Physics 210
Medical Physics
Midterm Exam
Winter 2017
February 10, 2017

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. *Ultrasound in the Treatment of Blood Clots*

Blood clotting, or coagulation, is an important process that prevents excessive bleeding when a blood vessel is injured. Platelets (a type of blood cell) in your blood and proteins in your plasma (the liquid part of blood) work together to stop the bleeding by forming a clot over the injury. Typically, your body will naturally dissolve the blood clot after the injury has healed. Sometimes, however, clots form on the inside of vessels without an obvious injury or do not dissolve naturally. These situations can be dangerous and require accurate diagnosis and appropriate treatment.

Deep Vein Thrombosis is a medical condition in which a blood clot forms in a vein deep in the body, mostly in the lower leg or thigh, as shown in the Figure #1 on the right. Clots form for many reasons in these veins and most often they occur in the *popliteal vein*. A blood clot in a deep vein can break off and travel through the bloodstream. *Ultrasound-accelerated thrombolysis* (the removal of the blood clot) involves the breaking down of blood clots that can form in the leg arteries or veins using ultrasound. Ultrasound-accelerated thrombolysis uses ultrasound energy to help accelerate the process of thrombolysis by breaking up the clot so the blood can flow freely. The procedure involves making an incision in the leg and a catheter is inserted into the vein containing the clot.

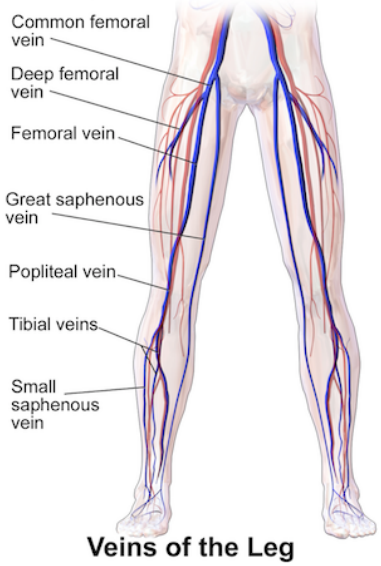


Figure #1: A schematic showing the major veins in the leg. https://en.wikipedia.org/wiki/Posterior_tibial_vein

Consider the image on left in Figure #2 which is a Doppler ultrasound scan of a blood clot in a vein and subsequent flow of blood around the clot. A rather invasive procedure to remove the clot can be performed in which an ultrasonic catheter is inserted into the vein and the ultrasonic catheter is designed to break up the blood clot using sound waves. A cartoon diagram of an ultrasonic catheter is shown on the right in Figure #3 below.

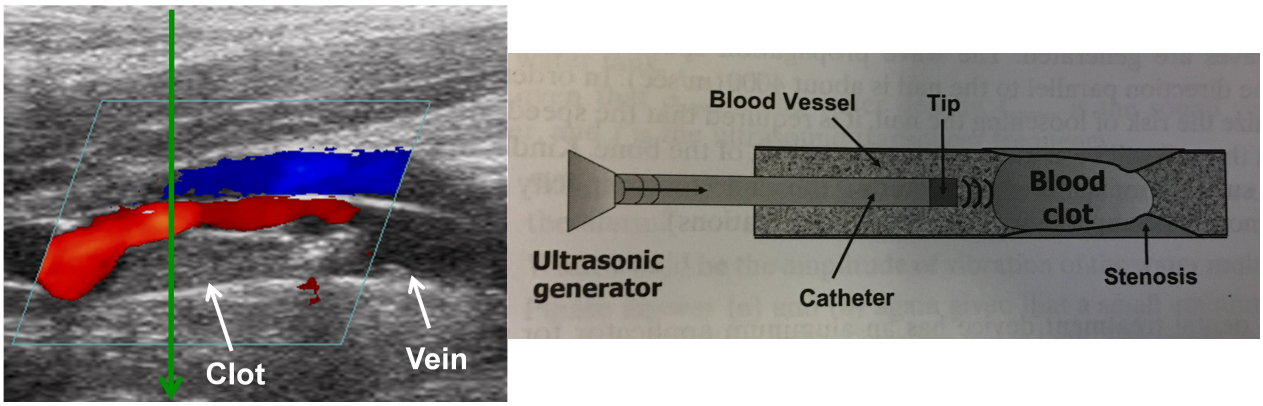


Figure #2: On the left is a Doppler US image of a blood clot, while on the right is a schematic of an intravenous device used to bread up the blood clot in the vein. Photograph on the lefthttps://www.nibib.nih.gov/news-events/newsroom/ultrasound-therapy-breaks-blood-clots and the schematic on the right *Basics of Biomedical Ultrasound for Engineers*, H. Azhari, Wiley, 2010, p. 319.

a. Suppose that $1MHz$ US waves were incident on the clot from the left towards the right with an intensity of $I_{incident} = 100\frac{W}{cm^2}$. Using data from the table #1 below, determine the reflected and transmitted intensities of the ultrasound pulse for the ultrasound waves incident on the left surface of the blood-clot interface?

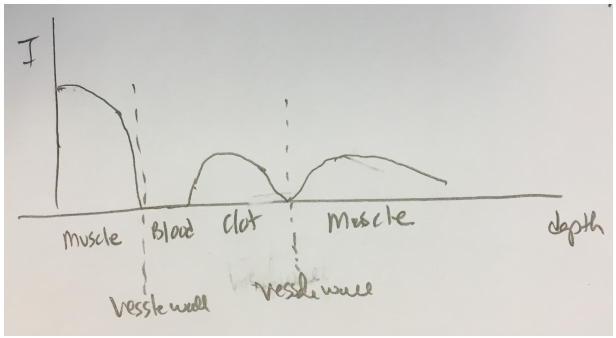
Substance	$Z\left(\frac{kg}{m^2 \cdot s}\right)$	$v\left(\frac{m}{s}\right)$	$\rho\left(\frac{kg}{m^3}\right)$
Blood	1.66×10^6	1566	1060
Clot	1.33×10^6	1466	920

Table #1: Some useful data for blood and the blood clot.

$$I_R = I_{incident}\left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = I_{incident}\left(\frac{1.66-1.33}{1.66+1.33}\right) = 0.012 I_{incident} = 1.2\frac{W}{cm^2}$$

$$I_T = I_{incident} - I_R = 100\frac{W}{cm^2} - 1.2\frac{W}{cm^2} = 98.8\frac{W}{cm^2}$$

b. Along the green line shown in the US scan in figure #2, what would an approximate A-mode US scan look like if your US scanner were located at the top of the figure and you listened along the direction of the red arrow. The vertical heights on your scan can be approximate, but they should be representative of the major structures seen as well as their approximate location. Be sure to label the structures in your diagram along the depth axis.



c. *Histotripsy* (from the Greek "*histo*" meaning soft tissue and "*tripsy*" meaning breakdown) is a new and novel technique being developed that uses a number of short (several μsec), high intensity ultrasound pulses to achieve mechanical fractionation of tissue, in this case blood clots. The ultrasound intensity used in *histotripsy* is hundreds of times higher than regular diagnostic imaging and similar to *"shock wave lithotripsy"* which is used for breaking kidney stones. At a fluid-tissue interface, here at the blood-clot interface, *histotripsy* results in localized tissue removal with sharp boundaries. In bulk tissue, *histotripsy* produces mechanical fragmentation of tissue resulting in a liquefied tissue. Histological studies demonstrate that treated tissue within the lesion is fragmented to subcellular level surrounded by an almost imperceptibly narrow margin of cellular injury. In other words the high intensity, short-pulsed US beams can create a well-defined region of damage. The idea behind *histotripsy* is to create microbubbles (cavitation) in the blood to breakup the clot using high intensity ultrasound on the outside surface of the patient. Explain, using full sentences and in as much detail as you can, why you think *histotripsy* might be a better/worse technique than the intravenous ultrasonic catheter.
(http://www.histotripsy.umich.edu/)

Advantages:	External to the patient and thus much less invasive. Less chance of vein collapse or injury Less risk of infection. Generally don't have to tolerate an surgery.
Disadvantages:	Create bubbles in the vein that could travel to the heart or brain. Need a very high intensity US wave –damage to surrounding tissue. Clot may not fully break up or may break up into large pieces.

2. *CT Imaging of Epidural Hematomas*

An *Epidural hematoma* is blood that pools between the skull and the brain's tissue-like covering, called the *dura*. *Epidural hematomas* are usually caused by a full-on blow to the head and are often associated with a skull fracture and diagnosis is usually made via a MRI or CT scan. Consider the axial CT image shown in Figure #3 of an epidural hematoma indicated by the yellow arrows.

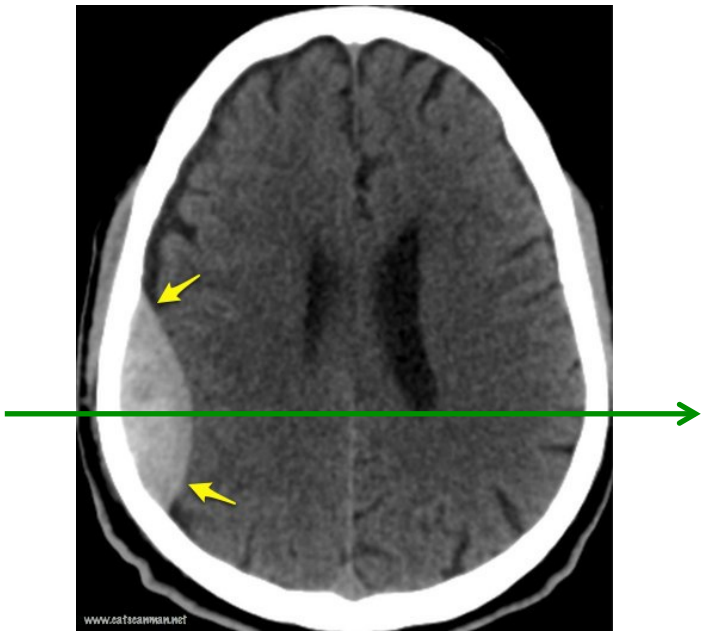


Figure #3: CT image of an *epidural hematoma*. https://medmnemonics.wordpress.com/2011/03/31/epidural-haematoma-findings-2/

a. CT scanners generally employ either a platinum or tungsten anode that us used to generate the x-rays for the scan. Consider a system in which a tungsten anode is used and is operated at a potential of $120kV$. Characteristic x-ray spectra for a tungsten anode operated at different potentials are given in Figure #4, where the principle x-ray lines of the tungsten anode are shown.

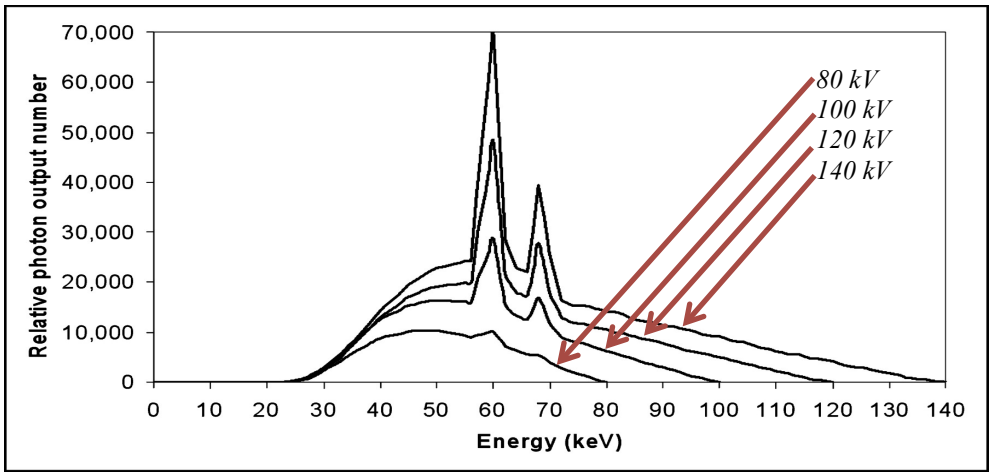


Figure #4: X-ray energy spectra from a tungsten anode tube operated at foour different potentials (voltages.) Low-energy x rays are removed by the use of an aluminum filter. The sharp spikes in the spectrum correspond to the production of characteristic x rays from the tungsten anode. The continuous spectrum arises from bremsstrahlung radiation. Changes in the x-ray tube current, for a given bias voltage, do not change the shape of the spectrum, just the magnitude of the x-ray flux. Thus doubling the tube current doubles the x-ray flux at all energies. http://tech.snmjournals.org/content/32/3/139/F5.expansion.html

How many photons are produced every second from the anode (of area $1.66\times10^{-6}m^2$) if approximately 1% of the incident electrons actually produce x-ray photons and what total energy (in Watts) is associated with these photons is produced every second? The current from the CT scan is $I = 300mA = 300\times10^{-3}\frac{C}{s}$ and the current is given as $I = \frac{\Delta Q}{\Delta t}$, where each electron has $1e^- = 1.6\times10^{-19}C$ of charge. (You may need the fact that $1eV = 1.6\times10^{-19}J$.)

$$I = \frac{\Delta Q}{\Delta t} = \frac{Ne^-}{\Delta t} \rightarrow \frac{N}{t} = \left(\frac{I}{e^-}\right)\times0.01 = \left(\frac{300\times10^{-3}\frac{C}{s}}{1.6\times10^{-19}C}\right)\times0.01 = 1.9\times10^{16}\frac{photons}{s}$$

$$Energy = \left(\frac{N}{t}\right)\times E_i = 1.9\times10^{16}\frac{photons}{s}\times\frac{61\times10^3 eV}{photon}\times\frac{1.6\times10^{-19}J}{1eV} = 183W$$

b. Using information from the table #2 below, along the green line in Figure 3, what is the size of the epidural hematoma? Assume that x-rays are incident on the body from the left with an intensity of I_0 and that the x-rays that mare seen on the detector on the right is 4.68% of I_0.

Substance	$\mu_\rho\left(\frac{cm^2}{g}\right)$	$\rho\left(\frac{g}{cm^3}\right)$	$x(cm)$
Blood	0.2057	1.060	?
Brain	0.1974	0.900	10.64
Bone	0.3148	1.850	0.63

Table #2: Some useful data on the human body.

$$\mu = \mu_\rho\rho$$

$$\mu_{bone} = \mu_{\rho,bone}\rho_{bone} = 0.3148\frac{cm^2}{g}\times1.85\frac{g}{cm^3} = 0.581cm^{-1}$$
$$\mu_{brain} = \mu_{\rho,brain}\rho_{brain} = 0.1974\frac{cm^2}{g}\times0.90\frac{g}{cm^3} = 0.178cm^{-1}$$
$$\mu_{blood} = \mu_{\rho,blood}\rho_{blood} = 0.2057\frac{cm^2}{g}\times1.06\frac{g}{cm^3} = 0.218cm^{-1}$$

$$I_{out} = I_o e^{-2\mu_{bone}x_{bone}-\mu_{brain}x_{brain}-\mu_{blood}x_{blood}}$$
$$0.0486I_o = I_o e^{-2\times0.581cm^{-1}\times0.63cm-0.178cm^{-1}\times10.64cm-0.218cm^{-1}x_{blood}}$$
$$\ln(0.04861) = -3.062 = -0.734-1.89-0.218cm^{-1}x_{blood}$$
$$-0.438 = 0.218cm^{-1}x_{blood}$$
$$x_{blood} = 2.0cm$$

c. 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 that have increasingly smaller detector areas, 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.

3. Colonoscopy

Colorectal cancer is the third most common cancer in men and women. Despite a reduction in incidence and mortality over the past two decades from early detection and treatment, an estimated 137,000 new diagnoses and 50,000 deaths were expected in 2014. (https://www.cancer.org/content/dam/cancer-org/research/cancer-facts-and-statistics/colorectal-cancer-facts-and-figures/colorectal-cancer-facts-and-figures-2014-2016.pdf) A colon polyp is a small clump of cells that forms on the lining of the colon. Most colon polyps are harmless. But over time, some colon polyps can develop into colon cancer, which is often fatal when found in its later stages. Anyone can develop colon polyps and you are generally at a higher risk if you're 50 or older, are overweight or a smoker, or have a personal or family history of colon polyps or colon cancer. Colon polyps often don't cause symptoms and it is important to have regular screening tests, such as colonoscopy, because colon polyps found in the early stages can usually be removed safely and completely. The best prevention for colon cancer is regular screening for polyps by getting a colonoscopy. A colonoscopy is a out-patient procedure in which a physician inserts an optical fiber scope, called a colonoscope, into the rectum and then into the colon as shown in Figure #5 below.

There are several types of colon polyps, including:

- *Adenomatous:* About two-thirds of all polyps are adenomatous. Only a small percentage of them actually become cancerous. But nearly all malignant (cancerous) polyps are adenomatous.
- *Serrated:* Depending on their size and location in the colon, serrated polyps may become cancerous. Small serrated polyps in the lower colon, also known as hyperplastic polyps, are rarely malignant. Larger serrated polyps, which are typically flat (sessile), difficult to detect and located in the upper colon are generally precancerous.
- *Inflammatory:* These polyps may follow a bout of ulcerative colitis or Crohn's disease of the colon. Although the polyps themselves are not a significant threat, having ulcerative colitis or Crohn's disease of the colon increases your overall risk of colon cancer.
(http://www.mayoclinic.org/diseases-conditions/colon-polyps/basics/definition/con-20031957)

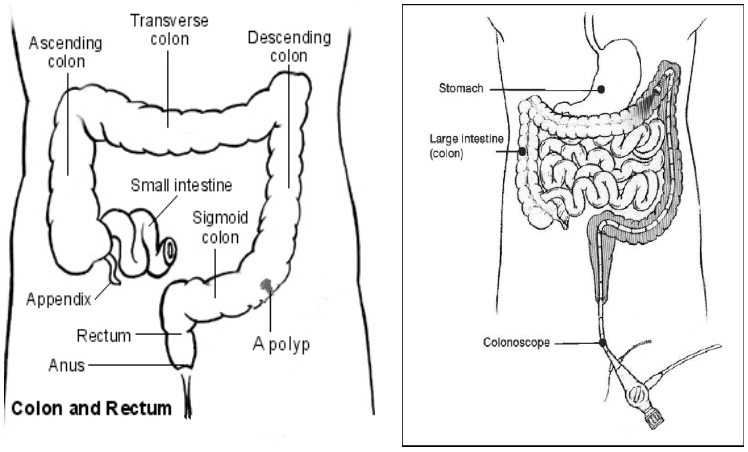


Figure 5: Cartoon diagrams showing the large intestine and the insertion of a colonoscope for a colonoscopy. Left image http://patient.info/health/bowel-colonic-polyps-leaflet and right image https://www.hey.nhs.uk/patient-leaflet/colonoscopy/.

a. Suppose that for your colonoscopy the physician uses a special 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 $\theta = 37^0$ with respect to the normal to the surface as shown in figure 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 $\theta = 37^0$) on the front surface of the colonoscope?

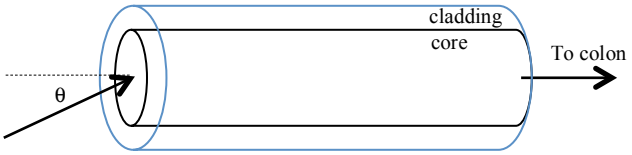


Figure 6: Schematic of the colonoscope used to view the colon and rectum.

At the front interface: $n_{air}\sin\theta = n_{core}\sin\theta_{core} \rightarrow 1.00\sin 37 = 1.49\sin\theta_{core} \rightarrow \theta_{core} = 23.8^o$

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

$\theta_{inc,top} = 90^o - \theta_{core} = 90^o - 23.8^o = 66.2^o$.

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 smaller than the critical angle, the light will not be totally internally reflected. To get total internal reflection we need to increase the angle of incidence on the upper cladding/core interface. This would decrease the angle of refraction between the air/core interface, and thus, we would have to have an angle of incidence on the front surface of the scope in air that is less than $\theta = 37^0$.

b. During a colonoscopy, any polyps seen are generally removed using the colonoscope. An image of a polyp and a schematic of the polyp removal (called a *polypectomy*) are shown in Figure #7. Suppose that on your colonoscope 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 intestine that was produced from the *polypectomy*. Suppose that you wanted to cauterize the tear with a laser. Which laser(s) would you use for the treatment and why?

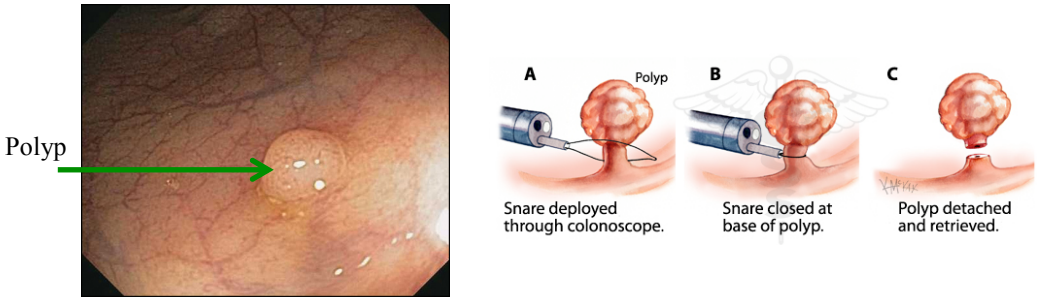


Figure 7: On the left, a photograph of an actual polyp in the large intestine. The polyp is removed using a tool on the colonoscope, a schematic of which is shown on the right. Left photograph: http://www.aafp.org/afp/2015/0115/p93.html, and right image http://colorectalsurgeonssydney.com.au/?page_id=425

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 ($\lambda = 577nm$).

c. Suppose that you were to use a laser that has a power output of $100\frac{W}{cm^2}$. If this laser were incident on a portion of the tear for $0.5s$, would you be able to cauterize (burn) a $1cm^2$ 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 $Heat = mc\Delta T = 4.19\frac{J}{^0C}\Delta T$, for a $0.5mg$ mass of tissue that say, you want to heat.)

Typical colon polyps have a range of sizes with an average size of about $6mm$. Polyps larger than $10mm$ are generally precursors to colon cancer.

The intensity: $I = \dfrac{E}{tA} \rightarrow E = ItA = \left(100\frac{W}{cm^2}\right)\times\left(0.5s\right)\times\left(1cm^2\right) = 50J$.

The energy translates to an increase in temperature: $E = mc\Delta T \rightarrow \Delta T = \dfrac{E}{mc} = \dfrac{50J}{4.19\frac{J}{^0C}} = 11.9^0C$.

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