X-ray Lab

Purpose:

The purpose of this lab is to "expose" students to the basic aspects projection x-ray imaging. Students will measure the dependence of x-ray tube output on kV and mA, and the dependence of the attenuation of materials of different atomic numbers on x-ray energy. We will also measure the amount of scatter detected at various exposure field sizes and object thicknesses. Images will be formed using a digital x-ray flat panel detector.

Background:

Prior to the lab, students should familiarize themselves or review the basic principles of x-ray imaging. Here is a brief summary of important points

For diagnostic x-ray imaging, x-rays are produced in an x-ray tube by bombarding a metal target with electrons. Electrons are accelerated toward the target using an electrostatic potential measured in kilovolts (kV). The number of electrons striking the target per unit time is controlled by the x-ray tube, measured in milliamps (mA). The product of the mA and the exposure time is measured in milliamp-seconds (mAs). X-ray tubes produce x-ray photons in a range of energies or wavelengths. The total intensity and the dose of an x-ray beam is determined by both the number of photons and the distribution of energies. The dose increases linearly with mA and exposure time. In the absence of significant absorption the dose increases approximately as kV^2. With an absorber in the beam exponent in the kV dependence is larger than 2. As the kV increases, the beam has a higher average photon energy and is more penetrating. Figure1 shows schematic x-ray spectra at two values of kV, with a thin and thicker absorber.

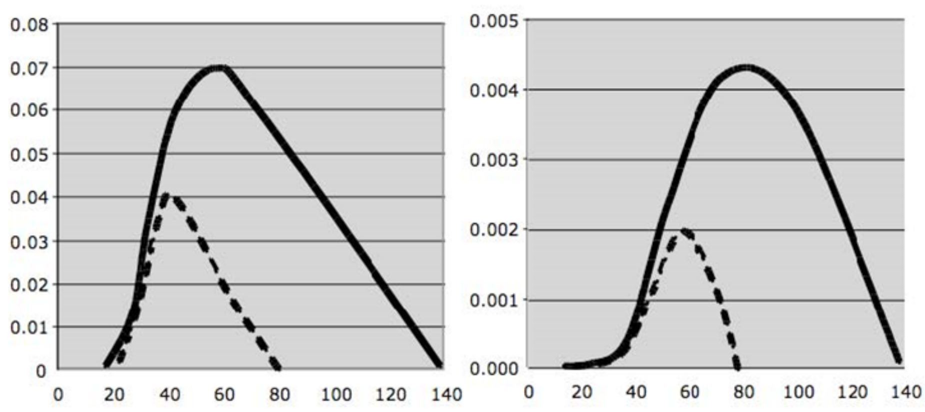


Figure 1: x-ray spectra at 80 kV (dashed) and 140 kV (solid) with a thin (left) and thicker absorber (right, note the different vertical scale). The horizontal axis is x-ray photon energy in keV and the vertical axis is the number of photons with that energy in arbitrary units. Note the shift to higher energies with increasing kV and with increasing absorption. The relative intensity is the area under the spectrum.

For monoenergetic x-rays (i.e., x-rays of the same energy), x-ray attenuation is exponential. The intensity transmitted by a thickness t of some material is

$$I = I_0 exp(-\mu t) \quad [1]$$

where I_o is the incident intensity and μ is the linear attenuation coefficient of the material at the particular energy of the photons, measured in units of cm^{-1}. The attenuation coefficient increases with the density of the material, and generally increases with atomic number and decreases with increasing energy. For the polyenergetic x-ray beams produced by x-ray tubes, the attenuation is not exponential, but can be approximately described by an exponential dependence over a modest range of attenuation as

$$I \sim I_0 exp\left(-\mu_{eff} t\right) \qquad [2]$$

where μ_{eff} is the effective attenuation coefficient. Generally, μ_{eff} is higher for higher atomic number absorbers and is lower at higher kV.

As x-rays travel through material, some are absorbed, some are unaffected and are transmitted unscathed, and some are 'scattered'. In fact, in x-ray transmission through low atomic materials such as plastics and soft tissues, most of the x-rays are scattered, and the scattered photons can reach the detector and contribute to the measured signal. These scattered photons act as a haze and degrade the quality of the images. The total measured intensity T is

$$T = P + S = P(1 + S/P) \qquad [3]$$

where P is the intensity of transmitted primary photons (the photons that penetrated unscathed), S in the intensity of the scattered photons, and S/P is the 'scatter to primary ratio'. S/P increases with the irradiated area and with the thickness of the absorber.

X-ray images have a random noise component. The most fundamental source of noise is the finite number of x-ray photons that contribute to the image. The signal-to-noise ratio of x-ray images is proportional to $\sqrt{N}$, where N is the number of photons per unit area, and therefore proportional to intensity or radiation dose.

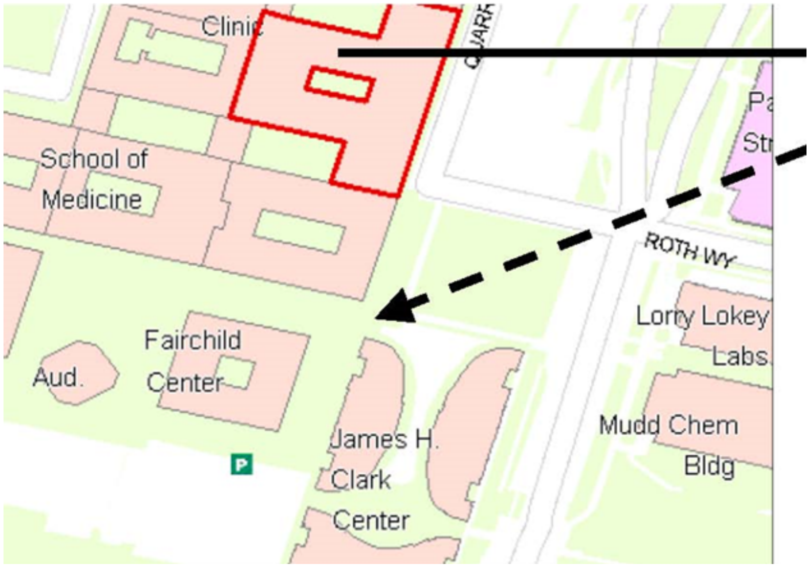
When x-ray images are recorded using a digital x-ray detector, there are imperfections of the detector that have to be corrected. Each pixel has an offset or 'dark current' signal. Also, each pixel may have a different gain (conversion of intensity to signal). One can correct for these effects using a 'dark current' image collected with no x-rays, and a 'flat field' image collected using uniform irradiation as follows:

$$Image = \frac{(L-D)}{(F-D)} \qquad [4]$$

where L is the raw data for the image of interest, D is the dark field image, and F is the flat field image. The resulting image is proportional to the ratio I/I_0 in Eqn. 2. Therefore, the negative logarithm of the image (-ln{Image}) is proportional to the quantity in the exponent of the second equation above. The advantage of a logarithmic image is that the contrast of a lesion is independent of the incident radiation intensity I_0, and therefore independent of whether the lesion is in a region of the image with high x-ray transmission or low x-ray transmission.

Organization of the lab:

The lab is conducted in S-086 in the basement of the Grant building.



The solid arrow is the location of S-086 (in the basement). We will meet at the location of the dashed arrow 10 minutes before the start time of the lab.

1. Equipment

For the methods section, note the brand name and model number of relevant equipment. For all of the measurements, set the distance between the flat-panel detector and the face of the collimator at about 120 cm. For the dose measurements, tape the ion chamber to the face of the flat-panel detector. (To avoid damage, use a gentle tape, not duct tape.)

2. Intensity as a function of kV and mA

Set the collimator blades to cover the ion chamber plus a couple of inches on each side. Use the light on the collimator to verify it. Using the x-ray generator touch-screen, set the x-ray tube current to 100 mA and the exposure length to 500 ms. With nothing between the x-ray source and ionization chamber, take measurements at 60, 80, 100, and 120 kV recording the dose with the RadCal radiation monitor.

Repeat at a fixed 100 kV and 25, 80, 160, and 250 mA.

Place 10 acrylic sheets roughly mid-way between source and ion chamber and repeat the above measurements. Each sheet is about 1.1 mm thick.

To use the radiation monitor, press the *enter* button, turn on the x-ray pulse, wait about 10 seconds (the monitor updates once a second) and then press *enter* again.

kV	mA	exposure time (ms)	acrylic thickness (cm)	dose (Gy)
60	100	500	0	
80	100	500	0	
100	100	500	0	
120	100	500	0	
100	25	500	0	
100	80	500	0	
100	160	500	0	
100	250	500	0	
60	100	500	11	
80	100	500	11	
100	100	500	11	
120	100	500	11	
100	25	500	11	
100	80	500	11	
100	160	500	11	
100	250	500	11	

3. Attenuation of plastic and copper

With the x-ray source at 60 kV, 100 mA, and 500 ms, measure the x-ray dose after attenuation with 0, 2, 6, 8, and 10 sheets of acrylic.

Repeat the measurements with 0, 1, 3, 5, and 7 copper sheets, each 0.1 mm thick.

Repeat the same measurements with the acrylic and copper layers but change the tube voltage to 120 kV and place 2 sheets of copper directly in front of the collimator to filter out the low energy x-rays.

acrylic sheets	acrylic thickness (mm)	dose at 60 kV	dose at 120 kV with filter
0			
2			
6			
8			
10			

copper sheets	copper thickness (mm)	dose at 60 kV	dose at 120 kV with filter
0			
1			
3			
5			
7			

4. Scatter

Set the x-ray source to 100 kV, 100 mA, and 500 msec.

Remove all plastic and copper from the x-ray beam and measure the dose with collimator settings of about 5x5, 10x10, and 15x15 inches at the ion chamber. Make sure the ion chamber is centered in the 5x5 field. For each field size, measure the dose with no acrylic, six sheets and 12 sheets.

field size (in)	dose with no acrylic	dose with 6 sheets	dose with 12 sheets
5x5			
10x10			
15x15			

5. Imaging

Use the Fluoroscopy mode for imaging. Check the settings page of the operator's notebook to see that the exposure time per frame is 13 msec. To obtain the images, go to *ViVA Rev K.05, Build 67DarkField*. Use the acquisition mode *020408 4030CB 2x2 G1 4pF*. Save the images to a folder in the User directory named for the course. Record the image file names below. When 40 frames are obtained, they are saved as a .seq file. The header is 2048 bytes and each frame is 1024x769 pixels and 16 bits. Single frames are saved as .viv files with the same size header.

5.1 Dark field and flat field

Go to *Acquisition, System Settings,* and turn off *Image Corrections*. Go to *Video, Allocate Buffers*, and set it to 40. Go to *Video* and turn on *Capture first 40 frames*. Click the green disk and, when done, the red square.

- dark field:

For the flat field, open the collimator so that the entire flat panel is covered. Set the voltage to 75 kV and current to 50 mA. Turn on the x-rays then click the green disk. Hold the x-rays on for at least 3 seconds.

- flat field:

In order to have an image to correct, place a cell phone or some other object of interest in the beam. Take a single frame. Only this first image will be corrected ‘by hand’. The remaining will use the ViVA software corrections.

- object:

For the remaining data, turn on the software calibration and do a gain calibration using 75 kV and 40 mA.

5.2 Step wedge image

Stack 10 acrylic sheets in the beam, displacing every 2 sheets laterally by about 2.5 cm to make a step wedge pattern. Tape ½ in spherical “targets” at about 10 cm below the top of the step wedge at two different thickness portions of the step wedge. Record 40 frames with 75 kV and 40 mA.

- step wedge:

5.3 Low contrast detectability as a function of dose

Place 10 sheets of acrylic in the beam and run the gain calibration again, this time with 75 kV and 80 mA. Then tape the low contrast pattern onto the entrance side of the acrylic at the vertical center of the beam. You can find the vertical center of the beam by turning on the collimator light and closing down the collimator. Open the collimator to cover the entire flat panel.

First obtain 40 frames with a high dose using 75 kV and 80 mA.

- high dose:

Measure single frame images at lower dose settings.

- 5 mA:
- 10 mA:
- 20 mA:
- 40 mA:
- 80 mA:

Tighten the collimator in both directions to come within about 2 or 3 cm of the low-contrast pattern to reduce the amount of scatter. Repeat the measurements.

- high dose:

Measure single frame images at lower dose settings.

- 5 mA:
- 10 mA:
- 20 mA:
- 40 mA:
- 80 mA:

5.4 Resolution test pattern

Remove the acrylic sheets and tape the line-pair phantom to the face of the flat-panel. Orient it at an angle in order to minimize the Moiré pattern. Acquire and average 40 frames of the line-pair phantom using 75 kV and 40 mA.

- line-pair phantom image:

Questions and Analysis

1. Plot the dose vs. mA. Is it linear? Plot dose vs. kV. Is it linear? If we assume that the output is related to kV by a power law:

$$dose = A \times kV^n$$

(where A is a constant), we can find the exponent by taking the log:

$$ln(dose) = ln(A) + n \times ln(kV)$$

So, plot ln(dose) vs. ln(kV). Is it linear? Calculate the slope of the fit to a straight line. Compare the value of n for measurements with and without an absorber.

2. Calculate the effective attenuation coefficient of acrylic and copper at 60 kV, and at120 kV with added copper filtration. Taking the log of both sides of Eqn. 2:

$$ln(I) = ln(I_0) - \mu_{eff} t$$

So, the slope of a plot of ln(I) vs. thickness (in cm) is $-\mu_{eff}$ (in units of cm^{-1}). Plot ln(I) vs. thickness for each of the 4 experiments and calculate $-\mu_{eff}$. Compare $-\mu_{eff}$ for acrylic and copper, and at low kV versus high kV with added filtration.

3. For the scatter experiment, plot the measured dose as a function of field size for each of the absorber thicknesses. For each of the absorber thicknesses, the intensity of primary photons should not change with increasing field size. What is the increase with field size due to? Fit a straight line to the data for each field size and extrapolate to a field size of zero (i.e., get the y intercept of the linear fit). This is an approximation to the dose due to primary x-rays. Using this as P, calculate the amount of scatter and the scatter-to-primary ratio (S/P) for each setting. How does S/P vary with field size and object thickness?

4. Correct each of the images for dark current and flat field as shown in Eqn. 4.

5. Compare the step wedge image with and without log processing (i.e., compare the corrected image from step 4 with the negative log of that image). Ideally, since the steps represent a constant increment in acrylic thickness, the steps in the image should be constant as well. Similarly, the contrast due to the spherical target should be the same at the two positions. Get profile plots through the step wedge and through the targets. Comment on the effect of log processing.

6. Calculate CNR as a function of dose level from the low contrast data, which you can do as follows. Starting with the high dose image, define two regions of interest, a=a region in the most easily seen target and b=a region in a nearby uniform region. b should be large enough to let you calculate the standard deviation (at least 10x10 pixels). Calculate I_a and I_b as the means in the regions a and b, I_{ave} as the average of I_a and I_b, and σ as the standard deviation in region b. The contrast is $C=|I_a-I_b|/I_{ave}$ and the CNR is $C/(\sigma/I_{ave}) = |I_a-I_b|/\sigma$. For "quantum noise", CNR should increase as the square root of dose, so a plot of ln(CNR) vs. ln(mA) should have a slope of ½. Compare the low contrast detectability as a function of dose by examining which target is near the threshold of detectability, and reporting the contrast of this target as a function of dose. Comment on the effect of scatter by comparing contrast and detectability in the wide beam vs. narrow beam exposures.

7. Find the limiting spatial resolution using the image of the resolution phantom. Each line pattern is labeled in units of line pairs per mm. A pattern at L line pairs per mm has bars and spaces that are each 1/(2L) mm wide.