Physics 210
Medical Physics
Midterm Exam
Winter 2016
February 12, 2016

Name___________________________

Problem 1	/24
Problem 2	/24
Problem 3	/24
Total	/76

For the exam, you may use your notes, any Power Point slides you'd like and your textbook. You may not use old exams, homework solutions or use worked out solutions to problems.

I affirm that I have carried out my academic endeavors with full academic honesty.

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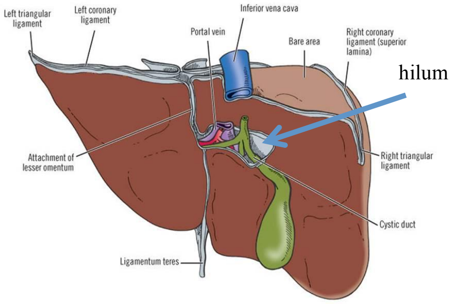
Signature

1. *Neuroblastoma* is the most common extracranial (outside of the skull) solid cancer in childhood and is the most common cancer in infancy, with an incidence of about 650 cases per year in the U.S. and 100 cases per year in the UK. Nearly half of *neuroblastoma* cases occur in children younger than two years. It most frequently originates in one of the adrenal glands (which sit atop of each of the kidneys), but can also develop in nerve tissues in the neck, chest, and abdomen.

   Neuroblastomas are one of the few human malignancies (cancers) known to demonstrate spontaneous regression from an undifferentiated state to a completely benign cellular appearance. Meaning that they can spontaneously cure themselves. It is a disease exhibiting extreme heterogeneity (diversity), and is classified into three risk categories: low, intermediate, and high risk. Low-risk disease is most common in infants and good outcomes are common with observation only or surgery, whereas high-risk disease is difficult to treat successfully even with the most intensive multi-modal therapies available.

   Consider the case below in which a two-year old child presented with a palpable (able to be felt by touching with the hand on the outside surface) abdominal mass. The child subsequently had a series of ultrasound scans (one of which is shown below) that showed an abnormal calcified mass in the liver hilum and the subsequent diagnosis of *neuroblastoma* was confirmed. In human anatomy, the *hilum* is a depression or fissure where structures such as blood vessels and nerves enter an organ.



Skandalakis JE, Colborn GL, Weidman TA, et al: *Skandalakis' Surgical Anatomy*: http://www.accesssurgery.com

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Figure 1: Schematic of the human liver showing the major parts including the hilum in the center. https://www.studyblue.com/notes/note/n/liver-gb-biliary-/deck/7417042

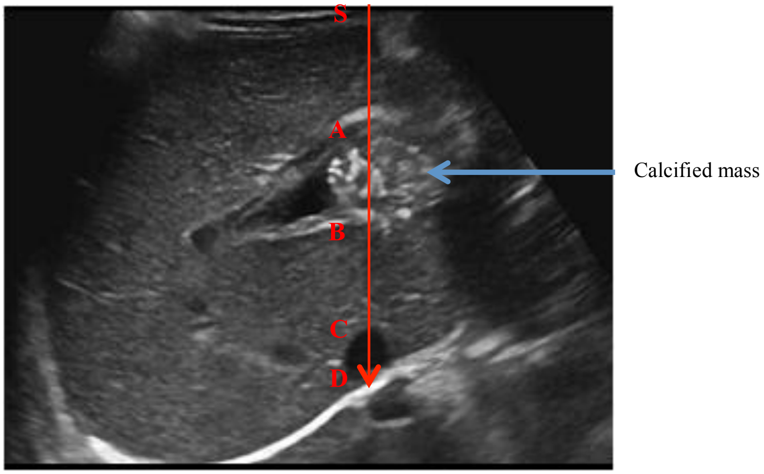


Figure 2: US image of a calcified mass (neurobalstoma) in the liver of a 2-year-old child. http://www.ultrasoundcases.info/Monthly-Case.aspx?month=269&show=1

   a. Using the data in the table below and approximating the mass as uniform and spherical, approximately what is the diameter of the mass?

Location	Arrival time for sound (μs)
S→A→S	13.0
S→B→S	15.4
S→C→S	25.2
S→D→S	27.5

$$t_{AS} = \frac{13\mu s}{2} = 6.5\mu s$$

$$t_{AS} = \frac{15.4\mu s}{2} = 7.7\mu s$$

$$v = \frac{d_{mass}}{\Delta t} \rightarrow d_{mass} = v\Delta t = 4080\,\tfrac{m}{s} \times \left(7.7\mu s - 6.5\mu s\right)$$

$$d_{mass} = 0.0049 = 4.9mm \sim 0.5cm$$

b. What would an approximate A mode scan look like if you were to scan along the RED arrow starting at S and ending at D in figure 2?

c. Suppose that $1MHz$ US waves were incident on the upper surface of the calcified mass (labeled A) with an intensity $I_{incident}$ what would be the reflected intensity at point B? Express your answer in terms of $I_{incident}$. (Hints: 1. Assume that the material surrounding the calcified mass to be fat. 2. Determine what gets transmitted into the mass first.)

Incident @ A:
$$I_{refl} = I_{inc}\left(\frac{z_{calc}-z_{fat}}{z_{calc}+z_{fat}}\right)^2 = I_{inc}\left(\frac{4.7-1.4}{4.7+1.4}\right)^2 = 0.293 I_{inc} \rightarrow 29.3\%\ \text{Reflected}$$

$$\mathrm{I}_{trans} = I_{inc} - 0.293 I_{inc} = 0.707 I_{inc} \rightarrow 70.7\%\ \text{Transmitted}$$

In the mass we lose (by the chart) $20\,\tfrac{dB}{cm} \times 0.5cm = 10dB$.

This translates to an intensity loss by:

$$dB_{loss} = -10\log\left(\frac{I_B}{I_A}\right) \rightarrow I_B = I_A 10^{-\frac{dB_{loss}}{10}} = \left(0.707 I_{inc}\right)10^{-\frac{10}{10}} = 0.0707 I_{inc}.$$

Lastly, the intensity reflected at B:

$$I_{refl@B} = I_{inc,B}\left(\frac{z_{calc}-z_{fat}}{z_{calc}+z_{fat}}\right)^2 = 0.0707 I_{inc}\left(\frac{4.7-1.4}{4.7+1.4}\right)^2 = 0.293\left(0.0707 I_{inc}\right) \rightarrow 2.1\%\ \text{Reflected}$$

d. There are several treatment options available to treat neuroblastoma. They include surgery to remove the tumor, chemotherapy (treatment of the tumor by using anti-cancer drugs), radiation therapy (using external sources of radiation, x-rays say, or nuclear techniques to eradicate the tumor,) or some combination of the above. If you were a surgeon what things might you have to worry about in choosing one of these procedures? Be as specific as possible.

- Dose of radiation to the patient – worry about their age (young) and the fact that it could be a dose of ionizing radiation.
- Tolerance to the chemotherapy drugs (age and health of the person)
- Tolerance to surgery
- Location of mass in hilum – blood vessels run through there and delicate surgery.

2. Bronchoscopy is a procedure in which a bronchoscope is inserted through the nose or mouth and snaked down the trachea into one of the two main branches of the bronchi. Suppose that you have the three pictures shown below in figure 4. The picture on the left is cartoon image to show the main parts and path of the bronchoscope. The middle image is a cadaver dissection to show the right and left main bronchi (the left is in blue). The right most image shows the result of a bronchoscopic procedure in which there is a foreign object lodged in the left main bronchus. This image was from a child who inhaled an object and the image shows the subsequent surrounding inflammation and mucous secretions. Suppose that your bronchoscope is optical scope with core and cladding of the optical fiber are made out of thin borosilicate glass with the index of refraction of the core $n_{core} = 1.49$ and cladding $n_{cladding} = 1.38$. Light is incident from air onto the front surface of the scope at an angle of $\theta = 25^0$ with respect to the normal to the surface as shown in figure 5.

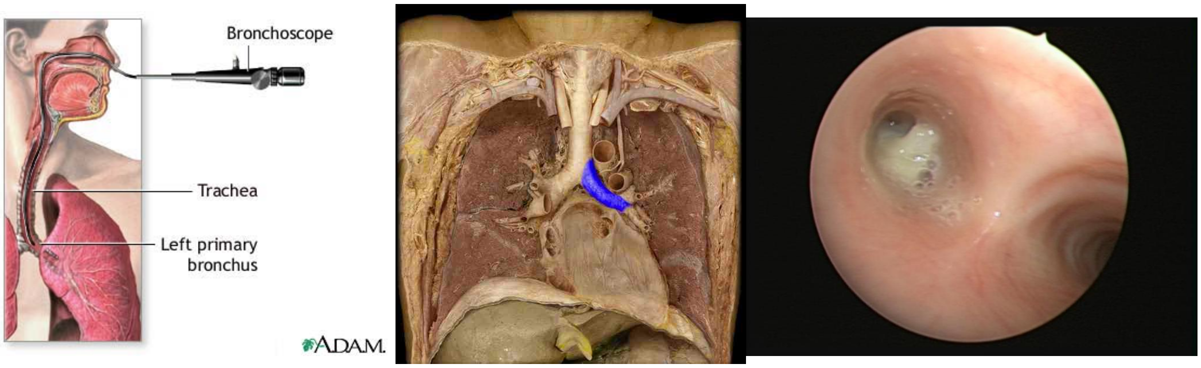


Figure 4: Cartoon diagram showing a basic setup for a bronchoscopy exam, a cadaver dissection showing the left main bronchus (in blue) and an actual bronchoscope image showing a foreign object lodged in the left main bronchus. Left image: http://www.healthcentral.com/encyclopedia/adam/bronchoscopy-4020401/; middle image: https://www.studyblue.com/notes/note/n/chapter-19-respiratory-system/deck/777231, right image: http://basicsofpediatricanesthesia.com/22-fb-left-main-bronchus/

a. Assuming that you have a single wavelength of light, what is the angle of refraction for light in the core? Will the light be totally internally reflected in the scope? If the light were not totally internally reflected in the scope, would you have to increase or decrease the angle of incidence (from $\theta = 25^0$) on the front surface of the scope?

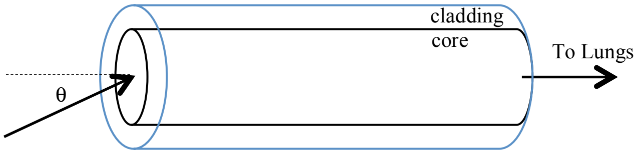


Figure 5: Schematic of the bronchoscope used to view the lungs.

At the front interface: $n_{air}\sin\theta = n_{core}\sin\theta_{core} \rightarrow 1.00\sin 25 = 1.49\sin\theta_{core} \rightarrow \theta_{core} = 16.5^o$

At the upper surface between the core and cladding the light strikes at:

$\theta_{inc,top} = 90^o - \theta_{core} = 90^o - 16.5^o = 73.5^o$.

For total internal reflection we need the critical angle:

$$n_{core}\sin\theta_{crit} = n_{cladding}\sin 90 \rightarrow \theta_{crit} = \sin^{-1}\left(\frac{1.38}{1.49}\right) = 67.9^o$$

Since the light is incident at an angle on the upper surface at an angle larger than the critical angle, the light will be totally internally reflected.

b. What is the critical angle between the core/cladding for light in the scope?

The critical angle: $n_{core}\sin\theta_{crit} = n_{cladding}\sin 90 \rightarrow \theta_{crit} = \sin^{-1}\left(\frac{1.38}{1.49}\right) = 67.9^{o}$

c. Suppose that on your bronchoscope there is a small tool used for the removal of the foreign object. After removal of the object, there is a small tear in the bronchus that was produced. Suppose that you wanted to cauterize the tear with a laser. Which laser(s) would you use for the treatment and why?

Since the tear probably is bleeding we want a to use a laser that will be absorbed by the blood and cauterize the wound. From the book possible lasers would include the Argon Laser ($\lambda = 488nm \,\&\, 514nm$), or perhaps the Dye laser ($\lambda = 577nm$).

d. Suppose that you were to use a laser that has a power output of $25\frac{W}{cm^2}$. If this laser were incident on a portion of the tear for $5s$, would you be able to cauterize (burn) a $0.5cm^2$ piece of tissue? If not, what change(s) could you make so that you could cauterize the tear? (Hint: To cauterize the tissue, you must get the tissue's temperature to rise to 48^0C (from http://www.nist.gov/fire/fire_behavior.cfm) from its initial temperature taken to be 37^0C (normal body temperature). The energy in the tissue shows up as heat and the amount of heat is given as $heat = mc\Delta T = \left(4.19\frac{J}{^0C}\right)\Delta T$, for a $1g$ mass of tissue that say, you want to heat.)

The intensity: $I = \frac{E}{tA} \rightarrow E = ItA = \left(25\frac{W}{cm^2}\right)\times(5s)\times\left(0.5cm^2\right) = 62.5J$.

The energy translates to an increase in temperature:

$E = mc\Delta T \rightarrow \Delta T = \frac{E}{mc} = \frac{62.5J}{4.19\frac{J}{^0C}} = 14.9^0C$.

To cauterize the wound we need a change in temperature of at least $\Delta T = 48^{o}C - 37^{o}C = 11^{o}C$ and out temperature change is above this so the wound would most likely be cauterized.

3. Breast cancer is a disease in which malignant (cancer) cells form in the tissues of the breast. The damaged cells can invade surrounding tissue, but with early detection and treatment, most people continue a normal life. One in eight women will be diagnosed with breast cancer in her lifetime. Breast cancer is the most commonly diagnosed cancer in women and is the second leading cause of cancer death among women. Each year it is estimated that over 230,000 women in the United States will be diagnosed with breast cancer and more than 40,000 will die. Although breast cancer in men is rare, an estimated 2,350 men will be diagnosed with breast cancer and approximately 440 will die each year. Over 2.9 million breast cancer survivors are alive in the United States today. (Facts from http://www.nationalbreastcancer.org/breast-cancer-facts.)

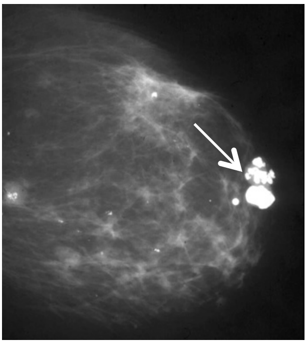
    a. Suppose that a patient has come to your office with concerns over a lump they found in their breast. You want to be able to tell the difference between a micro-calcification (the suspected breast cancer) and say just adipose or fatty tissue. To try to tell the difference we'll calculate the intensity of x-rays that pass through each type of tissue. Suppose that you have x-rays with intensity I_0 of incident on a $1mm$ thick piece of fatty tissue and a $1mm$ thick micro-calcification. What are the intensities of the x-ray beams that emerge in each case?

    Microcalcification: $I_{\mu calcification} = I_o e^{-\mu_\mu x_\mu} = I_o e^{-(23cm^{-1})(0.1cm)} = 0.1 I_o$

    Fat: $I_{fat} = I_o e^{-\mu_{fat} x_{fat}} = I_o e^{-(0.5677cm^{-1})(0.1cm)} = 0.95 I_o$

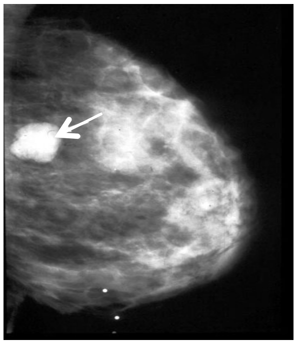
    b. Examine the two images (A and B) below. Both are CT images of the female breast. Based on your answer to part a, which image do you think corresponds to the micro-calcification and which corresponds to adipose tissue? The arrows in the images point to the suspects. Justify your answer. (Hint: Think about what more absorbing means in terms of Hounsfield Units.)

A



http://www.meddean.luc.edu/lumen/meded/radio/curriculum/surgery/mammography1.htm

B



http://www.meddean.luc.edu/lumen/meded/radio/curriculum/surgery/mammography1.htm

Based on the Hounsfield Unit, the more absorbing structure appears brighter. Based on part A, the microcalcification is more absorbing than adipose tissue, to the microcalcification would appear brighter on the CT scan. Thus image A would be the microcalcification and image B would be the adipose tissue.

c. For mammography studies one generally uses a molybdenum anode operated at a potential of $30kV$ the characteristic spectrum of which is shown below. The principle K_α line of molybdenum is approximately $17keV = 2.7\times10^{-15}J$. How many photons are produced every second from the anode (of area $7.85\times10^{-3}m^2$) if approximately 1% of the incident electrons actually produce x-ray photons and what total energy associated with these photons is produced every second? The current from the CT scan is $I = 376mA = 376\times10^{-3}\,\tfrac{C}{s}$ and the current is given as $I = \dfrac{\Delta Q}{\Delta t}$, where each electron has $1e^- = 1.6\times10^{-19}C$ of charge.

$I = \dfrac{\Delta Q}{\Delta t} = \dfrac{N_e e}{\Delta t} \rightarrow \dfrac{N_e}{\Delta t} = \dfrac{I}{e} = \dfrac{376\times10^{-3}A}{1.6\times10^{-19}C} = 2.35\times10^{18}\,\tfrac{e}{s}$ and if only 1% efficient, then this corresponds to $\dfrac{N_{photons}}{s} = 1\%\dfrac{N_{electrons}}{s} = 0.01\times2.35\times10^{18}\,\tfrac{e}{s} = 2.35\times10^{16}\,\tfrac{photons}{s}$ photons.

And this corresponds to a total energy per second of:

$$\frac{E_{total}}{s} = 2.35\times10^{16}\,\tfrac{photons}{s}\times\frac{2.7\times10^{-15}J}{photon} = 63.5\,\tfrac{J}{s} = 63.5W$$

d. We've said in class that you'd really like x-ray detectors that are small in size and have a fast response time. Assuming that you can manufacture x-ray detectors with increasingly smaller detector size, does this mean that you can continue to increase the spatial resolutions indefinitely? Is there a limit to the spatial resolutions that you can achieve? Explain your answer fully.

The feature size that you can image is on the order of the wavelength of the light used. Thus the smaller the detectors are size the finer the features you can image in theory. However, in practice you are limited by the wavelength of the x-ray no matter how small you make the detector. So yes there is a limit to the spatial resolution you can make (it's the wavelength of the x-rays you're using) no matter how small you can make your detector.

Material	Speed (m/s)	Z ($x10^6 kg/m^2 s$)	μ (cm^{-1})	US intensity loss (dB/cm)
Air	343	0.0004	0.001	12
Blood	1570	1.6	0.885	0.15
Bone	3500	7.8	7.6	14.2
Calcium Deposit	4080	4.7	23	20
Fat	1460	1.4	0.568	0.6
Water	1480	1.5	0.810	0.0022
Muscle	1580	2.2	0.853	1.4

Table 1: Speeds of sound, acoustic impedance, x-ray attenuation coefficients (at 30keV), and US intensity loss in various materials. Values are taken from http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html, http://www.nist.gov/pml/data/xraycoef/, and Physics of Radiology, 2nd Ed., Anthony Wolbarst, p120.