsy". Compare their capabilities for tissue imaging by completing the following table. Provide a brief explanation to support your answers.

Imaging mode	**OCT**	**Confocal**
Typical spatial resolution		
Usual direction of sectioning (perpendicular or parallel to tissue surface)		
Typical imaging depth (How deep can it image into the tissue?)		
Origin of imaging contrast (elastic scattering, Raman scattering, absorption, or fluorescence)		

Therapy:

Selective photothermolysis is the basis of many skin laser therapies.

(a) Describe the three basic requirements for using "selective photothermolysis" to successfully treat a skin disease.

(b) What are the target chromophores, and why, for laser hair removal and port wine stain treatment respectively?

Electives Question MRI (40marks)

Part A: Consider the following experiment. A sample with thermal equilibrium magnetization $\mathbf{M_0}$ is excited by a short 90° RF pulse. Right after the excitation, the sample has initial transverse and longitudinal magnetization components $M_T(0) = M_0$ and $M_Z(0) = 0$. Assume that magnetization relaxes towards $\mathbf{M_0}$ exponentially at rates T_1 and T_2 for longitudinal M_Z and transverse M_T components, respectively.

Write down the individual components and overall magnitude of the 3D magnetization vector as a function of time $|\mathbf{M}(t)|$.

Part B: It can be seen that if T_2 is very large compared to T_1, our theory predicts an unrealistic situation where the magnetization for repeated RF pulses is larger than the equilibrium magnetization magnitude.

i) Prove that for realistic samples satisfying $T_2 \leq T_1$ there is no amplification of the magnetization vector in the above experiment.

ii) Prove that an even less strict requirement: If $T_2 \leq 2T_1$ is satisfied, there is no "amplification" as well.

Period 2: Question: Nuclear Medicine Elective – chose ONE of the elective questions

<u>Electives Question NucMed (scaled to 40marks)</u>

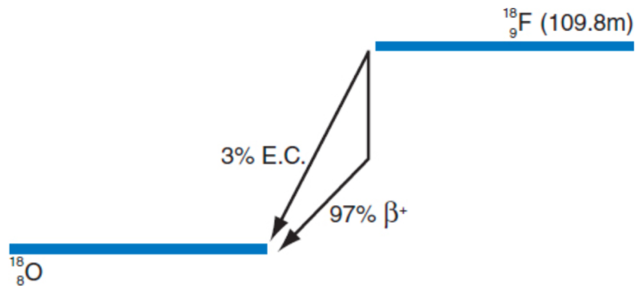
1. A sample contains 1.0 GBq of Strontium-90 (t_1/2= 29a) and 0.62 GBq of Yttrium-90 (t_1/2=64h).
    a. Which total activity can be found in the sample 10 days later? (2 points)
    b. Which total activity can be found in the sample 29 years later? (2 points)
2. Radiation protection is very important for people working with radioactivity. Consider the following examples and choose which one leads to smaller radiation exposure. Estimate the relative radiation exposures between the two examples. (4 points)

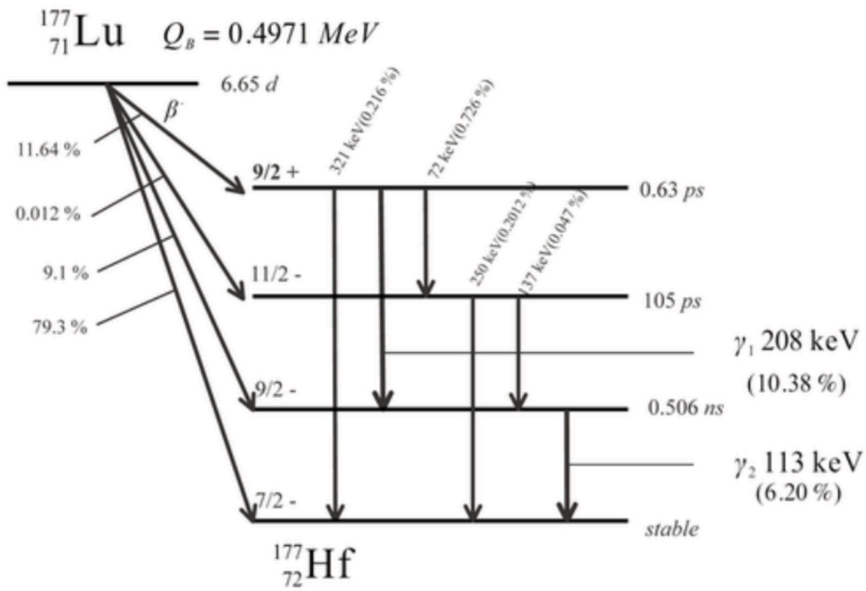
    i) A person is holding a syringe with Yttrium-90 directly in the hand (distance 1cm) but works fast with 1 minute duration.

    ii) A person uses a pincer to work with a syringe of Yttrium-90 (distance 10 cm) but is slow with approximately 2 minutes working duration.
3. To use for therapy or not:
    a. Consider 18F-FDG which is used widely for imaging. What particle does this radiopharmaceutical emit before production of gamma rays? (1 point)
    b. Below is an image of FDG where tumors are shown. Why shouldn't we simply massively increase the amount of injected radioactivity for this patient to treat him/her using those particles? (2 points)

    c. Consider the following decay schemes for F-18 and for Lu-177, the latter being used frequently for radiopharmaceutical therapy (note that for F-18 nearly any emitted beta+ leads to gamma emissions). Given the frequency of emissions, mention a reason why therapy using F-18 may be an issue, unlike Lu-177, for safe, local targeting of tumors. (2 points)

Period 2: Question: Nuclear Medicine Elective – chose ONE of the elective questions





d. The tumor to background ratio of uptake by a radiopharmaceutical can significantly increase over time. Given this point, mention yet another reason why using F-18 for therapy may not be as effective as Lu-177 for therapy. (2 points)

4. Generators:

a) In a generator we have at least three species: parent, daughter, granddaughter. Assume the decay constant for these species are λ_p, λ_d, λ_g, and derive the formulas describing the activity of parent and daughter from ordinary differential equations. Consider the initial values of parent species to be N_0, and the initial values of daughter and granddaughter species to be zero. (4 points)

b) Consider the half-life of parent species to be longer than the daughter's half-life. What is the relationship between time at which activity of daughter is maximized, and time at which it becomes equal to parent radioactivity? Make an example plot for both parent and daughter activities over time. (4 points)

c) Consider the half-life of parent species to be much longer compared to the daughter's half-life. What approximate formulas do you arrive at? Make an example plot for both activities over time. (2 points)

d) Imagine a hypothetical scenario (never done in practice) where the half-life of parent species is much smaller compared to the daughter's half-life. What approximate equations and plot do you arrive at? (2 points)

5. In this question, we aim to understand the dissociation rate of radiopharmaceuticals. In radiopharmaceutical therapy we target the tumor cells with radiolabeled peptides; e.g. in the case of neuroendocrine tumors, tumor cells express high levels of sstr2 receptors which can be targeted using radiolabeled DOTATATE peptides. Two parameters are used to describe the kinetics of peptides which are k_on and k_off.

$$\frac{dN_f}{dt} = k_{off}N_b - k_{on}N_f$$
$$\frac{dN_b}{dt} = k_{on}N_f - k_{off}N_b$$

where N_f is the number of free peptides and N_b is the number of bound peptides. The ratio of K_off/k_on is known as the dissociation rate K_D.

a. Use the following initial conditions and solve the set of differential equations, finding the formulas describing N_f and N_b over time. Evaluate the behavior of the system (values of N_f and N_b) when time goes to infinity. (4 points)

$$N_f(0) = n_f$$
$$N_b(0) = n_b$$

b. Another alternative to evaluate the behavior of a system when time goes to infinity is by using statistical physics. In this case we want to use Boltzmann statistics for our analysis. According to Boltzmann statistics, the probability of finding a system (at a thermal equilibrium with a reservoir with temperature T) at state "s" is equal to:

$$P(s) = \frac{e^{-E(s)/K_BT}}{\sum_i (e^{-E(s_i)/K_BT})}$$

where "T" is the temperature of the reservoir (body in this case), K_B is Boltzmann constant, E(s) is the energy of system at state "s", and sigma in denominator is the sum over all states. Suppose that the energy of receptor-peptide complex (bound) is zero and the energy of a free, unbound peptide is ε (epsilon). By assuming that there are only two possible states (free and bound) for peptide, calculate the steady state probability of P(bound) and P(free). (4 points)

c. Compare your results in part "b" with your results in part "a" (the behaviour of system at t=inf). What is the equation for K_D that we can deduce by comparing these two results? (2 points)