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Analysis Of the Performance Of Iodinated Contrast X-Ray Attenuator Under Physiologically Relevant Conditions

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A Capstone Project Submitted in Partial Fulfillment of the Requirements of the Renee Crown University Honors Program at Syracuse University

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Honors Capstone Project in Biomedical Engineering

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Abstract

X-ray is a radiological tool utilized in healthcare institutions around the world to diagnose abnormalities such as bone fractures or the presence of foreign material within patients. The ability for healthcare providers to properly diagnose a problem is improved with advancements in the quality of radiological images. One way to improve image quality is to optimize the contrast range within a single image created by different attenuating characteristics in various types of tissue. In this study, I used a proof-of-concept prototype model of an x-ray attenuation system and an experimental protocol to examine its capacity to equalize x-ray beam signal values. A scout object consisting of different thicknesses of aluminum with the thickest section representing the most attenuated section and the target for equalization was used as a model of different types of tissue in a patient. The performance of the device and procedure was studied at various x-ray power levels and base acrylic thicknesses to represent anatomically relevant conditions. The different base acrylic thicknesses were used to represent standard attenuation in different sized patients. A statistical analysis was conducted using an unpaired t-test on the data results to identify whether the results are statistically significant and represent an improvement in image quality. The calibration equations developed to calculate the amount of iodinated contrast necessary at certain conditions were tested at intermediate levels to test performance under other conditions. The unpaired t-test was also conducted on these results. The analysis showed the exposure levels in each column were optimized to reduce the dynamic range of signal values.

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1. Introduction

1.1 History of Radiology

The first radiological systems developed for diagnostic purposes used a technology known as traditional film screen radiography. This system has been replaced over the past 15 years by a new technology known as computed radiography (CR) (1,2). CR differs from traditional film-screen radiology through the use of an imaging plate that captures that x-ray beams and is then read and processed before being stored in a digital format (3). CR is becoming more widely accepted as the diagnostic imaging technique of choice due to improvements in the dynamic range used in taking images as well as the ability to store the data on a computer rather than as a physical screen (1,2).

One problem that has arisen, specifically with chest radiography, is in the different signal levels created by various attenuating values of the different types of tissue such as bone and soft tissue (i.e. lung and cardiac muscle) (4,5). This has been an issue with both film-screen radiography as well as CR. Optimization of the dynamic range of a particular image allows a doctor making a diagnosis to detect problems that might otherwise go unnoticed. In a wide dynamic range, the contrast a fine fracture in a bone makes with the actual bone might not be detected. Reducing the dynamic range enhances the ability to detect the contrast between similar signal levels (6). Signal levels or values in this paper refer to measured values of x-radiation intensity.

Some methods that will be discussed in the next section have been developed for both CR and film-screen radiography. There is still room for drastic improvements to the systems so that there is a smaller dynamic range in signal values in a single image. While image quality should be improved, it should not result in increased doses of x-radiation being delivered to patients undergoing a CR examination (4,7). In addition, an optimal technique must be sufficiently fast that the procedure would occur within one breath repetition by the patient so as to avoid any motion artifact that could reduce image quality (5). The ideas for beam equalization that will be discussed next generally focus on finding rapid methods of adding measured amounts of attenuating material between the beam source and the imaging plate. Beam equalization is the approach many techniques use to send different amounts of x-ray exposure by adding attenuating material to specified locations (4).

1.2 Previous Methods of Attenuation

One previous method developed to solve the issue of the wide dynamic range created in chest CR is known as the AMBER system created by Vlasbloem and Kool (4). This method involves a piezoelectric actuator that applies an attenuating element to cover a certain section of the image as shown in figure 1.

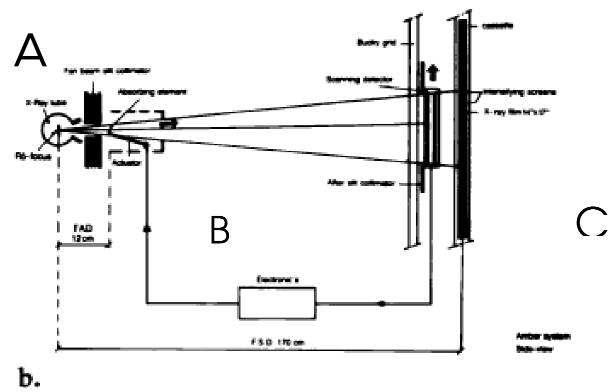


Figure 1: AMBER principle schematic side view. At section A is the x-ray source. After that near point B is the modulator and attenuating element. C refers to the area where the patient is located with the platform on the far right representing the imaging plate or x-ray film (adapted from 4).

The amount of material the actuator brings to the image section is calculated using an initial system scan that measures the exposure in all areas to be imaged. Drawbacks to this system included an artifact due to electronic instability of the system as well as potentially requiring more x-ray energy and exposing the patient to more x-radiation (4).

A technique developed by Hasegawa et. al. (10) at the University of Wisconsin focused on creating an attenuating pattern of cerium oxide specific for an individual patient based on an initial scout scan as shown in figure 2.

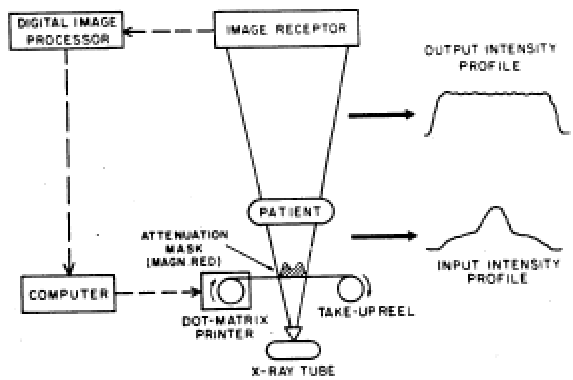


Figure 2: Schematic showing the Patient-specific beam attenuator system developed by Hasegawa et. al. The dot-matrix printer shows the individual attenuation mask created using the digital image processor and computer (adapted from 10).

Imaging results for this system were reported to be fairly successful. However, the printing of the patient-specific patterns reportedly required too much time to be avoid patient-motion artifact. In addition, Hasegawa et. al. believe cerium may not have been the best choice for an attenuating agent in chest radiography (8-12).

Area beam equalization was an idea proposed by Tong Xu et. al. (5) proposed the idea of area beam equalization that is similar to the area beam equalization with patient specific patterns printed by Hasegawa. In this case, however, the attenuating material is controlled by an automatic piston array as shown in figure 3.

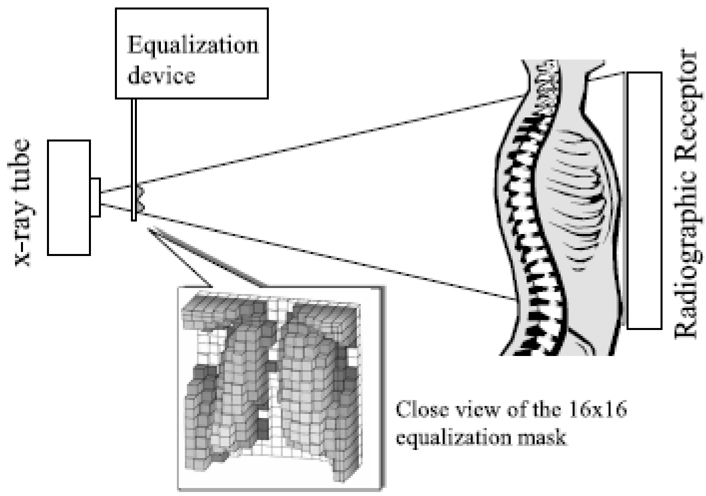


Figure 3: Schematic of the area beam equalization technique developed by Xu et. al. The close up view of the equalization mask demonstrates how a piston mechanically pushes a specific amount of attenuating material as different elements. Note the lower amounts of attenuating material where the spinal column is located (adapted from 5).

Although the amount of time required to generate the mask was reduced from 30 minutes in the Hasegawa technique to 3 minutes here, it is still not a clinically applicable approach to beam equalization. The piston array technique was also studied by Molloi et. al. (13).

This study looks at the performance of a device described in the next section that utilizes a liquid iodinated contrast as an attenuating agent. Currently the device involves a manual protocol where many of the other techniques previously described used an automatic system. The objective is to test the manual protocol to show the device is capable of optimizing the dynamic range within individual images. With this accomplished, further work may be done to incorporate an automatic technique to reduce the procedural time.

1.3 Device Design

The device used for the experiments in this paper was designed as a capstone project in the Department of Biomedical Engineering at Syracuse University by Peter Frey, Larry Kim, and Stephen Decker in conjunction with Dr. Kent Ogden of SUNY Upstate Medical University. The experiments conducted utilize the proof of concept model shown in the diagrams in figures 4 and 5.

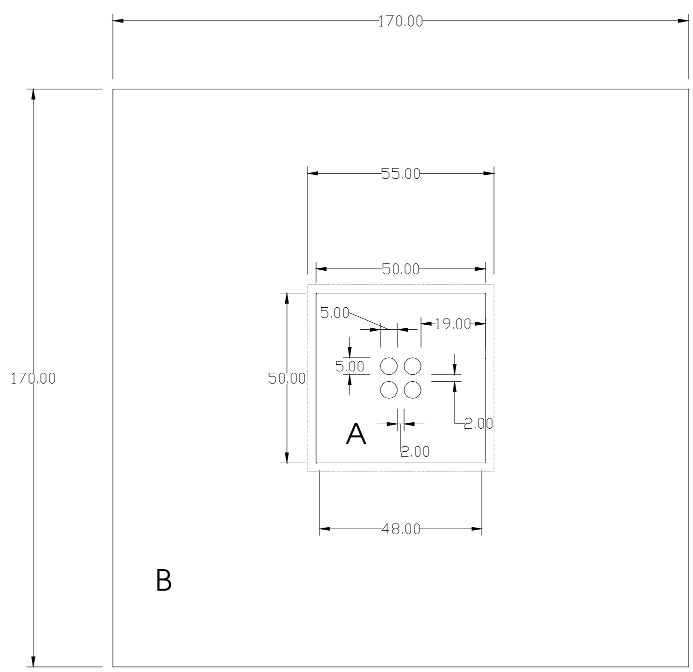


Figure 4: Top view CAD drawing of the attenuator device used in the experiments. A) Center piece with four individual filter element chambers. B) Sliding aluminum mount that holds device in place within collimator on x-ray beam source. All measurements within the schematic are in millimeters.

The center piece of the device (Fig. 4 A) forms the actual portion that is filled with iodinated contrast solution. It consists of four chambers. The larger rectangular piece surrounding this (Fig. 4 B) serves as the sliding mount that allows the attenuator device to be placed in any standard filter slot on an x-ray machine. Each of the four filter elements denoted on the center piece by A in figure 4 is filled with an iodinated contrast liquid that helps to optimize the dynamic range. The dynamic range is improved by adding the iodinated contrast to increase attenuation in overexposed areas such as under lung tissue.

In addition, a more advanced prototype with a larger number of smaller chambers was also machined as part of this project but is beyond the scope of this paper. The proof of concept device was created to conduct performance testing to see if the technique would be capable of improving image quality by reducing the dynamic range of the signal through beam equalization.

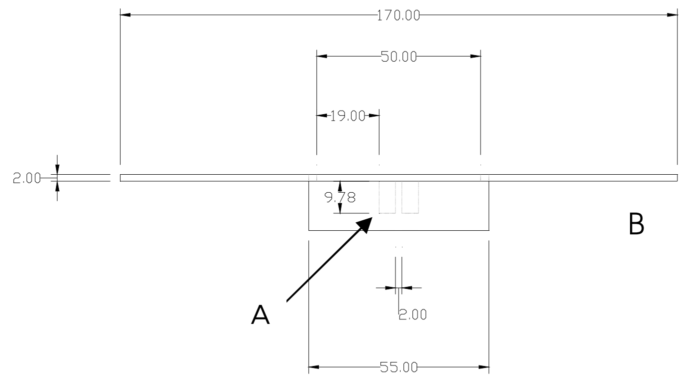


Figure 5: Side view CAD drawing of the attenuator device used in the experiments. A) Chambers within acrylic block for addition of iodinated contrast liquid. B) Outer mounting flange for insertion into the collimator slide on the x-ray tube. All measurements on this CAD drawing are in millimeters.

In a related study, an automatic filling device to load the chambers of the prototype is also being examined. That study focuses more on making the overall device and the technique for using it a more clinically applicable tool by reducing the amount of time necessary to measure and apply the iodinated contrast fluid.

A picture of the device mounted on the underside of the x-ray source is shown in figure 6.

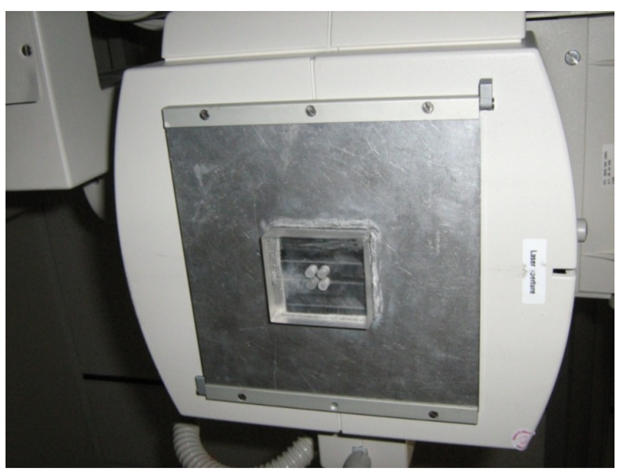


Figure 6: Photograph of attenuator device mounted on x-ray source.

1.4 Objectives

The goal of this paper is to continue the work of investigating the capability of the design described in the 1.3. Preliminary data suggested that the technique and device would be effective at reducing the dynamic range of the x-ray signal values in a scout image. In the current study, a more complex technique will be used intended to reflect more accurate and dependable calibration curves.

The previous study of this device looked at data for only one experiment. Repeatability was not a factor examined. Four repetitions of the procedure under each of the conditions were conducted to demonstrate consistency and repeatability in the procedure in producing an improvement. A sample size of four under each of the individual conditions will also provide a larger amount of data to conduct a statistical analysis of the results. In the previous study, the equations used to quantitatively express the relationship between desired x-ray signal change and volume of iodinated contrast necessary were only studied at standard acrylic thicknesses. These standard thicknesses were the same used to calculate the equations. In this study, new equations are calculated and tested for other thicknesses to test for utility across a range of possible conditions.

Finally, a statistical analysis was conducted for each of the conditions to reach a conclusion as to whether the device could achieve the goal of reducing the dynamic range of signal values in the image. Suggestions will be made based on the conclusion of this research as to the performance of the procedure and device. This will help to plan the future direction of the development of this method.

2. Materials and Methods

2.1 Calibration

The first step of the process for this experiment is to calculate calibration curves. A previous study examined the relationship between the areal densities of iodine in the chambers and the resulting attenuation through of the signal values calculated as measurements of the x-ray exposure on the final image. Images of the aluminum scout object were taken using the Fuji Computed Radiography System (FujiFilm Corporation, Tokyo, Japan) to collect this data used to quantify the relationship between desired signal change and volume of iodine. This produced a somewhat artificial result as the data were collected over specific amounts of aluminum that influenced the relationship between attenuating material and signal value change. The calibration curves in this study are calculated using the device with measured amounts of iodine over different base thicknesses of acrylic. Exclusion of the scout object produced equations that looked at the relationship between iodinated contrast amounts and resulting differences in x-ray exposure.

Additionally, the x-ray machine was used in Linearity Mode that effectively turns off automatic features of the machine that alter the beam properties depending on the amount of material present in path of the scan. Linearity mode allows the user to completely control the beam properties. In this manner, the equations calculated to quantify the relationship between iodinated contrast amounts and signal change are not influenced by automatic features of the CR system.

Each of the four chambers of the attenuator device is filled with specific amounts of iodinated contrast liquid using a 1 ml syringe. The measured volume in the syringe is equated to an areal density using the geometry of the columns. These areal densities are then related to the measured signal values from EFilm Lite (MERGE Healthcare, Milwaukee, WI) image processing software for each of the chambers.

The relationship between the areal densities and the associated signal values was quantified by entering the data into

TableCurve v. 3.01 (SPSS Inc., Chicago, IL) and generating calibration curves. The equations generated then utilize two input variables. These input variables are the acrylic thickness the scout is placed upon each time and the desired signal change calculated from the image of the scout object necessary to equalize the x-ray beams. Three calibration equations are generated. Each equation is for a different standard use x-ray power level (80 kV, 100 kV, and 120 kV). The calibration curve equations are then entered into an Excel (Microsoft Corporation, Redmond, WA) spreadsheet to compute areal density from the input variables.

2.2 Testing

In the testing phase, a scout image is taken at a specific x-ray power level and acrylic thickness. Figure 4 below shows a photograph of the test object used in every experiment within this study.

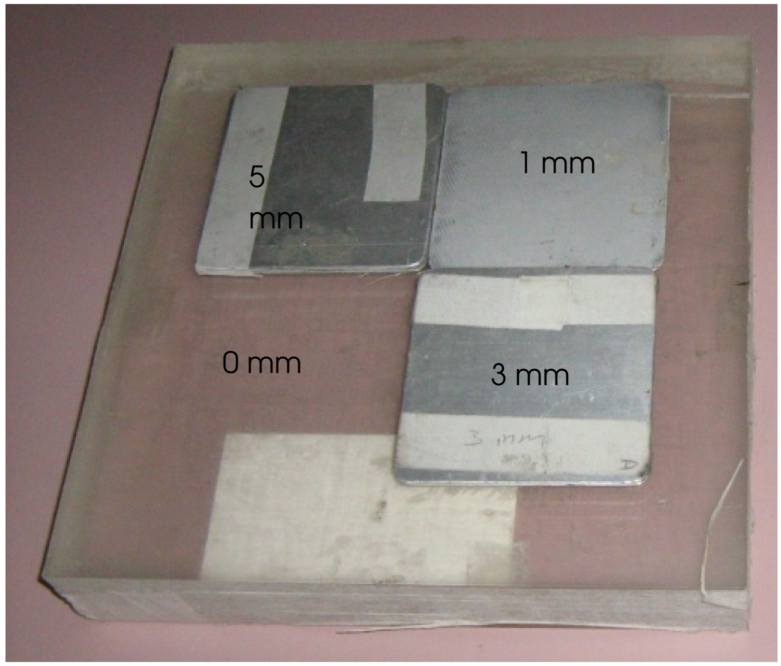


Figure 7: Scout object used to test the calibration equations and attenuator device. Three sections of aluminum rest on a block of acrylic. Each of the four rectangular sections represents the different thicknesses of tissue simulated by the scout object. All measurements are in millimeters.

The three different thicknesses of aluminum were placed on top of the acrylic base. The different thicknesses include 1, 3, and 5 mm. Each of these represents a different type of tissue as they all have different attenuation values and result in a wide dynamic range of x-ray exposure values similar to an image of a chest.

The acrylic base and aluminum arrangement must be properly aligned with the center of the x-ray source tube. This is due to the placement of the attenuating device directly in the center of the x-ray source. Proper alignment may take several test images. An image is then taken and processed using Fuji Computer Radiography Image Processing (10). The data are then transferred to a database for storage on a CD. The images can then be analyzed on any PC with eFilm Lite software that is automatically loaded to the CD. This software allows for measurement of the signal values in different areas of the image. Figure 8 shows an example of an image resulting from the setup described above.

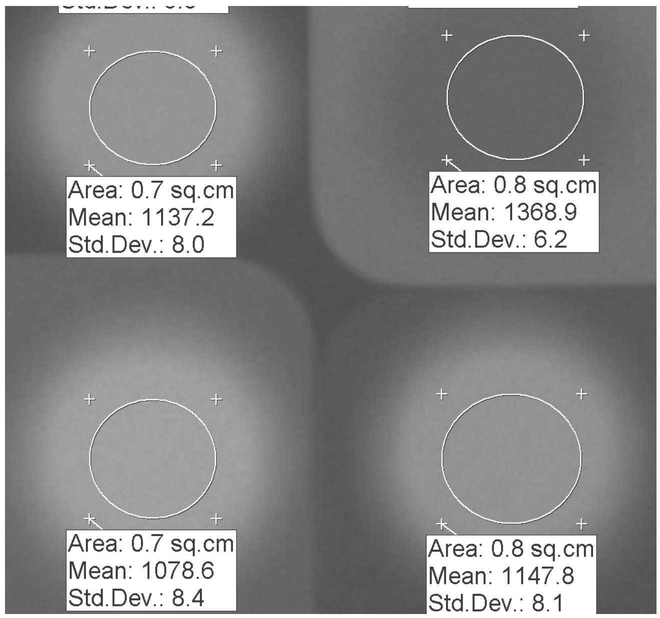


Figure 8: Example of image analysis using eFilm to measure signal values within certain areas. The white circles in each quadrant represent user defined areas that the software analyzes. The circular shape of a different brightness in each quadrant is the filter chamber. The upper right is the section with 5 mm aluminum and appears brightest. Its chamber does not contain any iodinated contrast. The lower left is the second highest brightness. Therefore this section represents the 3 mm section of aluminum. The lower right is 1 mm while the upper left has no aluminum. The area statistic is the area of the user specified region. The mean and standard deviation are statistics of the x-radiation exposure signal values for each pixel.

Measurements of the x-radiation exposure signal values taken of each of the areas directly under the filter columns can then be used to establish a target signal value in the column over the 5 mm sheet of aluminum. This region represents the thickest "tissue" that the x-ray must penetrate and, without iodine, contains the lowest x-radiation exposure signal value. Iodinated contrast is added to the other columns over lesser amounts of aluminum to try to match the attenuation properties of the 5 mm of aluminum. The difference between the actual signal value and the target signal value under a given column is known as the desired delta signal. Desired delta signal and the thickness of the acrylic base are the two input variables used to calculate an areal density of iodinated contrast necessary to match the attenuation in the target region. Table 1 shows an example at 4" of acrylic and 80 kV x-ray power. The input variables (acrylic thickness and desired delta) are listed in the first column.

Input	Acrylic	Power	Aluminum	Signal	Desired	Desired Delta	AD	Height	Volume
4, 180.2	4	80	0	1495.7	1315.5	180.2	61.40272	0.614027	0.1205335
4, 151	4	80	1	1466.5	1315.5	151	53.05733	0.530573	0.1041515
4, 88.6	4	80	3	1404.1	1315.5	88.6	27.91534	0.279153	0.0547978
4, 0	4	80	5	1315.5	1315.5	0			

Table 1: Example of iodinated contrast volume concentration for the testing of the procedure. The first column includes the two input variables (acrylic thickness, desired delta signal. These are again listed in the 2nd and 7th columns. The 3rd column represents the x-ray power level. The 4th column reports the thickness of aluminum in mm under that given region. The 5th column contains the signal level measured from the scout image while the 6th repeats the desired or target signal level from the 5 mm region. The AD column reports the areal density calculated using the appropriate calibration equation and the given input variables. This is then equated to column height and iodinated contrast liquid volume in columns 9 and 10 respectively.

Calculated volumes of contrast medium such as those shown in the right-most column of table 1 above are then injected into each of the columns and the device is placed back into the collimator slide on the x-ray source. A second image is then taken with the iodinated contrast present. This process of measuring the contrast agent, filling the columns, and taking an image is repeated 3 times so there are 4 measures at each condition. This creates a total of 36 tests with 12 at each x-ray power level.

Next, the accuracy of the calibration curves for acrylic thickness outside of the standard 4, 7, and 10" used to create the relationship is tested. The acrylic thicknesses selected for examination are 2, 3, 5, 6, 8, and 9". These thicknesses are only tested on the 120 kV power level setting as this is the most clinically appropriate for chest scans. Again, each combination of conditions is tested a total of 4 times to investigate repeatability of the method.

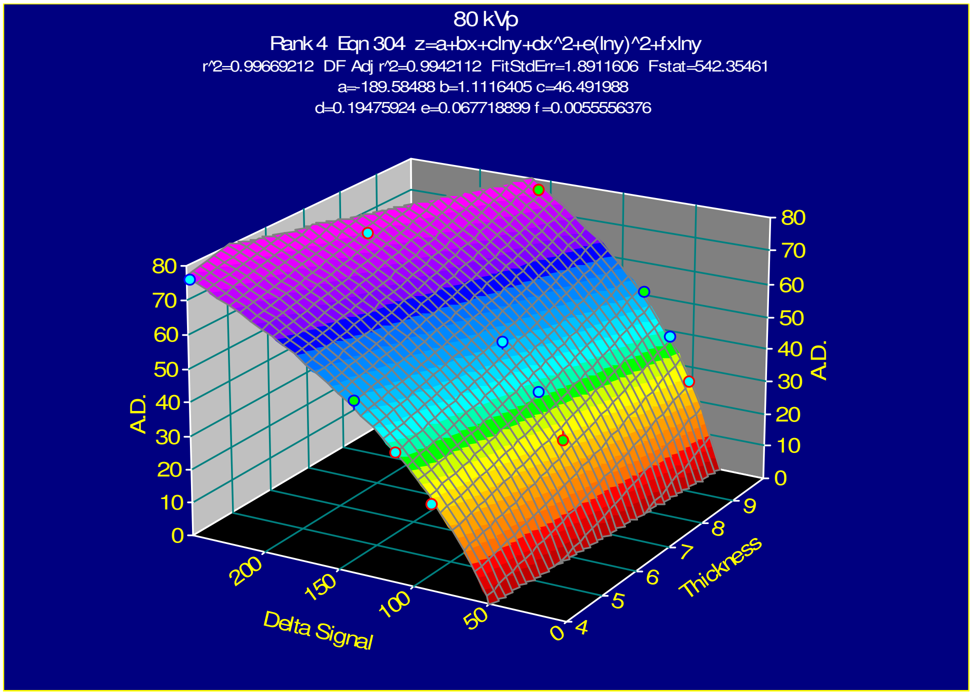
2.3 Analysis

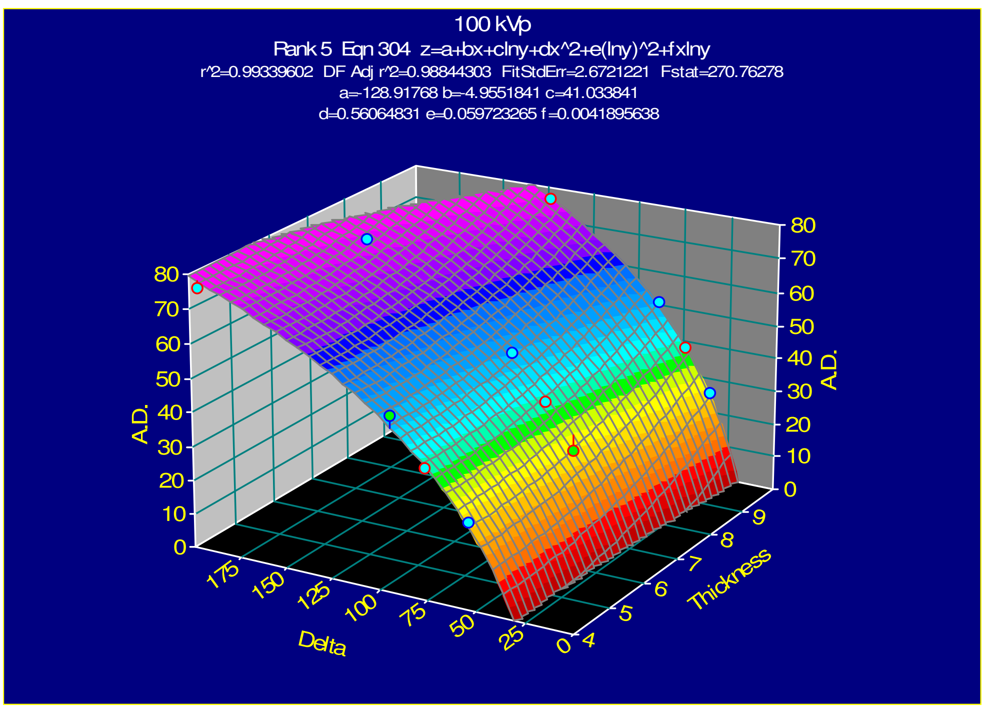
An unpaired t-test for samples with equal variances is conducted to compare the results from the test under each of the conditions with the final signal level of the target column over the 5 mm section. First, an f-test to test for equal variance is conducted. Then an unpaired t-test is conducted depending on the type necessary for the sample (i.e. whether the variances of the samples are equal or not). The t-test describes to what confidence level it can be determined that the signal values have been equalized. These tests are conducted for each of the conditions in both of the tests described above.

3. Results

3.1 Calibration

The calibration of the device at different signal levels resulted in three equations generated using the TableCurve program. Each of these was based on data collected from x-ray images of the acrylic bases with known amounts of iodinated contrast medium in the attenuator columns. The data used to create the descriptive equations are shown in appendix 1. The plots in figure 6 show the three-dimensional representations of the calibration equations.


80 kVp
Rank 4 Eqn 304 z=a+bx+clny+dx^2+e(lny)^2+fxlny
r^2=0.99669212 DF Adj r^2=0.9942112 FitStdErr=1.8911606 Fstat=542.35461
a=-189.58488 b=1.1116405 c=46.491988
d=0.19475924 e=-0.067718899 f=0.0055556376
A.D.
Delta Signal
Thickness


100 kVp
Rank 5 Eqn 304 z=a+bx+clny+dx^2+e(lny)^2+fxlny
r^2=0.99339602 DF Adj r^2=0.98844303 FitStdErr=2.6721221 Fstat=270.76278
a=-128.91768 b=-4.9551841 c=41.033841
d=0.56064831 e=-0.059723265 f=0.0041895638
A.D.
Delta
Thickness

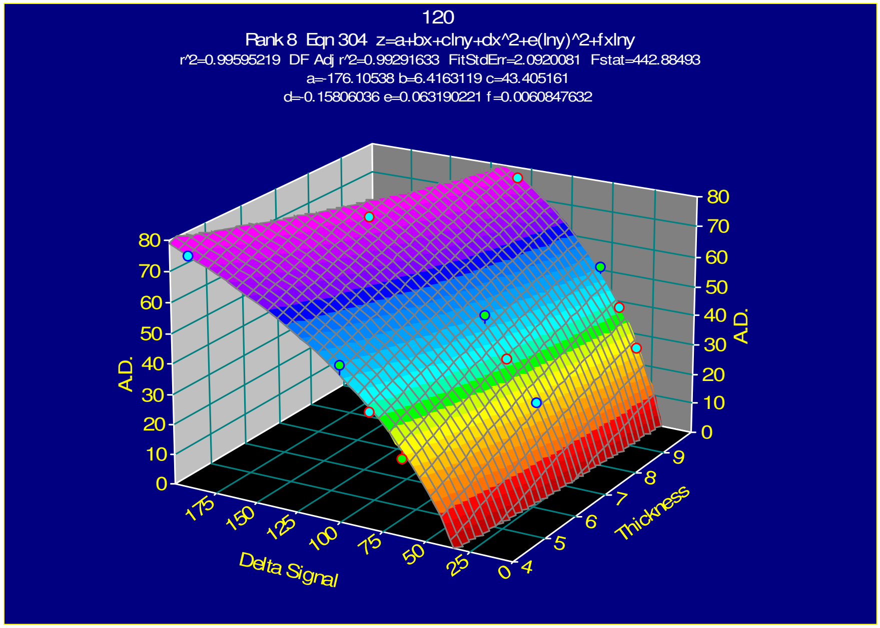


Figure 9: TableCurve generated representations of the calibration relationships between delta signal, acrylic thickness, and areal density of iodinated contrast for 80 (top), 100 (center), and 120 (bottom) kVp x-ray power levels. Automatic data at the top of each plot represents the quantitative relationship between the input and output variables. These equations are written below. The plot in each part shows the input variables as desired delta signal change and acrylic thickness as the x and y axes. The z (vertical) axis corresponds to the areal density of iodinated contrast necessary to achieve the desired delta signal change at the specified acrylic thickness.

The equation that was selected for each plot is shown below in equations 1-3. The three equations all take a similar form with different coefficients. This equation type was selected for the combination of its limited number of terms and high correlation coefficient.

Eq. 1 80 kVp

$$AD = -189.585 - 1.112 * AT + 46.492 * \ln(DS) + .1948 * AT^2 + .0677 * \ln(DS)^2 + .0056 * AT * \ln(DS)$$

Eq. 2 100 kVp

$$AD = -128.918 - 4.955 * AT + 41.034 * \ln(DS) + .5606 * AT^2 + .0597 * \ln(DS)^2 + .0042 * AT * \ln(DS)$$

Eq. 3 120 kVp

$$AD = -176.105 - 6.416 * AT + 43.405 * \ln(DS) + .1581 * AT^2 + .0632 * \ln(DS)^2 + .0061 * AT * \ln(DS)$$

Where:

AD= Areal Density (mg/cm^2)
AT= Acrylic Thickness
DS= Delta Signal

The three equations listed above were then all implemented in an Excel spreadsheet so that the two input variables could easily be entered and converted to an associated areal density of iodinated contrast that could be injected in the chambers. The areal density was subsequently converted into a volume of iodine base on the geometry of the device elements. The relationships are described in the equations below.

Eq. 4 $$Volume = \frac{AD}{IC} * Area$$

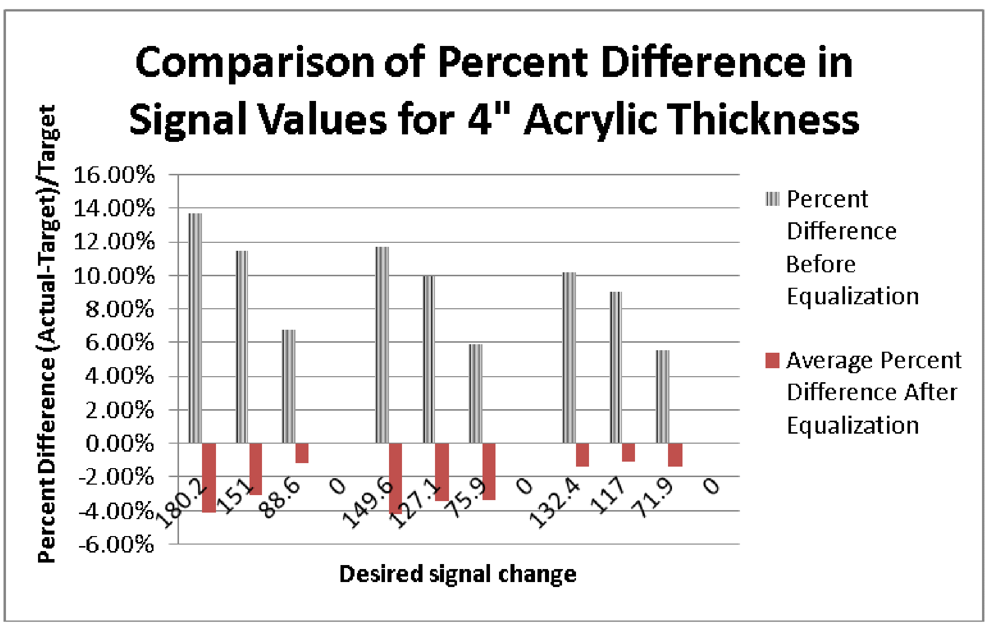
Where:

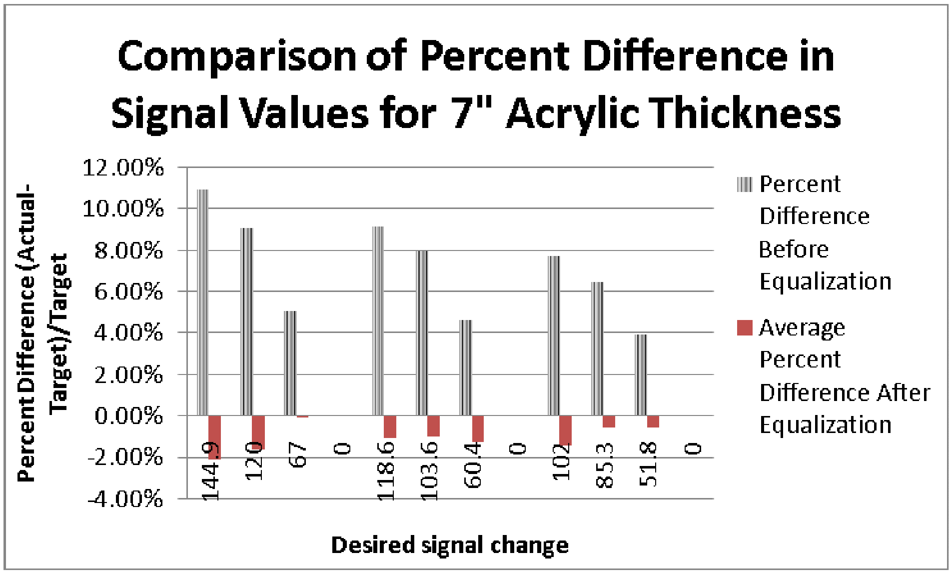
IC = Iodine Concentration = 100 mg/cm^3
Area = Attenuator Element Area = .1963 cm^2

In this manner, given input variables of delta signal and acrylic thickness yield a volume of iodinated contrast to inject into the chambers for each of the conditions.

3.2 Testing

The testing of the calibration equations, attenuation method and device yielded data represented in appendix 2. The first set of results was collected from testing the attenuator device at a set of combinations of standard acrylic thickness and x-ray powers. The most relevant statistic of the results to examine was decidedly the percent difference between the signal value at each condition and the target signal value. The comparison of this statistic before and after the addition of iodinated contrast in the attenuator is shown in figure 10. Similar plots for the data resulting from the investigation of alternate acrylic thicknesses at 120 kV x-ray power are shown in figure 11. This statistic shows the difference between the signal level at each condition and the target signal level as a percentage of the target signal level. The comparison before and after the injection of contrast medium is a way to measure the optimization of the dynamic range.





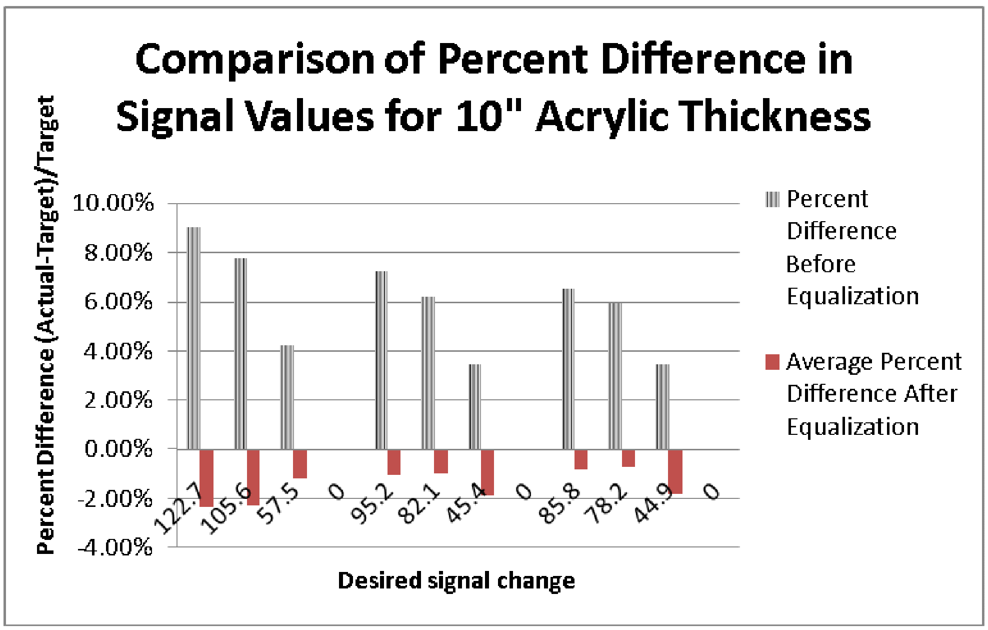
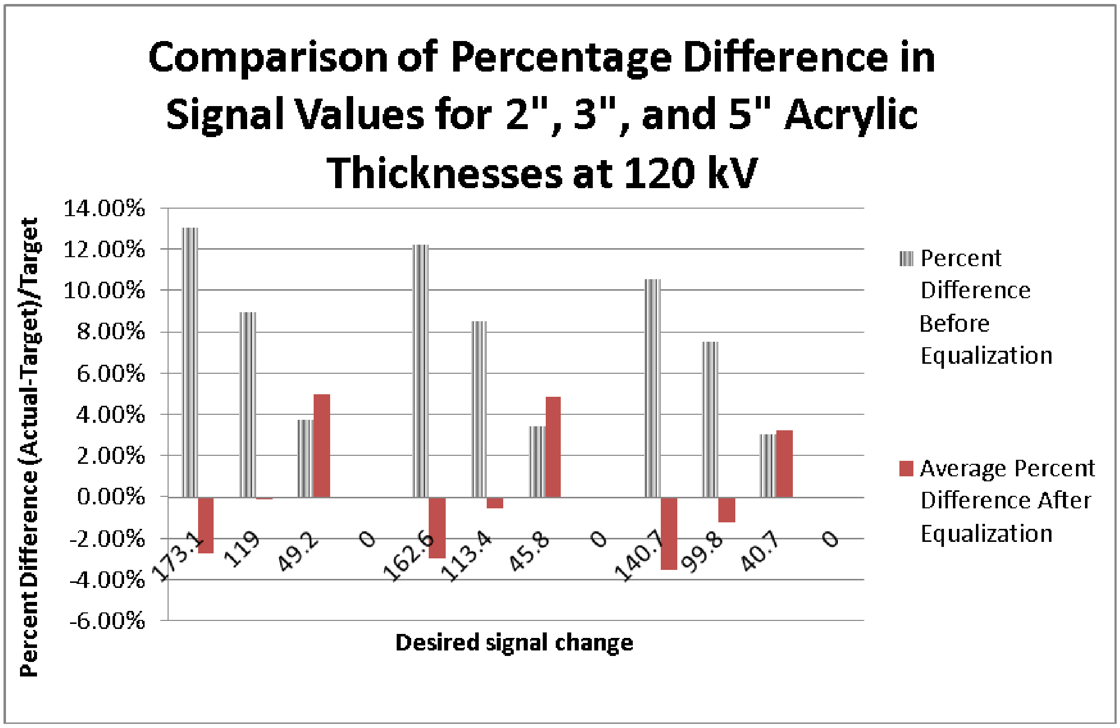


Figure 10: Plots showing before and after percent differences between actual and target signal values for conditions tested on different acrylic bases. The x-axis shows the input desired delta signal while the y-axis compares the percent difference in signal values before and after the injection of iodinated contrast medium. The first four values were recorded at 80 kV x-ray power. The middle 4 represent the 100 kV x-ray power and the final 4 were generated at 120 kV. The 0 elements indicate the 5 mm section of aluminum as this was always the location of the target signal value. The first plot shows the data from the test object on 4” of acrylic, the second on 7” of acrylic, and the bottom on 10” acrylic.



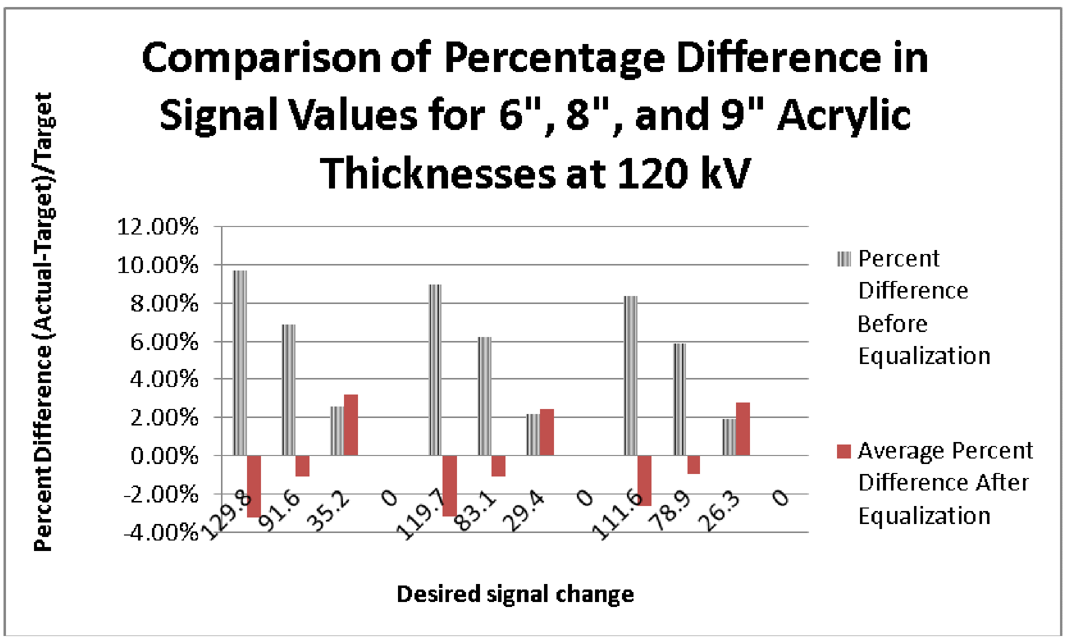


Figure 111: Plots showing before and after percent differences between actual and target signal values for conditions tested on different acrylic bases. The x-axis shows the input desired delta signal while the y-axis compares the percent difference in signal values before and after the injection of iodinated contrast medium. All data were recorded at 120 kV x-ray power. The 0 elements indicate the 5 mm section of aluminum as this was always the location of the target signal value. The first plot shows the data from the test object on 2", 3", and 5" of acrylic. The second shows data collected from the test object on 6", 8", and 9" of acrylic.

3.3 Analysis

The first step of the statistical analysis for each set of experiments was to conduct an f-test to find out if the sample sizes had equal variances to determine the type of t-test to use. In the first set of data, the p values returned were all higher than the .05 selected for alpha as the confidence level value of 95% (not shown). This indicates that the sample data could be tested using an unpaired t-test for samples of equal variance. Next, the t-test was conducted using excel to determine if the average attenuated signal value for each condition was reasonably equal to the signal value in the target region. The data showing the p values for the t-test at each input variable or condition is shown in table 2.

Condition (Input Variables)	P
4, 180.2	0.0001
4, 151	0.0008
4, 88.6	0.0144
4, 149.6	0.0188
4, 127.1	0.0523
4, 75.9	0.0412
4, 132.4	0.0799
4, 117	0.1800
4, 71.9	0.1431
7, 144.9	0.0362
7, 120	0.0936
7, 67	0.9359
7, 118.6	0.2462
7, 103.6	0.2560
7, 60.4	0.2013
7, 102	0.1173
7, 85.3	0.5478
7, 51.8	0.5123
10, 122.7	0.0408
10, 105.6	0.0413
10, 57.5	0.2799
10, 95.2	0.1956
10, 82.1	0.2008
10, 45.4	0.2123
10, 85.8	0.3048
10, 78.2	0.3268
10, 44.9	0.0783

Table 2: P values for each condition of acrylic thickness and desired signal change resulting from unpaired t-tests for samples with equal variance at a 95% confidence level.

The same steps were followed for the data from the study at varying acrylic thicknesses to first test for equal variance in the samples and then to conduct a t-test. Again, the f-test returned p values (not shown) indicating that the samples fell within the category of having equal variances. Again, an unpaired t-test for samples with equal variances was used to obtain the p values shown in table 3 below.

Condition (Input Variables)	P
2, 173.1	0.023603
2, 119	0.862807
2, 49.2	0.000164
3, 162.6	0.001990
3, 113.4	0.028967
3, 45.8	0.000001
5, 140.7	0.000003
5, 99.8	0.000095
5, 40.7	0.000011
6, 129.8	0.000005
6, 91.6	0.000044
6, 35.2	0.000001
8, 119.7	0.000003
8, 83.1	0.000205
8, 29.4	0.000005
9, 111.6	0.000030
9, 78.9	0.002888
9, 26.3	0.000015

Table 3: P values for each condition in the second study of varying acrylic thicknesses resulting from unpaired t-tests for samples with equal variance at a 95% confidence level.

4. Discussion

4.1 Calibration

The calibration equations reported as equations 1-3 provided a more reliable way to quantify the relationship between the volume of contrast medium and resulting change in signal level than in previous studies. Previously, the interaction of aluminum amounts from the test object was not removed during collection of data. In addition, TableCurve allowed for the generation of a smaller number of equations. The dependence on two different variables in the equation eliminated the need for a different equation for each acrylic thickness. The use of TableCurve also allowed for a much larger variety of possible best fit equations for the relationship. The equations described in section 3.1 were deemed the most appropriate from the options in TableCurve given the amount of data used to generate each curve (15 data points) and the excellent fit of the equation as demonstrated by the correlation coefficient.

4.2 Testing

The results from the set of experiments studying the attenuator device at various x-ray power levels were very promising. Figure 10 illustrates a vast improvement upon the percent difference between the actual and target signal values at each condition. In every case, the absolute percent difference was reduced indicating that there was a decrease in the dynamic range of the signal values in the image. One observation to note is that in every case from this data set, it appears that the target value was overshot when adding the iodinated contrast. This tends to suggest some sort of overestimation by the calibration equation. Another possibility is an extra amount of contrast agent being added when manually measuring the liquid to add to the columns. This could be either due to an inaccuracy of the syringe used to apply the contrast or an incorrect calculation of the areal density and volume of contrast medium needed.

Figure 11 illustrates the changes in percent difference before and after injection of iodine for the study at 120 kV with different acrylic thicknesses. It appears that the results are not as promising. Many of the cases again show a reduction in the percent difference and consequently a reduction in the dynamic range. However, it appears that the data point for the lowest delta signal condition for each of the acrylic thicknesses illustrates an increase in the percent difference after the injection of contrast medium.

One explanation for this increase in the difference between the condition's signal value and the target is the small size of the delta signal input variable results in a marginally small amount of iodinated contrast medium being added to the element. It is possible that there is not in fact any iodine being added in these cases due to the imprecision of the syringe applicator. There is likely also some property of the interaction of the x-rays and the presence of the contrast medium in the other elements that results in an effective wider dynamic range for these smaller delta signal values. In any case, it can be seen that the percent difference under these conditions is already significantly lower than the percent differences at the larger desired delta signal conditions. The low percent difference indicates a narrower dynamic range that would not necessarily need to be optimized.

4.3 Statistical Analysis

The unpaired t-test for samples with equal variances proved to be a promising measure of the results obtained from the first set of experiments. Table 2 lists the various p values as generally larger than the .05 confidence level set for the test. This finding demonstrates that under most of the conditions, the technique was able to reduce the dynamic range of the images so that the average signal values for many of the conditions were virtually the same as the target signal values with 95% confidence. There were 6 cases in this set of experiments where the t-test rejected the hypothesis that the mean signal level and the mean target signal level were equal. These conditions tended to be at the lower end of the acrylic thicknesses and x-ray powers tested.

The t-tests conducted on the data from the second set of experiments suggested that the hypothesis that the mean signal levels were equal be rejected every time. The p values in all cases but one were much lower than .05. This indicates that the calibration equations tested at various other acrylic thicknesses were not as accurate in recommending areal densities of iodinated contrast needed to equalize the signal levels.

5. Conclusion

The iodinated contrast x-ray attenuator tested in this paper has been shown to be an effective method for x-ray beam equalization to improve image quality. The results from the study at varied x-ray powers were conducted with a manual approximation of the measurements of iodinated contrast. These results showed the manual method was still successful in reducing the dynamic range of the signal levels to a point where a t-test with a 95% confidence level showed the mean signal value of each condition was equal to the mean target signal value. Future experimentation can be conducted with more precise methods of measuring the volume of iodinated contrast medium to be injected. The use of a micropipette will improve the precision of the volume of iodinated contrast medium injected. This could result in smaller percent differences after injection and could also reduce the likelihood of the delivery of too much contrast medium.

To further improve the system, a method of automation must also be developed to improve the speed with which the system can operate. Many of the other attenuating techniques that have been developed prior to this have been faster than the one described in this paper. The speed is an important factor as two images should ideally be taken in one breath hold so that patient motion artifact is not an issue. The discussion of potential automation methods is beyond the scope of this paper.

With an improved method of automation, a more thorough study can be conducted on the more advanced prototype also developed last semester. This prototype device is fitted with 400 attenuating chambers. Manual application of iodinated contrast to these much smaller, more numerous chambers is inefficient and should be computer controlled simultaneously. Future studies can examine the performance of the prototype over a more complex scout object. This can only occur, however, after an automation method has been developed.

6. Appendix

6.1 Data tables used to generate equations

Power	Thickness	Delta
80	4	0
80	4	87.25
80	4	110.85
80	4	136.85
80	4	247.35
80	7	0
80	7	72.1
80	7	88.3
80	7	113
80	7	205
80	10	0
80	10	52.2
80	10	65.5
80	10	84.8
80	10	158

Power	Thickness	Delta
100	4	0
100	4	53.35
100	4	75.45
100	4	93.45
100	4	195.05
100	7	0
100	7	55.98
100	7	70.28
100	7	88.38
100	7	167.08
100	10	0
100	10	35.6
100	10	48.9
100	10	63.3
100	10	124

Power	Thickness	Delta
120	4	0
120	4	62.88
120	4	81.88
120	4	98.58
120	4	188.18
120	7	0
120	7	41.7
120	7	59.4
120	7	72.7
120	7	142.3
120	10	0
120	10	34
120	10	45.6
120	10	56.7
120	10	108.1

6.2 Results from varied acrylic thickness and x-ray power study

Column1	Power	Aluminum	Signal	Desired	Desired Delta	AD	Volume	Percent Difference Before	Average Percent Difference
4, 180.2	80	0	1495.7	1315.5	180.2	61.4	0.1205335	13.70%	-4.07%
4, 151	80	1	1466.5	1315.5	151	53.06	0.1041515	11.48%	-3.03%
4, 88.6	80	3	1404.1	1315.5	88.6	27.92	0.0547978	6.74%	-1.13%
4, 0	80	5	1315.5	1315.5	0			0.00%	0.00%
4, 149.6	100	0	1425.4	1275.8	149.6	67.15	0.131815	11.73%	-4.16%
4, 127.1	100	1	1402.9	1275.8	127.1	60.36	0.1184925	9.96%	-3.41%
4, 75.9	100	3	1351.7	1275.8	75.9	38.92	0.0763932	5.95%	-3.33%
4, 0	100	5	1275.8	1275.8	0			0.00%	0.00%
4, 132.4	120	0	1430.5	1298.1	132.4	60.73	0.1192098	10.20%	-1.38%
4, 117	120	1	1415.1	1298.1	117	55.28	0.1085201	9.01%	-1.09%
4, 71.9	120	3	1370	1298.1	71.9	33.86	0.0664652	5.54%	-1.33%
4, 0	120	5	1298.1	1298.1	0			0.00%	0.00%
7, 144.9	80	0	1469.4	1324.5	144.9	60.96	0.1196572	10.94%	-2.13%
7, 120	80	1	1444.5	1324.5	120	52.06	0.1021901	9.06%	-1.61%
7, 67	80	3	1391.5	1324.5	67	24.59	0.0482605	5.06%	-0.08%
7, 0	80	5	1324.5	1324.5	0			0.00%	0.00%
7, 118.6	100	0	1416.7	1298.1	118.6	61.06	0.1198562	9.14%	-1.08%
7, 103.6	100	1	1401.7	1298.1	103.6	55.43	0.1088073	7.98%	-1.03%
7, 60.4	100	3	1358.5	1298.1	60.4	32.99	0.064763	4.65%	-1.25%
7, 0	100	5	1298.1	1298.1	0			0.00%	0.00%
7, 102	120	0	1422.3	1320.3	102	63.36	0.1243761	7.73%	-1.47%
7, 85.3	120	1	1405.6	1320.3	85.3	55.49	0.1089255	6.46%	-0.56%
7, 51.8	120	3	1372.1	1320.3	51.8	33.55	0.0658659	3.92%	-0.61%
7, 0	120	5	1320.3	1320.3	0			0.00%	0.00%
10, 122.7	80	0	1483.6	1360.9	122.7	66.46	0.1304526	9.02%	-2.33%
10, 105.6	80	1	1466.5	1360.9	105.6	59.37	0.1165501	7.76%	-2.28%
10, 57.5	80	3	1418.4	1360.9	57.5	30.72	0.060303	4.23%	-1.17%
10, 0	80	5	1360.9	1360.9	0			0.00%	0.00%
10, 95.2	100	0	1411.9	1316.7	95.2	65.58	0.1287241	7.23%	-1.06%
10, 82.1	100	1	1398.8	1316.7	82.1	59.42	0.1166317	6.24%	-0.97%
10, 45.4	100	3	1362.1	1316.7	45.4	34.79	0.0682923	3.45%	-1.88%
10, 0	100	5	1316.7	1316.7	0			0.00%	0.00%
10, 85.8	120	0	1397.2	1311.4	85.8	67.02	0.1315517	6.54%	-0.84%
10, 78.2	120	1	1389.6	1311.4	78.2	62.93	0.1235366	5.96%	-0.73%
10, 44.9	120	3	1356.3	1311.4	44.9	38.53	0.0756344	3.42%	-1.82%
10, 0	120	5	1311.4	1311.4	0			0.00%	0.00%

6.3 Results from 120 kV, varied acrylic base study

Column1	Power	Aluminum	Signal	Desired	Desired Delta	AD	Volume	Percent Difference (Before)	Average Percent Difference
2, 173.1	120	0	1501.8	1328.7	173.1	61.54	0.1208045	13.03%	-2.71%
2, 119	120	1	1447.7	1328.7	119	45.04	0.0884038	8.96%	-0.11%
2, 49.2	120	3	1377.9	1328.7	49.2	6.203	0.0121773	3.70%	4.98%
2, 0	120	5	1328.7	1328.7	0			0.00%	0.00%
3, 162.6	120	0	1493.1	1330.5	162.6	64.44	0.1264964	12.22%	-2.99%
3, 113.4	120	1	1443.9	1330.5	113.4	48.57	0.0953391	8.52%	-0.56%
3, 45.8	120	3	1376.3	1330.5	45.8	8.709	0.0170951	3.44%	4.84%
3, 0	120	5	1330.5	1330.5	0			0.00%	0.00%
5, 140.7	120	0	1471.3	1330.6	140.7	68.43	0.1343294	10.57%	-3.51%
5, 99.8	120	1	1430.4	1330.6	99.8	53.3	0.1046376	7.50%	-1.22%
5, 40.7	120	3	1371.3	1330.6	40.7	13.87	0.0272363	3.06%	3.20%
5, 0	120	5	1330.6	1330.6	0			0.00%	0.00%
6, 129.8	120	0	1463.4	1333.6	129.8	69.59	0.1365963	9.73%	-3.19%
6, 91.6	120	1	1425.2	1333.6	91.6	54.24	0.1064665	6.87%	-1.03%
6, 35.2	120	3	1368.8	1333.6	35.2	12.2	0.0239514	2.64%	3.24%
6, 0	120	5	1333.6	1333.6	0			0.00%	0.00%
8, 119.7	120	0	1453.3	1333.6	119.7	74.48	0.1462085	8.98%	-3.15%
8, 83.1	120	1	1416.7	1333.6	83.1	58.41	0.1146622	6.23%	-1.07%
8, 29.4	120	3	1363	1333.6	29.4	12.75	0.0250259	2.20%	2.50%
8, 0	120	5	1333.6	1333.6	0			0.00%	0.00%
9, 111.6	120	0	1446	1334.4	111.6	75.15	0.1475261	8.36%	-2.60%
9, 78.9	120	1	1413.3	1334.4	78.9	59.89	0.1175544	5.91%	-0.95%
9, 26.3	120	3	1360.7	1334.4	26.3	11.61	0.022789	1.97%	2.80%
9, 0	120	5	1334.4	1334.4	0			0.00%	0.00%

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8. Capstone Summary

Computed radiography (CR) is the modern widely-used technology for diagnostic imaging of patients in healthcare. The technology improves upon the traditional film-screen system that utilizes hard copies of each image by storing images digitally. In computed radiography, an imaging plate is used to capture the pattern of x-ray beams sent at a patient in the form of radiation. The amounts of radiation that reached different parts of the plate are then read by a digital system to form an image that can be displayed on a computer screen. A current problem that exists in computed radiography is developing a way to improve image contrast and diagnostic ability.

The ability to process, view and store images in a digital format is certainly an advantage over previous radiography systems. There still exist characteristics of the system that are not optimal for diagnosis of certain conditions. The chest cavity is one of the most common areas imaged using CR. This area encompasses several different types of tissue including bone in the spinal cord and ribs, as well as soft tissue in the heart and lungs. Soft tissue and bone have vastly different properties. The higher density of bone tissue absorbs much more of the radiation passing through a patient to the image plate as than does the soft tissue of the lung. As a result, the amounts of radiation recorded as a signal value on the image plate under the two tissues will differ greatly. This is recorded on the image as a darker area where more radiation passed through the body, and lighter areas under an area where less passed through. Thus there is a large range of contrast in the image.

The wide difference in these signal values can complicate proper diagnosis by masking finer details such as a fracture in a bone. In images with a wide range of x-ray exposures, it can become impossible for doctors to be able to make out hair-line fractures. Many attempts have been made to develop a system or tool that reduces the wide range that is often produced in CR chest scans. These generally implement the addition of more material over area of soft tissue so as to equalize the exposure level to that of the area where bone is located. Some systems have been fairly successful at reducing the range of exposure levels. However, these systems have failed to address other important characteristics of the system.

To be clinically useful, the procedure must be a relatively quick process. In processes lasting longer than a normal "breath-hold", the patient often moves. Any patient motion during the imaging can make the image useless. Additionally, the procedure should not add so much material so as to require a higher amount of radiation exposure to the patient. Many of the systems developed and studied thus far have produced undesirable results in terms of these two characteristics.

The study seeks to test the ability and practicality of a recently designed device to equalize the exposure levels in the different areas of a CR image. If successful, further work can be conducted to expedite the process and ensure limited additional exposure to the patient.

The device is a block of acrylic housing four individual filter columns that can be manually filled with iodinated contrast solution. The iodinated contrast solution blocks some of the radiation from passing through. A relationship between the volume of iodinated contrast solution and its effective reduction in exposure is developed using a set of test data for three different power levels of the system. These relationships are then used for different sets of experiments to understand if the device produces the desired results.

One set of experiments looked at the performance of the device at different thicknesses of material (acrylic). These different thicknesses served to represent different amounts of body tissue that might be found in different sized patients. In these experiments, different thicknesses of aluminum were arranged on top of the acrylic base. The different aluminum thicknesses represented the different types of body tissue within the chest cavity. Each experiment was run a total of four times to assess the consistency in the device's performance. In each experiment, a scout image was taken to measure the exposure levels under each of the filter columns. Each contrast column was located over a different thickness of aluminum.

From the scout image, the radiation levels in the image due to the different thicknesses of aluminum were measured and a signal difference was established. This signal difference could then be entered into the model created between iodine volume in the column and the resulting effective exposure reduction in the image. From this relationship one can then calculate the amounts of iodine to inject into each of the columns to reduce the range of exposure contrast in the image. This study was conducted at three different base amounts of acrylic and at three different radiation power levels. As already mentioned, each experiment was run a total of 4 times resulting in a total of 36 experiments. The experiments were then run again with the calculated volumes of iodinated contrast solution in each column. The exposure levels in the resulting image were then compared to the previous image under each column. This comparison yielded a final percent difference in exposure level between each column and the target that could be compared to the beginning percent difference in exposure level.

The other experiments were conducted specifically at an x-ray power level more characteristic of clinical chest CR scans. This study also consisted of running four repetitions of each experiment at various amounts of acrylic to understand more the reliability of the relationship between iodinated contrast volume and reduction in radiation exposure level. The method used in the experiments in this study was the same as the one described above used for different acrylic thicknesses and power levels. The improvement in contrast was again measured using the comparison made between before and after percent difference in exposure levels.

A statistical analysis was conducted on the resulting exposure levels to test whether they were truly equalized by looking at the mean and the variance in each case.

It was determined from this study that the method and device were successful at reducing the exposure levels to reduce the contrast range within a single image. This was done with a fairly imprecise syringe used for measurement of contrast volume. A more accurate method of delivering iodinated contrast medium to the columns would improve the resulting image contrast. Theoretically, this implies that the contrast would be improved and finer differences in exposure levels such as in a fracture could be detected. With this improvement in exposure levels, further work can be conducted to develop a rapid automated method for injecting the columns with iodinated contrast so as to improve the total speed of the system. In addition, more detailed studies can be conducted with an already constructed prototype device. This device has smaller and more numerous columns so finer control of contrast across the image will result. It is designed for us with an automatic injection method and so it is ideal for the next step of the project.