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Title: Patient Radiation Exposure Variability and Minimization in Mobile, C-arm Fluoroscopy

Abstract approved:

Camille J. Lodwick

BACKGROUND: The frequency of C-arm fluoroscopy procedures is increasing and it has become prudent to increase the awareness of patient radiation exposure to minimize patient risk. There is a strong potential for variability in patient exposure levels and a need for minimizing unnecessary exposure. The variability in C-arm fluoroscopy can be characterized in 2 parts; settings and techniques under the control of the C-arm operator, and the automatic fluoroscope output differences based on equipment type and patient size.

METHODS: The two areas of potential variability were studied in the current literature and through exposure measurement research. In order to examine the inherent variability in patient exposure, radiation exposure data were collected from 99 C-arm units, encompassing 21 medical sites, primarily hospitals, with the C-arm units that were in use at these sites. Measurements were conducted to analyze the variation in patient exposure, overall, per site, and per machine manufacturer, using the standard 1.5 inch aluminum attenuation block. Additional measurements were conducted to analyze the variation as a function of patient thickness using multiple 1 inch thick Lucite plates.

CONCLUSIONS: Significant patient exposure variability exists in C-arm fluoroscopy and there is potential for unnecessary exposure. Based on literature review and measurement results, the ability to minimize patient exposure relies both on the equipment operator and the inherent design of the C-arm equipment. Measurements demonstrated up to a 261% difference in exposure rates when compared between C-arm manufacturers. Comparison within manufacturers suggests that newer models have improved technology, reducing both exposure rates and associated variability. Exposure rates increased as a function of patient thickness, demonstrating about a 350% increase in dose when patient thickness went from 4 to 8 inches. Recommendations for optimizing operator controlled and equipment design factors are presented.

Patient Radiation Exposure Variability and Minimization in Mobile, C-arm Fluoroscopy

by
Robert T. Van Wieren

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APPROVED:

Major Professor, representing Radiation Health Physics

Head of the Department of Nuclear Engineering and Radiation Health Physics

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Robert T. Van Wieren, Author

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Patient Radiation Exposure Variability and Minimization in Mobile, C-arm Fluoroscopy

1. INTRODUCTION

Medical radiation exposure levels have risen dramatically in recent years[1]. Considerable advances in medical imaging technology have resulted in a number of new and useful applications for improving patient diagnosis and treatment. This increasing use requires an increased focus on minimizing patient radiation exposure to ensure that the medical benefits outweigh the radiation risks.

The largest increases in radiation exposure to the United States population have been shown to result from patient exposure during medical procedures[2]. Considerable focus has been given to the procedures that involve the highest potential for elevated medical radiation exposures, including cardiac catheterization, interventional radiology, and computed tomography[2]. While studying and optimizing these procedures may have the greatest potential for keeping radiation dose to a minimum, another area of concern exists. The availability and use of mobile, C-arm fluoroscopy is also rising steadily. Many of the procedures performed with this type of equipment do not result in the exposure levels of the previously listed procedures, but the overall large amount of different uses for this equipment has the potential to significantly affect the patient population dose[3]. In addition, the availability and ease of use of mobile, C-arm fluoroscopes allows them to be operated by a number of different personnel with differing levels of radiation safety training. Considering this, there exists a strong

potential for variability in patient exposure and potential for minimizing unnecessary exposure.

The purpose of this thesis is to examine factors involved in radiation exposure variability of C-arm fluoroscopes, consider methods of reducing this exposure, and educate operators of this equipment in order to minimize patient radiation exposure. A two-part approach will be taken to accomplish this purpose. First, the exposure variability factors that are under the control of the C-arm operator will be reviewed through published literature. A review of these procedures and important considerations will be discussed in order to analyze the importance of C-arm operator education in the role of minimizing patient exposure during these procedures. The second part of the approach will focus on the variability in C-arm exposure rates that is inherent in the design of the equipment. In order to investigate the variation of different types of C-arm units, measurements will be conducted using the same 1.5 inch aluminum attenuation block with the same geometry at various medical sites with the C-arm machines currently in use at these sites. The goal will be to show potential differences in patient exposure rates based on the demands of each type of C-arm unit. Additional measurements to analyze the variation in exposure rates as a function of patient thickness will be performed using Lucite slabs. This is another factor that affects patient exposure that is outside of the operator's control. It is hoped that these measurements will improve awareness to potential variations in patient exposure during C-arm procedures and point out any areas of potential unnecessary exposure.

2. LITERATURE REVIEW AND BACKGROUND

2.1. Medical Radiation Exposure Trends

Medical procedures have historically been a major contributor to the overall ionizing radiation exposure of the population[2]. It has been justified, in part, by the benefits gained in diagnosis and treatment outweighing the risk of radiation exposure. Recent studies are causing concern due to an increase in medical radiation exposure. The National Council on Radiation Protection and Measurements (NCRP), a United States advisory body on radiation protection, has documented this fact. According to the NCRP Report 160 (2009), the largest radiation exposure increase to the United States population, since the previous NCRP Report 93 (1987), is a result of medical patient exposures. NCRP Report 93 reports an average annual exposure from medical procedures as 0.53 mSv (53 mR), compared to 3.0mSv (300mr) in NCRP Report 160. The result is a 600% increase over the 22 year period between these reports[2]. While improving technology has allowed reduction of individual exposures in many cases, the overall increase in radiation exposure can be attributed to a large increase in the number of procedures being performed. Figure 1 shows the overall contributors in population radiation exposure based on NCRP Report 160:

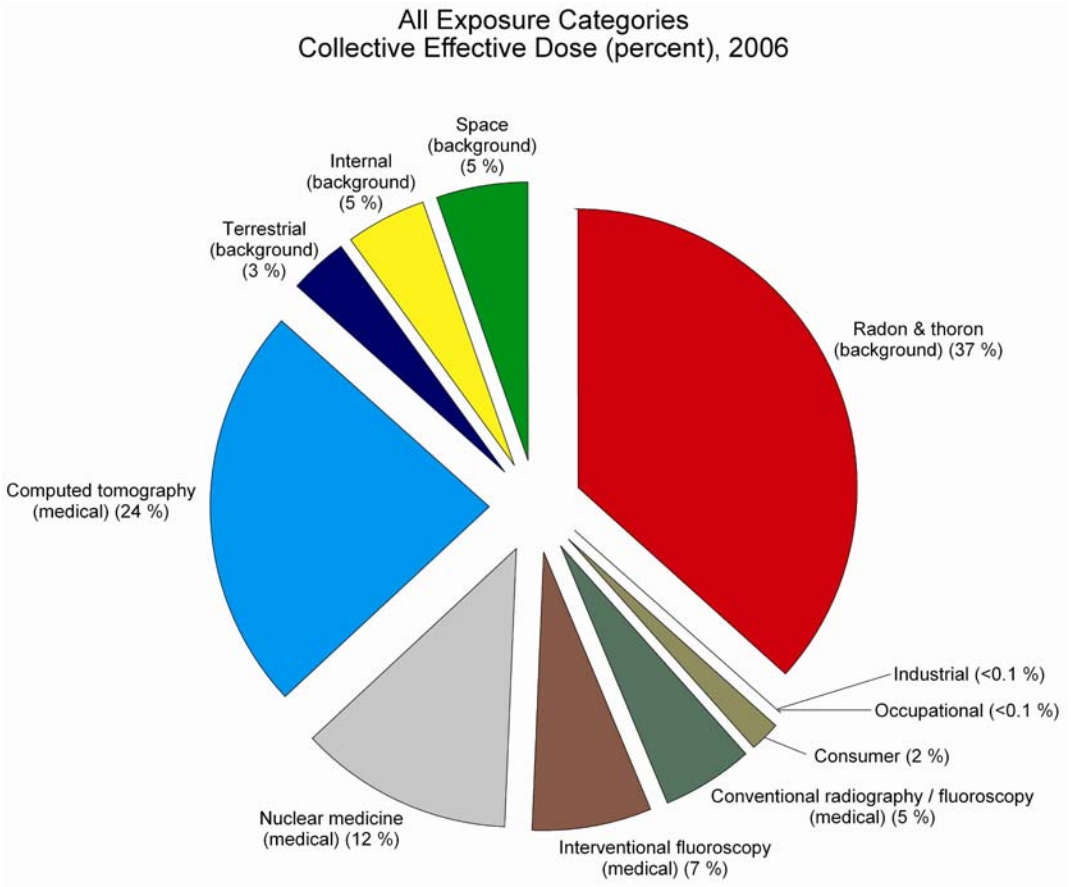

Figure 1. Percent contribution of population dose. NCRP Report 160.

Also of concern, the Center for Devices and Radiological Health of the Food and Drug Administration (FDA) has identified a number of reported cases of radiation injury to the skin of patients as a result of interventional fluoroscopic procedures. The injuries have ranged from skin burns (erythema), to skin death (necrosis) which required skin grafting. FDA also believes it is probable that the reported injuries are only a fraction of the actual number of incurred injuries[3]. Investigation of these reported injuries revealed those performing the procedures lacked understanding of the magnitude of skin dose that could result from long fluoroscopy exposures[4].

FDA issued recommendations for reducing the potential for radiation-induced skin injuries as follows[3]:

- Establishing standard procedures and protocols for each procedure, including consideration of fluoroscopy exposure time.
- Determining the radiation dose rates for specific fluoroscopy systems and for all operating modes.
- Assessing each protocol for the potential for radiation injury to the patient.
- Modifying protocols, when appropriate, to minimize cumulative absorbed dose to any specific skin area and using equipment which aids in minimizing absorbed dose.

In addition, the FDA suggested that exposure information be recorded for each patient to allow estimation of the skin dose received from each procedure[5].

In response to the growing concern over medical radiation exposure in fluoroscopy, the Conference of Radiation Control Program Directors (CRCPD) has issued a resolution on the prevention of unnecessary patient fluoroscopy exposure[6]. This resolution recognizes:

- The potential for radiation-induced skin injuries due to the increase in the number, type, and time of many fluoroscopic procedures.
- The lack of a comprehensive patient exposure monitoring system.
- A number of different personnel operate fluoroscopy equipment, including some who do not have training in radiation safety and radiation biology.

Based on these realizations, the resolution resolves:

- Encouragement of appropriate training and education for all fluoroscopy users to understand exposure variables, radiation safety, and radiation biology.
- Monitoring and recording of patient exposure.
- Comparing radiation exposures to established standards.

Through all of this, it has become evident that knowledge of the variables involved in fluoroscopy exposure to patients has become very important for personnel administering these procedures.

2.2. Relevant Fluoroscopy Studies

A positive result of these reports of medical exposure increase is a renewed concern for minimizing patient radiation exposure. The goal in medical imaging should always be to obtain the necessary clinical information with the least amount of radiation exposure. This requires an understanding of the imaging modality and the variables involved in patient dose and image quality. The areas of largest growth and highest exposure have received the most attention in the literature, which is prudent. The procedures using the most radiation dose also have the most potential for dose optimization. Interventional radiology and cardiac catheterization procedures were one of the major contributors to the medical radiation dose increase shown in NCRP Report 160. A review of current literature shows:

- The complexity of interventional fluoroscopy has been increasing rapidly along with increasing use of fluoroscopic guidance for these complex procedures[7].

- Significant variation in fluoroscopic exposure rates (4 to 6 fold) for similar patient sizes[6].
- Exposure variation was not consistently linked to improved image quality[6].
- A wide variation in patient radiation dose is due to clinical technique differences, and types of equipment used[7].
- Dose-area product (DAP) monitors on fluoroscopy equipment are inadequate, on their own, in measuring exposures and associated risks[7]. DAP estimate uncertainties can be as much as 30-40%[8].
- The actual extent of skin injury issues is largely unknown since there are no current requirements for reporting or maintaining this information[9].

The wide variation of interventional fluoroscopy exposure indicates that there is potential for reducing patient exposure in a number of cases. The uncertainties and complications of dose-area product monitors on the fluoroscope make reliance on this technology alone insufficient.

While much of the literature on fluoroscopy exposure is focused on fixed interventional and cardiac catheterization laboratories due to the potential for very high doses, other fluoroscopy modalities also offer the potential for high exposures. C-arm fluoroscopy units are used in a number of surgical procedures, some having similar potential for radiation induced skin injuries. Even for the many lower-exposure procedures performed with C-arm fluoroscopes, there is potential for unnecessary exposure. The availability and ease of use for these units makes them a popular choice for a growing number of procedures. In addition, the users of this equipment may not always be trained in radiation safety and radiation biology. An inclusive radiation safety program should always seek to keep radiation exposure to

levels as low as reasonably achievable (ALARA) through monitoring and user education. Mobile C-arm fluoroscopy exposure monitoring and minimization has become very important and is the subject of this study.

2.3. Biological Effects of X-Ray Exposure Overview

In order to understand why exposure minimization in C-arm fluoroscopy is important, a basic background of the biological effects of radiation is important. This section is meant to provide an overview of the interaction of x-rays in the body, effects on cells and deoxyribonucleic acid (DNA), different cell sensitivities, deterministic versus stochastic effects, and radiation exposure risk estimation.

X-ray photons deposit energy when they are absorbed. Because of the probabilistic nature of x-ray interactions, energy is deposited unevenly in 'packets' of energy. The primary result of this energy being deposited is the creation of fast electrons, termed *ionization*. The fast electrons can ionize other atoms in this tissue, resulting in the breaking of chemical bonds, which can lead to biologic damage. The energy of diagnostic x-rays primarily results in indirect ionization, meaning the fast electron interaction occurs in the surrounding water molecules rather than the critical DNA structure in the cell. This interaction produces free radicals, which are highly reactive, and can result in chemical changes by breaking bonds in the more sensitive part of the cell. It is estimated that approximately 66% of the biologic damage from x-rays occurs through the indirect action of free radicals[10].

There is strong evidence that the DNA is the critical part of the cell for biologic damage due to radiation. The basic structure of the DNA molecule consists of two spiral strands connected by hydrogen bonds. The ionization

produced by x-rays can cause a break in one or both strands of the DNA. Breaks in a single strand of the DNA occur most frequently, but are readily repaired by the cell. However, breaks in both strands, opposite of each other, are believed to lead to biologic damage that includes cell death, carcinogenesis, and mutation[10]. Studies of cells exposed to radiation have shown the most sensitivity to radiation damage occurs during cell division, or mitosis[10]. Thus, cells that divide more rapidly will have a higher percentage in the mitosis phase and will be more sensitive to radiation damage. A result is that certain tissues in the body are more vulnerable to the effects of x-rays, and also explains why children are more sensitive to radiation than adults. This fact makes exposure reduction in fluoroscopy even more important for pediatric or young adult patients as well as procedures involving radiosensitive tissues such as the breast.

If the radiation dose is large enough, certain tissues in the body will be affected. Tissue damage from radiation doses can be divided into two categories: non-stochastic (deterministic effects) and stochastic risk (cancer risk). Deterministic effects occur after a threshold dose has been reached and the severity of the effect increases as the dose increases above this threshold. The most notable deterministic effects for patient exposure during fluoroscopy are skin effects. The threshold doses and various deterministic effects for the skin are summarized in Table 1 below:

Table 1. Deterministic skin effects from acute skin exposures.[10]

Skin Dose Range (Gy)	Prompt Effects	Early Effects	Mid Term Effects	Long Term Effects
2 - 5	Transient erythema	Epilation	Epilation recovery	None expected
5 - 10	Transient erythema	Erythema; epilation	Prolonged erythema and permanent epilation possible	Recovery likely; possible dermal atrophy
10 - 15	Transient erythema	Erythema; Epilation; moist desquamation possible	Prolonged erythema and permanent epilation	Telangiectasia; dermal atrophy
> 15	Transient erythema; edema and acute ulceration	Erythema; Epilation; moist desquamation	Dermal atrophy; secondary ulceration; dermal necrosis possible	Telangiectasia; dermal atrophy; skin breakdown and deep lesions likely

The stochastic (cancer) risk occurs when the exposed cell has been modified by the irradiation, but continues to live. There is typically a considerable time period between exposure and onset of malignancy, termed latency. Latency periods can range from 5 to 7 years for leukemia, to 60 years or more for solid tumors[10]. Studies of atomic bomb survivors have shown higher cancer probabilities at high dose levels and the data are linearly extrapolated to conservatively predict increased risk at lower doses. The Biologic Effects of Ionizing Radiation (BEIR) VII reports published in 2005 by the National Academy of Science is the latest analysis of stochastic risks from radiation exposure[10]. The most radiosensitive organs at risk for cancer induction are thyroid, stomach, colon, liver, lung, female breast, uterus, ovaries, prostate, and bladder. Physicians considering radiation

exposure risks should be especially sensitive to procedures that involve exposure to parts of the body that include these radiosensitive organs. Overall, stochastic risk estimation for low doses remains difficult to quantify. The International Council on Radiation Protection (ICRP) has suggested a risk estimate, based on the BEIR reports, of 0.05 excess cancer deaths per sievert of dose for low doses and low dose rates for the general population[10].

2.4. Mobile C-arm Fluoroscopy Overview

The function of mobile C-arm fluoroscopy units is to provide real-time images and the ability to view dynamic anatomical or surgical functions as they occur. These units are able to provide precise and fast moving x-ray images in a wide variety of medical situations. The system can be easily transported to many different locations. The advantage of a mobile system is that the imaging system can be brought to the patient, rather than bringing the patient to an imaging room. This makes these units ideal for a number of medical procedures including neurological function imaging, vascular function imaging, therapeutic needle insertion procedures, and orthopedic surgical imaging. The ability to view internal functions externally allows the procedure to be performed with much less invasiveness. The convenience, versatility, and ease of use of these systems, along with an increased cost-effectiveness, make them very popular.

The fluoroscopic imaging components are illustrated in Figure 2.

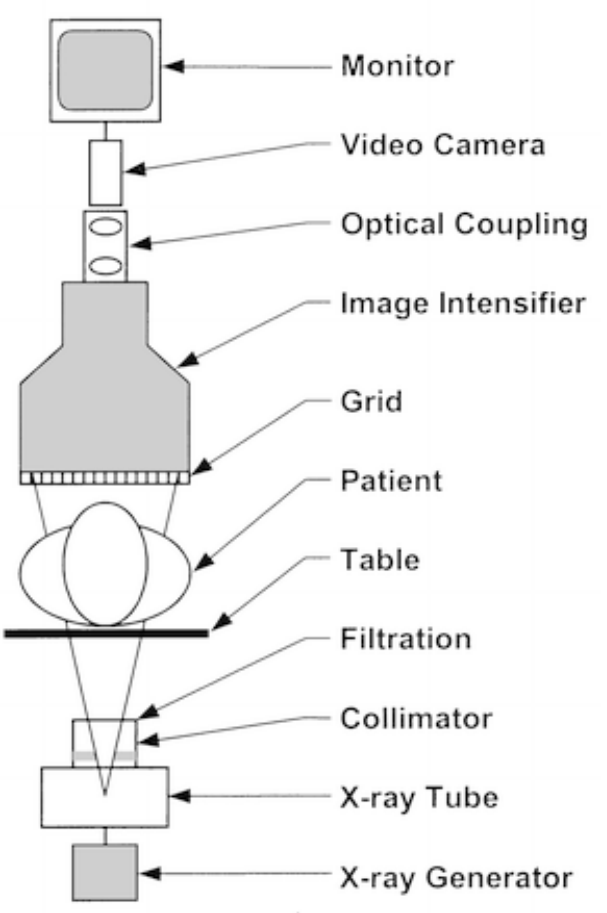

Figure 2. Fluoroscopic Imaging Components.[11]

The imaging process starts with the x-ray generator. The generator provides control of the peak kilovoltage (kVp) and milliamperage (mA) that is sent to the x-ray tube. The generator also controls the choice of continuous or pulsed imaging by delivering the mA in a continuous or pulsed fashion. The choice of pulsed fluoroscopy reduces the patient exposure rate, but results in a flickering image that may not be ideal in some imaging situations. However, the short pulses are better at reducing the motion blur of fast-moving structures. Another very important generator control is automated exposure control, also referred to as automatic brightness control

(ABC). This feature varies the output of the generator electrical energy (kVp and mA) according to the thickness and density of the patient in order to provide consistent image brightness. In other words, as the area being scanned attenuates more x-rays, the unit automatically increases exposure factors to compensate and produce an acceptable image. As a result, the ABC function is also controlling the radiation exposure to the patient.

The x-ray tube uses the kVp and mA sent from the generator to produce x-rays. X-rays are produced by accelerating electrons and converting the kinetic energy of the electrons into electromagnetic radiation. An illustration of the basic components of an x-ray tube is given in Figure 3 below:

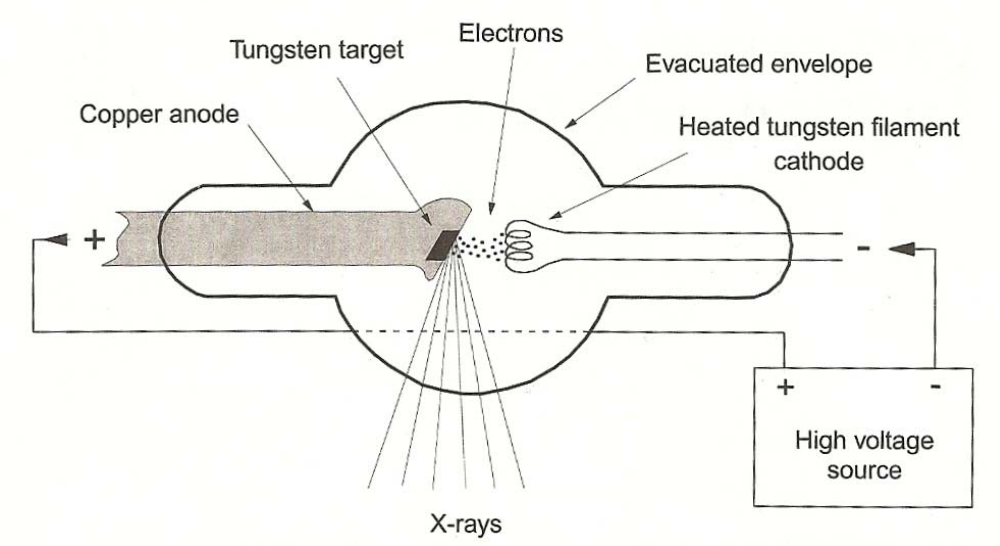

Figure 3. X-ray Tube Components[12].

The electrical energy reaches the x-ray tube in a heated filament at one end of the evacuated tube. At the other end, a positively charged anode draws the electrons from the filament, accelerating them through the vacuum according to the large potential kilovoltage difference. The electrons interact with the anode (usually made of tungsten) nuclei and are decelerated. This

deceleration converts the kinetic energy to x-ray photons, termed *bremsstrahlung*. The energy of the x-rays varies depending on the proximity of the electron interaction with the target nucleus. Additional x-rays are produced when accelerated electrons interact with inner shell electrons in the target. When the energy is high enough to eject an inner shell electron, an electron from an outer shell drops to fill the vacancy and an x-ray photon is produced which is equal in energy to the difference in shell energy levels. This photon is termed a *characteristic x-ray*, because they are produced at discreet energies that are characteristic of the element involved.

The next component, the collimator, controls the size of the focused x-ray beam. This is done with moveable shutter blades that fully attenuate the x-rays. Many units allow the choice of either rectangular or circular beam collimation. The collimation limits the size of the x-ray beam to the area of the image intensifier. Since the C-arm provides a fixed orientation of the x-ray tube and image intensifier, this prevents the primary x-ray beam from traveling any further, protecting the area beyond. The C-arm user can adjust the beam down further to only the area of clinical interest which prevents unnecessary patient exposure.

Before the beam reaches the patient, it passes through aluminum filters. The bremsstrahlung produced by the x-ray tube creates a spectrum of x-rays, some useful in medical imaging and some are not. The filtration attenuates the lower-energy x-rays that would end up being absorbed by the patient instead of contributing to the image, thus reducing patient exposure without affecting the image quality.

The patient table must attenuate the x-rays as little as possible to reduce the amount of radiation needed, and optimize image quality. A common

material for this is carbon fiber as its attenuation is low, but is strong enough to provide proper patient support.

After the x-ray beam passes through the table and patient, it encounters the grid. The primary purpose of the grid is to intercept scattered x-rays before they reach the image intensifier. Scattered x-rays are traveling on an altered path compared to transmitted x-rays. The result of allowing scattered x-rays to reach the image is a loss of sharpness and reduced image contrast. While the grid improves image quality, it comes at the cost of increased exposure. In cases of minimal scattered radiation, due to a reduced field size or a small anatomy thickness, the use of the grid may not be necessary, and would greatly reduce patient exposure. However, the removal of the grid may not be easy or even possible depending on the fluoroscope.

Once the transmitted x-rays are ‘cleaned up’ by the grid, they reach the image intensifier. Here the x-rays are absorbed by the input phosphor (usually made of cesium iodide) and converted into a visible light image. This image is then intensified by a factor of about 10,000 in order to make it viewable. The components of the image intensifier are shown below in Figure 4:

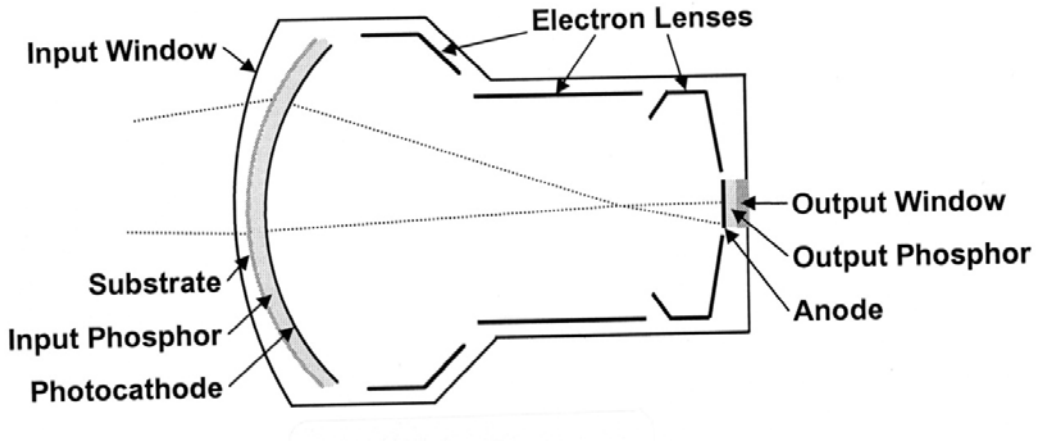

Figure 4. Image intensifier components[7].

The image intensifier allows selection of different image magnifications or fields of view. As the magnification is increased, the amount of radiation exposure also must increase. This is an important consideration when trying to minimize patient exposure.

The optical coupling sends the light from the image intensifier to multiple components. This usually includes a video camera for the television monitor and other recording devices. This system allows real-time viewing and recording of the fluoroscopic images.

Each of these components, in a compact, mobile configuration, adjustable in each imaging axis, make up the C-arm fluoroscope. The monitor is typically separately mobile to allow multiple viewing positions. A typical C-arm unit is illustrated below in Figure 5:

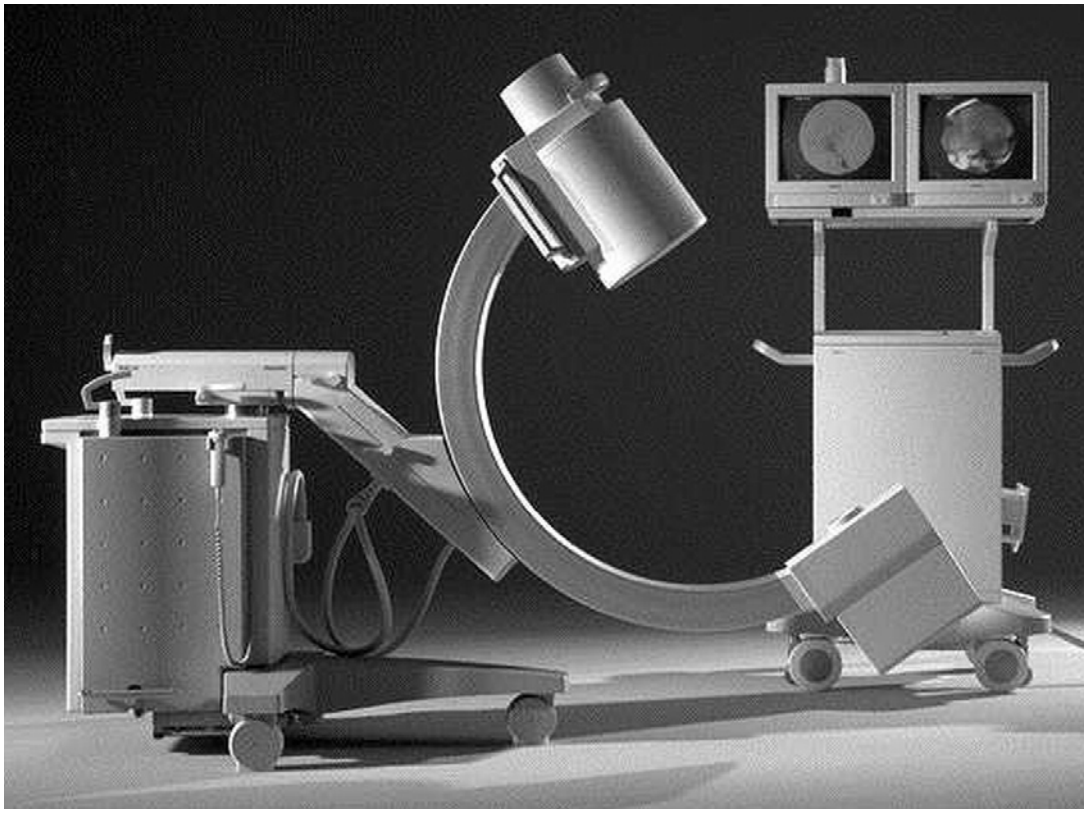

Figure 5. Mobile C-arm fluoroscope. (Courtesy of Philips Medical Systems North America, Shelton, Conn.)[7].

Levels of patient radiation exposure from C-arm fluoroscopy are not insignificant. Entrance exposure rates for an average sized patient are typically in the 2 R/minute range. Considering a chest x-ray entrance exposure is typically 15 mR, 1 minute of fluoroscopy would be roughly equivalent to 130 chest x-rays[13].

2.5. Monitoring Patient Exposure

In an attempt to allow monitoring of patient exposure, many C-arm units are equipped with a Dose-Area-Product (DAP) meter. These meters are large-area, transmission ionization chambers. The ionization chamber is placed

perpendicular to the x-ray beam central axis and intercepts the entire area of the x-ray beam. The DAP, with known information on x-ray field size, can be used to determine the average dose produced by the x-ray beam at any distance from the location of the ionization chamber multiplied by the area exposed. DAP is typically expressed in units of gray-cm^2 (Gy-cm^2). A recent improvement in the ionization chamber design used in DAP meters has resulted in an instrument that measures both DAP and the dose delivered by the x-ray beam. This design effectively combines data from a small ionization chamber that is completely irradiated by the beam and independent of the collimator adjustments with the conventional DAP meter[14].

DAP meters have been in use for a number of years, and were actually used in the 1964 and 1970 U.S. X-ray Exposure Studies. Many will contend that the DAP is a better indicator of risk than entrance dose alone, since DAP uses the entrance dose and the area exposed. DAP has been shown to correlate well with the total energy imparted to the patient, which is related to the effective dose and therefore to overall cancer risk[9].

However, there are several issues with the use of the DAP value. The configuration of the DAP meter may introduce a bias to the DAP value. If any material is placed between the meter and patient, the patient will be exposed to less than what is indicated by the DAP value. In many cases, this would be the patient table. Overall, the use of DAP to measure skin entrance exposure or skin dose is complex. This is complicated by fluoroscopic procedures where multiple beam directions, source-skin distances, and field sizes are used. These meters are also difficult to calibrate and maintain. Large variation in the DAP meter response can happen over time, and calibration needs to be done after any major changes

in equipment or usage and at least annually. The DAP meter indication does not include and x-ray field non-uniformities, or backscatter produced during exposure. In addition, the actual dose to the patient is dependant on patient body characteristics which cannot be accounted for by the DAP meter[15].

2.6. Fluoroscopy Exposure Regulations

The U. S. Department of Health and Human Services, Food and Drug Administration (FDA) regulates x-ray equipment performance for diagnostic radiation emitting products. There are a number of standards that apply specifically to limiting fluoroscopic exposure to patients, summarized as follows[16]:

- Filtration standards are in place to ensure that the fluoroscopy unit has enough filtration to remove the low-energy bremsstrahlung x-rays that would otherwise add to the patient exposure without contributing to the image.

- X-ray beam limitation standards are in place to ensure that the size and alignment of the x-ray beam is no larger than needed to produce the necessary images.

- Standards have also been set to establish a minimum source to skin distance of 30 centimeters for C-arm units, preventing the patient from being too close to the x-ray source where the rate of exposure is very high.

- In an effort to make fluoroscopy operators aware of the total exposure time during the exam, a timer is required which after five minutes produces a signal and requires a timer reset.

- Dose rate standards are in place to limit the maximum exposure rate for any fluoroscopy unit to 10 R/min (88 mGy/min.).

- Last-image hold (LIH) is required for fluoroscopic equipment manufactured on or after June 10, 2006. LIH continually displays the last fluoroscopic image, even after the exposure has stopped. This allows operators to study details of the image without having to produce a continuous exposure.

- Also for units manufactured on or after June 10, 2006, the air kerma rate and cumulative air kerma (DAP meter) readings are required to be displayed.

While these standards work to limit patient exposure during fluoroscopy, there are areas that are not regulated. The maximum rate of exposure is limited, but this rate is well above the normal exposure rate needed for most patients. There is no definition of what a 'normal' exposure rate really should be, allowing much room for variability. In addition, there are no limits for the total amount of exposure or fluoroscopy time per exam. This decision is left up to the judgment of the operator of the equipment.

2.7. Operator Controlled Exposure Variability

Even though the exposure factors (kilovolts and milliamps) are selected automatically by the C-arm's automatic brightness control, the C-arm

operator still plays a role in patient exposure. The first, and most obvious, factor controlled by the C-arm operator is the exposure time. Depending on the type of procedure, a certain amount of fluoroscopy time will be needed to visualize what is needed. However, the efficiency of the visualization process may be highly variable depending on a number of factors including operator training and experience, patient cooperation, and a conscious effort to expose only as needed[17]. Most radiologists are trained to use the fluoroscope intermittently to view patient and device positioning rather than using a continuous exposure. This technique makes full use of the last image hold feature of the C-arm.

Another very important patient exposure variable that is under control of the operator is patient positioning. The important consideration in patient positioning is keeping the patient as far from the x-ray tube, and as close to the image intensifier as possible. This not only minimizes patient exposure, but maximizes image quality due to the decrease in scattered radiation reaching the image. In many cases, acceptable images can be obtained without optimal positioning so awareness again is vital. Figure 6 below illustrates optimal and suboptimal positioning geometry:

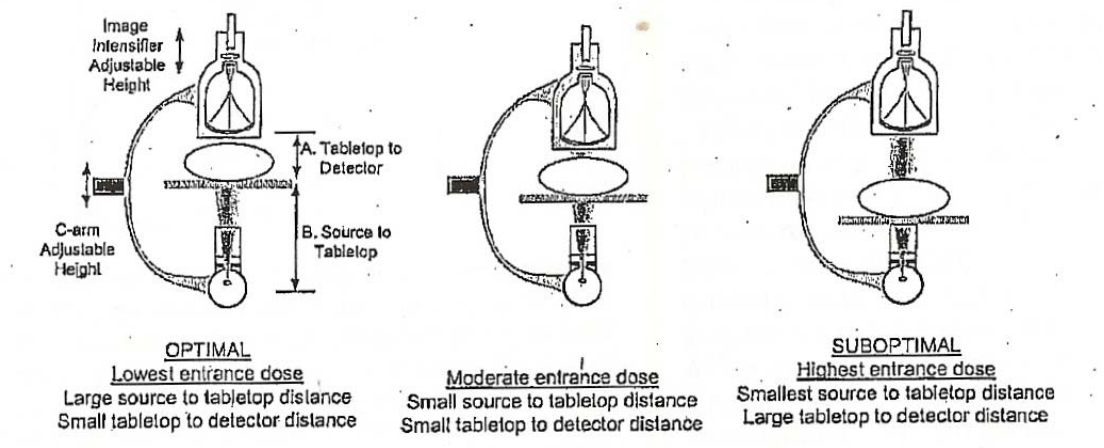

Figure 6. Patient positioning variability[18].

In some cases, the size of the full fluoroscopic beam may exceed the size of the area being imaged. In this situation, the operator can reduce patient exposure by reducing the size of the x-ray beam using the adjustable collimator. While this does nothing to change the intensity of the x-ray beam striking the patient, it does reduce the amount of patient area receiving exposure. Any radiation striking the patient that does not contribute to the image is unnecessary and should be eliminated.

Sometimes the image must be magnified in order to visualize smaller details. The amount of image magnification needed for the procedure can be controlled by the operator. Magnification is achieved electronically by focusing a smaller radiation image intensifier input area over the same image intensifier output area. This results in a reduction in radiation reaching the image intensifier and the automatic brightness control system compensates by increasing radiation production which increases the exposure. The use of magnification modes should be kept to a minimum to reduce dose to the patient[19]. Figure 7 below illustrates electronic magnification and associated radiation exposure increases:

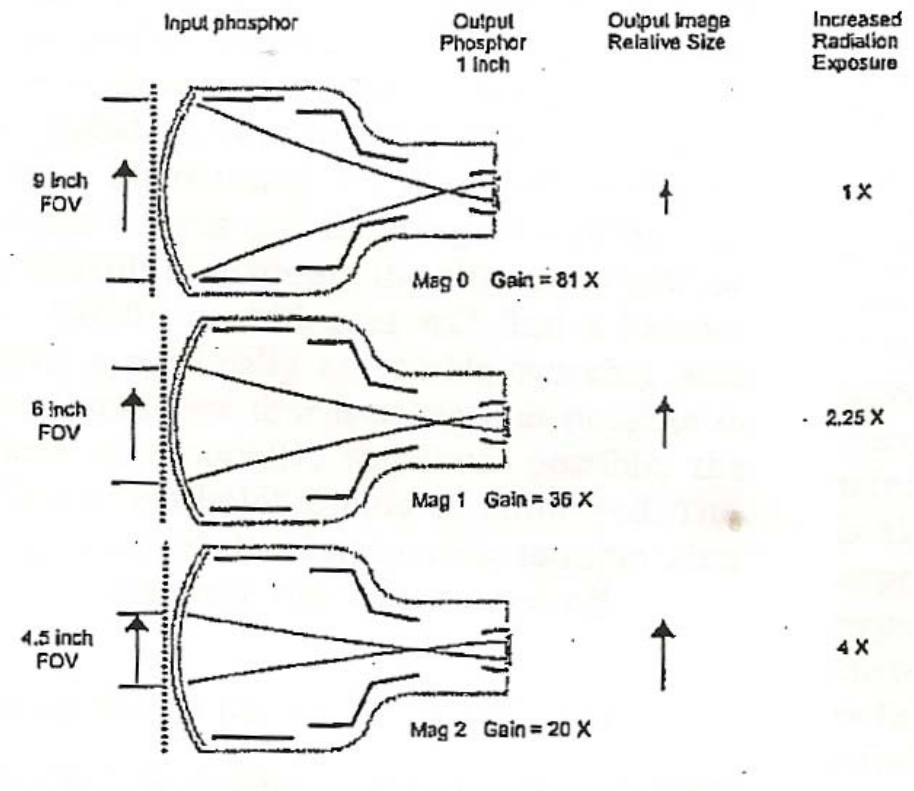

Figure 7. Electronic magnification and radiation exposure effects[23].

Pulsed fluoroscopy, rapid bursts of radiation instead of continuous, can also be used to minimize patient exposure. Modern C-arm units allow the operator to select different pulse rates. Slower pulse rates reduce the amount of exposure, but result in 'flickering' of the real-time image. The loss of image quality may be a deterrent to the use of pulsed fluoroscopy in many cases. The use of pulsed fluoroscopy can result in a 22% to 49% exposure reduction[21]. However, the demands of the procedure and the amount of familiarity with a pulsed image may dictate how much it can be used[20].

2.8. C-arm Fluoroscope Operator Training.

The proper use of a C-arm fluoroscope and the operator controlled variables affecting patient dose ultimately comes down to the training, experience, attitude and awareness of each user. C-arm procedures are performed by a variety of medical personnel. A study of fluoroscopically guided interventional pain procedures in university pain clinics showed significant differences in fluoroscopy exposure times and radiation exposures among different teaching physicians, even in the same university setting[21]. This suggests a possibility that some procedures are being performed using higher exposures than necessary, depending on the operator. Another study searched for the word “radiation” in non-radiology journal articles dealing with vertebroplasty and kyphoplasty C-arm procedures. Only 1.3% had any discussion of radiation dose to the patient[22]. The study suggests that there may be a lack of knowledge or an indifference to radiation exposure issues. It also suggests that procedures may be conducted without training or understanding of fluoroscopic imaging equipment, related exposures, and safety issues.

Uniform national standards addressing necessary qualifications to operate fluoroscopy systems, or what minimum level of training is needed, do not exist to date[23]. Radiologists receive special training in radiation biology and radiation safety, however many other physicians do not. Most medical specialty boards do not include these radiation topics in their curriculum[23]. Considering the increasing availability and use of C-arm fluoroscopy, and the number of operator controlled variables in patient exposure, there is a surprising lack of formal training in radiation safety and a significant need for improving operator training for C-arm fluoroscopy.

3. INHERENT EXPOSURE VARIABILITY TESTS

3.1. Purpose

There are a number of variables in patient fluoroscopy exposure that can be minimized by a properly trained C-arm operator. However, since a primary radiation output determinant is the automatic brightness control of the C-arm itself, its impact on patient exposure should be studied. Another critical factor in the variable exposure of the automatic brightness control is patient thickness. The automatic brightness control is intended to help balance radiation exposure and the required image resolution despite the patient's size by automatically adjusting the operating exposure settings. While this feature can be valuable, it is important to understand the correlation of additional radiation exposure that accompanies increased patient size.

In order to examine the inherent variability in patient exposure during C-arm fluoroscopy procedures, radiation exposure data were collected at 37 different medical sites, primarily hospitals, with the various C-arm units that were in use at these sites. An additional 43 measurements were conducted to determine the relationship that patient thickness has on skin exposure during C-arm procedures.

3.2. Materials

Following are the materials used for obtaining this data:

1. A variety of C-arm fluoroscopy machines were selected based on a sampling of 37 medical institutions and what units were in use at each of

these sites. There were a total of 99 C-arms tested, which included 9 different manufacturer and model combinations.

2. Attenuation blocks were used to simulate different patient sizes. These blocks are needed to intercept the x-ray beam and force the automatic brightness control to adjust the exposure rate accordingly. The first attenuator consisted of 1.5 inch thick aluminum having dimensions of 20 centimeters by 20 centimeters, of type 1100 aluminum alloy. This attenuator meets the FDA 21CFR1020 standards for a dose measurement attenuation block. The other attenuation blocks consisted of poly(methyl methacrylate) (PMMA) ("Lucite") in 8 sheets, 1 inch thick, with dimensions of 23 centimeters by 28 centimeters. This material was used for the patient thickness variability testing because it has a density of 1.18 grams per cubic centimeter, which is closer to the density of tissue for better patient thickness simulation.

3. An RTI Barracuda X-ray multimeter with R100B solid state detector was used for radiation exposure measurement. The detector size is 20 x 45 x 7.4 mm with an active detector area of 10 x 10 mm. The detection range is 0.1 mR/min through 3000 R/min with an inaccuracy of ±5 % or ±0.05 mR/min. The R100B is a solid state dose detector for the Barracuda multimeter. It is specially designed for low dose rate measurements. The detector is small to minimize interference with the automatic brightness control of the C-arm fluoroscopes. It can be used both for continuous and pulsed fluoroscopy and has a fast response which makes it ideal for pulsed fluoroscopy. It can detect the individual pulses, determine pulse rate and show waveforms even at the highest pulse rates used on modern fluoroscopy systems. It is not sensitive to backscatter and it does not need correction for temperature or pressure

and needs no bias voltage. The detector was fixed on the end of an aluminum extension piece to allow for proper positioning.

3.3. Solid State Detection Overview

An overview of the type of x-ray detection used for this project is included for additional background information. The main part of the R100B detector is a PIN semiconductor photodiode. Silicon and Germanium are commonly used materials in the production of photodiodes. When an x-ray photon strikes the diode, an electron is exited, resulting in a free electron and a positively charged electron hole. The holes move toward the anode, and the free electrons move toward the cathode, and a photocurrent is produced. The produced current is proportional to the intensity of the interacting x-rays. Since the diode responds differently to different x-ray energies, a filter is used in front of the detector to correct for its energy dependence. The produced photocurrents are measured with an electrometer and are converted to x-ray exposure values.

3.4. Methods

Entrance exposure data were collected from the C-arm units at 37 different medical sites, primarily hospitals in Michigan and Wisconsin, as a part of routine medical physics testing of the x-ray units at these sites. An additional 43 measurements were conducted to determine the relationship that patient thickness has on skin exposure during C-arm procedures. This random sampling should provide a reasonable representation of the types of C-arm units currently in use, including a range of models of varying ages. In order to examine the inherent variability in patient exposure from these different sites and different C-arm manufacturers, the x-ray exposure rates,

for a total of 99 C-arm units, were collected by positioning the C-arm, attenuation blocks, and x-ray detector according to Figure 8 below:

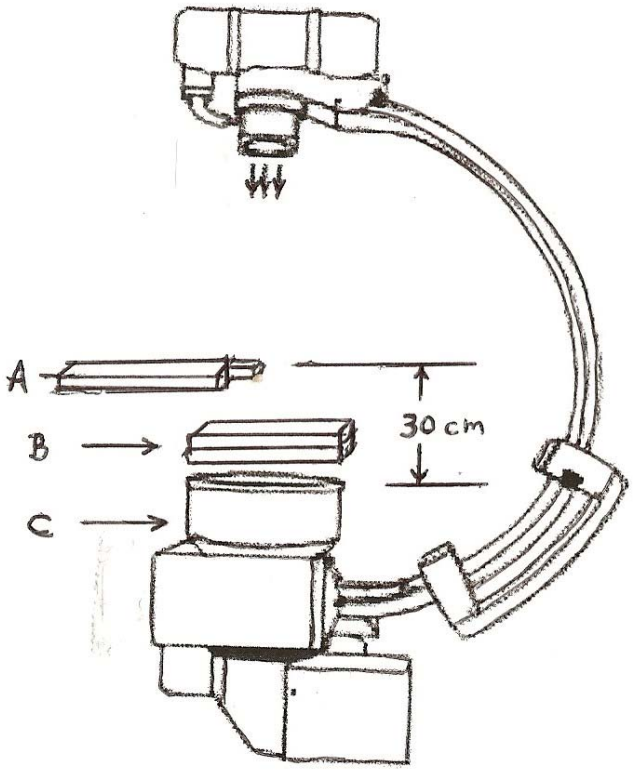

Figure 8. Entrance exposure measurement orientation. A) RTI Barracuda R100B solid state detector; B) Attenuation plates; C) C-arm image intensifier.

Positioning: Each C-arm unit was positioned in a vertical orientation with the x-ray tube up and the image intensifier down. For each measurement a tape measure was used to consistently measure and position the detector at a distance of 30 cm above the image intensifier. This is done to simulate

the point where the x-ray beam first enters the patient, which is the point of the highest exposure rate to the patient. In reality, this point changes depending on the size of the patient, but to allow inter-comparison of C-arm units, it was kept at a consistent 30 cm distance. The 1.5 inch aluminum and 1 inch Lucite plates were positioned on the image intensifier, intercepting the entire x-ray beam. The field of view closest to 20 inches was selected for all C-arm units and the beam was collimated to just inside the edges of the attenuation plates to prevent unattenuated x-rays from reaching the image intensifier and influencing the automatic brightness control.

Exposure: Once the unit, detector, and attenuators were properly positioned and powered up, the detector was set to read exposure rate, at the skin entrance point, in units of R / min (roentgens per minute of exposure). The exposure switch was activated and allowed to expose until the automatic brightness control and measured exposure rate stabilized. The resulting exposure rates were recorded for 99 C-arm x-ray units using the 1.5 inch aluminum attenuation block to assess the variation in patient exposure by C-arm manufacturer/model and by site due to the inherent automated response of the units to a standardized patient and geometry. An additional 43 units, from 21 different facilities, were measured to investigate the influence of patient thickness on their rates of exposure during a C-arm fluoroscopy exam. Lucite plates ranging in thickness from four to eight inches were utilized to represent varying patient thickness.

3.5. Results

Two sets of data were collected. The first set of data used the 1.5 inch aluminum attenuation blocks specified above as the attenuation according to

FDA 21CFR1020 requirements for dose measurement. Exposures were made using each unit's automatic exposure control settings and the resulting kilovolts peak (kVp), and milliamp-seconds (mAs), selected by the C-arm unit for the given amount of attenuation, were recorded along with the resulting skin entrance exposure rate in R/min. These data were collected at 37 different hospital sites with the C-arm units that were in use at each site. A total of 99 different C-arm units are represented. The data for these measurements are located in the appendix under Table A1.

The above data were sorted to analyze variation at each location, depending on the C-arm unit selected. The minimum and maximum exposure rates for each site and the percentage increase from the minimum to the maximum is listed for each site and overall in Table 2 below:

Table 2. C-arm fluoroscopy variation by location.

Site	Minimum Exposure Rate (R/min)	Maximum Exposure Rate (R/min)	Minimum to Maximum % Increase	Notes
A	2.67	2.67	0.00	
B	0.64	1.49	133	
C	0.71	1.24	74.6	
D	1.49	1.49	0.00	1 unit only
E	0.84	2.41	187	
F	0.99	1.56	57.6	
G	1.23	1.23	0.00	1 unit only
H	0.64	0.79	23.4	
I	0.82	1.18	43.9	
J	0.59	0.78	32.2	
K	0.71	2.61	268	
L	0.46	1.02	122	
M	0.87	0.87	0.00	1 unit only
N	0.71	0.72	1.40	

O	0.74	1.39	87.8	
P	1.32	1.32	0.00	1 unit only
Q	0.81	0.95	17.3	
R	2.48	2.48	0.00	1 unit only
S	0.92	2.02	120	
T	1.26	1.37	8.70	
U	0.83	1.44	73.5	
V	2.79	2.99	7.20	
W	0.53	1.51	185	
X	0.98	0.98	0.00	1 unit only
Y	1.40	1.40	0.00	1 unit only
Z	0.63	1.47	133	
AA	1.05	1.35	28.6	
BB	2.05	3.51	71.2	
CC	0.65	1.24	90.8	
DD	0.72	0.72	0.00	1 unit only
EE	0.68	0.68	0.00	1 unit only
FF	0.62	1.65	166	
GG	0.87	0.87	0.00	1 unit only
HH	0.72	1.54	114	
II	0.94	1.25	33.0	
JJ	0.69	0.81	17.4	
KK	0.76	0.92	21.1	
Overall	0.46	3.51	663	
	Low	High		

Because the exposure rate is primarily controlled by the requirements of each unit's automatic brightness control, the data were separated into groups by manufacturer and model. These data are listed in the appendix as Table A2. Units that had at least 10 data points were compiled and the average data for each unit is located in Table 3. Figure 9 plots the variation in average exposure rate for the six different C-arm units.

Table 3. C-arm fluoroscopy average exposure data by manufacturer.

	Average kVp	Average mA	Average R/min	Standard Deviation
Man.A/Mod.1	72.6	2.4	1.31	0.450
Man.A/Mod.2	73.7	2.5	0.92	0.225
Man.A/Mod.3	72.1	2.4	0.79	0.091
Man.B	66.8	3.3	0.75	0.216
Man. C	68.3	2.7	1.48	0.444
Man. D	65.8	5.9	2.71	0.422

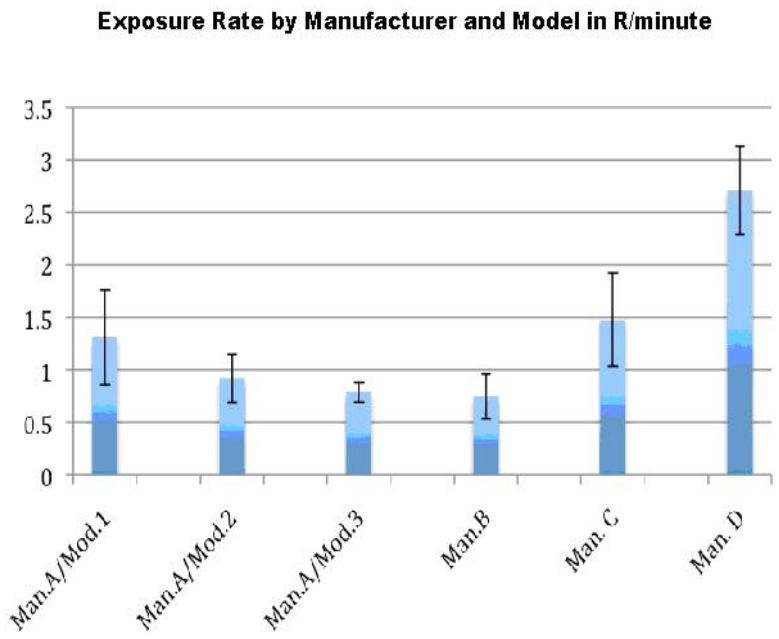

Figure 9. Exposure Rates by Manufacturer and Model.

The second set of collected data used 4, 6, and 8 inch thicknesses of Lucite plates specified above as the attenuation in order to determine the effect of varying patient thickness on exposure rates. Exposures were made using each unit's automatic exposure control settings and the resulting exposure rate in units of R/min was recorded. These data were collected at 21 different hospital sites with the C-arm units that were in use at each site. A total of 43 different C-arm units are represented. The data for these measurements are located in the appendix under Table A3.

Using the data from Table A3, the average exposure rate, for each Lucite thickness, was then calculated along with the percent increase in exposure rate. This was done to analyze how increasing patient size affects the exposure rate selected by the C-arm automatic brightness control. The results are listed in the appendix in Table 4 below:

Table 4. C-arm fluoroscopy thickness effect on exposure.

	Average Exposure (R/min)	**Percent Increase**
4" lucite	0.429 +/- 0.20	N/A
6" lucite	0.823 +/- 0.39	91.84 +/- 43.4
8" lucite	1.532 +/- 0.67	86.15 +/- 37.6

4. DISCUSSION

4.1. C-arm Automatic Exposure Variability

The data in Table A1 show an average selected kilovoltage of 71.2 kVp with a standard deviation of 4.46 kVp. The maximum was 81 kVp and the minimum was 59 kVp for a difference of 22 kVp. The average selected

milliamp*seconds was 2.9 mAs with a standard deviation of 1.03 mAs. The maximum was 6.0 mAs and the minimum was 1.9 mAs for a difference of 4.1 mAs. The average exposure rate was 1.12 R per minute with a standard deviation of 0.58 R/minute. The maximum was 3.51 R/minute and the minimum was 0.46 R/minute for a difference of 3.05 R/minute, or an increase of 663% from low to high.

These results show a significant variation in exposure rate, even with identical patient size and orientation. The different C-arm automatic brightness control demands appear to require significantly different amounts of exposure in order to produce their images. A number of reasons may exist to account for these differences, but overall it reflects differences in the efficiency of each unit's image intensifier system in converting the transmitted x-rays into an image.

Since any given site may have multiple C-arm machines, purchased over an extended time period and using different manufacturers and models, the amount of variation between machines per location was analyzed in Table 2. Comparing the percent increase from the lowest C-arm exposure rate to the highest at each site having more than 1 unit showed a minimum increase of 1.4% and a maximum increase of 268%. This means that patients undergoing a C-arm procedure at the site with this maximum variation may receive almost 3 times more exposure depending on which unit is selected or available for their medical procedure.

Since the data show such a large variation in C-arm exposure rates, and this exposure is primarily controlled by the requirements of each unit's automatic brightness control, the data were separated into groups by manufacturer and model and is located in the appendix in Table A2. Based on the

standard deviation results, each unit by itself varied less than the overall variation. This seems to indicate that most of the noted variability is due to the difference between C-arm manufacturers and models rather than variation within models. The highest model exposure average was 2.71 R/minute and the lowest model exposure average was 0.75 R/minute, or a 261% increase between models.

This variability should be of concern. While C-arm doses, even at the higher exposure rates measured, can be kept low enough to prevent deterministic skin damage, the variation does not meet the ALARA principle. While the FDA regulations address the maximum exposure rate for fluoroscopy at 10 R/minute, there is no regulation on the limits of the normal exposure rate. The fact that a patient may be subjected to many times more exposure depending on the C-arm fluoroscope that is used should be cause for further study and development in the standards for the manufacture and use of this equipment.

The data in Table 3 also show another important finding. Manufacturer A had 3 different models, or generations, of C-arms in common use. While the actual date of manufacture of each C-arm was not recorded for this study, it is reasonable to compare successive machine models for their improvements in exposure rates. A study of exposure rates and standard deviations between models by manufacture date would be a good subject for further analysis. In this case, the oldest generation model, A1, required the highest exposure rate of 1.31 R/min and had the most variability with a standard deviation of 0.45. Both the exposure rate and the variability improved with each generation after this. This seems to indicate that that the newer models have improved in image intensifier technology and associated electronics allowing for lower and more consistent exposure

rates. This generational improvement is something that would be expected as the technology advances, regardless of the lack of regulations in this area.

4.2. Patient Size Exposure Variability

Additional testing was done to illustrate another cause for variability in patient exposure during C-arm procedures that is outside of the operator's control. The data in Table 4 demonstrate an increase in exposure rates as patient thickness increases. It illustrates the automatic brightness control function and how it responds to different thicknesses. The average exposure rate using 4 inches of Lucite was 0.43 R/minute with a standard deviation of 0.20 R/minute. An increase to 6 inches of Lucite resulted in an average exposure rate of 0.82 R/minute with a standard deviation of 0.39 R/minute which represents a 91.8% increase. Adding another 2 inches to give a total of 8 inches of Lucite resulted in an average exposure rate of 1.53 R/minute with a standard deviation of 0.67 R/minute. This represents an 86.2% increase from the 6 inch thickness. The overall increase in required exposure rates from a 4 inch thickness to an 8 inch thickness was 257%. A plot of this increase is shown in Figure 10 below:

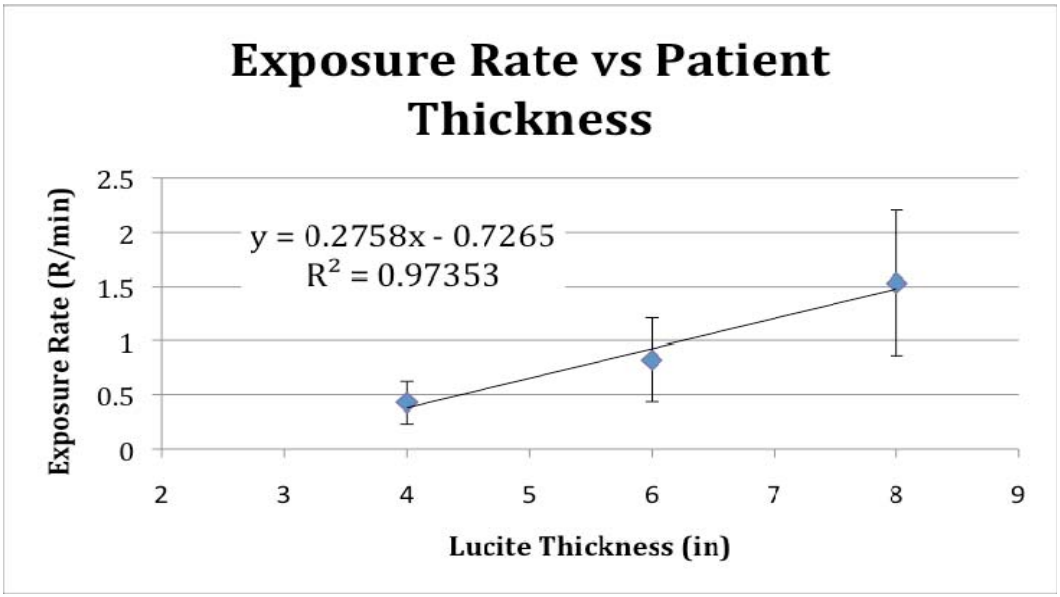

Figure 10. Average Exposure Rate vs. Lucite Thickness.

The data show a large difference in exposure rates depending on thickness alone. In this case, doubling the Lucite thickness from 4 inches to 8 inches resulted in an increase in exposure rate from 0.43 R/min to 1.53 R/min, a factor of about 3.5. In addition, these data were taken at a consistent source to detector distance. In reality, the source to skin distance will become shorter as patient size increases, resulting in an even greater increase in exposure rates at the skin. It can be concluded that patient thickness has a very significant effect on the potential skin exposure of any C-arm procedure. Clinically, this means that larger patients will be much more likely to reach the deterministic effect of skin tissue damage and they will also have an increased stochastic (cancer) risk.

5. Conclusion

The mobile C-arm fluoroscope has become an invaluable tool in a number of diagnostic, therapeutic, and surgical procedures. The number of applications for C-arm fluoroscopy and the developing technology has resulted in a significant growth in the use of C-arm fluoroscopy. The resulting patient radiation exposure is increasing accordingly. While the benefits of these procedures almost always outweigh the radiation exposure risks, unnecessary radiation exposure should be prevented. Complex procedures with a need for a large amount of fluoroscopy time can result in radiation exposure damage to the skin. In addition, the increase in patient population radiation exposure, at levels below deterministic effects, creates concern for the increased risk of long-term stochastic (cancer) effects. Therefore, the increased use of C-arm fluoroscopy should be accompanied by an increased awareness for the variables involved in patient exposure and how to minimize them.

This study has demonstrated that significant patient exposure variability exists and there is potential for unnecessary exposure. The ability to minimize patient exposure relies both on the equipment operator and the inherent design of the C-arm equipment. Following are recommendations, based on the literature review, for C-arm operators in order to minimize patient radiation exposure:

- Use the least amount of fluoroscopy time necessary to perform the procedure. Take advantage of the ‘last image hold’ feature instead of continuous fluoroscopy visualization. Keep track of the amount of fluoroscopy time that has elapsed during the procedure.

- Insure proper patient positioning. Maximize distance between the x-ray tube and the patient. Minimize distance between the patient and the image intensifier.

- Use x-ray beam collimation to limit the field size to only the area necessary for the exam.

- Limit the use of electronic magnification modes to only when necessary.

- Use the pulsed fluoroscopy option and a low frame rate which can reduce exposure by as much as 50 percent.

In order to understand and properly follow the above recommendations, and maintain a high level of awareness for the radiation exposure risks, proper operator training and experience is essential. The physician involved in the procedure must be educated so they can judge the risks and benefits of each patient case individually. This judgment must include radiation risk variables such as age, x-ray beam location and exposed tissue sensitivity, and previous radiation exposure. Beyond the initial training, the continual advancements in equipment and procedures make continuing education in these areas also essential.

While this study is limited to patient radiation exposure from C-arm fluoroscopy, the personnel involved in these procedures are also exposed to scattered radiation. In general, reducing patient exposure has the effect of reducing the amount of scattered radiation received by personnel. A number of other variables, including C-arm orientation, scatter angles, and

distances are involved in this exposure and could be the subject of another study.

Analysis of the data collected for this study indicates that there is significant variation in radiation exposure rates that is outside the control of the C-arm operator. With all other variables being equal, the demands of the automatic brightness control of each C-arm result in a wide range of exposure rates. Equipment age, calibration, and technology can all be reasons for this variability. Manufacturers continue to make advancements in C-arm equipment to provide optimal images with less required exposure. Each facility should establish a quality assurance program, supervised by a medical physicist, for C-arm equipment in order to monitor, calibrate and document radiation output of each of their units. This information can be used to permit estimation of patient exposure on a case by case basis.

Analysis of study data for variable patient thickness demonstrates that this is a significant factor in patient exposure. The exposure rate increased considerably with patient thickness. While this factor is not under the operator's control, it is something that the physician must be aware of when assessing the potential for excessive exposure and the risks versus benefits of the procedure. Because the exposure rates are so variable depending on patient size, tracking patient exposure time alone is not sufficient in determining patient risk.

Much of the control in the variability of patient exposures is left up to the equipment manufacturers and the individual institutions and physicians in charge. Federal regulations do not specifically address normal C-arm exposure rates, only the maximum. Nor do they specify quality assurance requirements or patient exposure documentation. The health care

community as a whole must know and understand patient exposure variables, promote awareness, provide quality assurance and continuing education, and continually monitor, calibrate and document radiation exposures in order to contribute to the effort of minimizing patient risk from radiation.

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APPENDIX

Table A1. C-arm fluoroscopy exposure data with 1.5 inch aluminum phantom.

Facility	Man./Model	kVp	mA	Exposure Rate (R/min)
A	D	68	6.0	2.67
B	A / 2	71	2.3	0.94
	A / 2	71	2.2	0.77
	A / 3	70	2.2	0.64
	A / 2	75	2.6	0.87
	A / 1	72	2.3	1.49
C	A / 2	74	3.5	1.24
	B	66	3.6	0.78
	B	66	3.5	0.77
	B	69	3.4	0.72
	A / 2	73	2.4	0.83
	A / 2	72	2.3	0.71
D	A / 1	66	2.9	1.49
E	A / 2	75	2.6	0.84
	A / 1	78	2.9	2.41
F	A / 1	63	2.5	0.99
	C	66	3.0	1.56
G	E	67	1.9	1.23
H	A / 2	71	2.2	0.79
	B	65	3.2	0.64
I	A / 1	70	2.2	1.18
	A / 2	76	2.6	0.82
	A / 3	73	2.4	0.88
J	A / 2	70	2.2	0.78
	B	71	2.6	0.59
K	D	63	6.0	2.61
	A / 2	70	2.2	0.71
	D	65	6.0	2.56
L	A / 2	75	2.6	1.02
	B	59	4.3	0.75

	B	66	2.1	0.46
	A / 2	68	2.1	0.71
	B	59	4.7	0.77
	B	65	3.3	0.69
M	A / 2	72	2.4	0.87
N	A / 2	72	2.4	0.71
	A / 3	71	2.3	0.72
O	A / 1	70	2.2	1.39
	A / 2	73	2.5	0.74
	A / 2	76	2.7	0.97
P	A / 1	72	2.3	1.32
Q	A / 2	72	2.4	0.88
	A / 1	70	2.1	0.81
	B	77	2.8	0.84
	C	76	2.3	0.95
R	D	67	6.0	2.48
S	A / 2	78	2.9	1.35
	A / 2	75	2.5	0.92
	C	66	2.8	2.02
T	A / 1	73	2.4	1.26
	A / 2	81	3.1	1.37
	C	65	2.7	1.37
U	B	68	2.5	1.44
	A / 2	71	2.3	0.83
	A / 3	71	2.3	0.90
V	D	64	6.0	2.99
	D	66	6.0	2.79
W	A / 2	74	2.5	0.98
	A / 2	81	3.1	1.51
	A / 1	81	3.0	0.53
	A / 3	71	2.3	0.76
X	A / 2	71	2.2	0.98
Y	A / 1	71	2.3	1.40
Z	A / 2	80	3.1	1.47
	A / 2	71	2.2	0.63
AA	A / 2	75	2.6	1.05
	B	68	4.0	1.35
BB	D	72	5.9	3.51
	D	61	5.6	2.05
CC	A / 2	72	2.3	0.84
	A / 2	77	2.7	1.24

	A / 2	73	2.4	0.88
	A / 2	74	2.4	0.84
	A / 1	70	2.2	1.13
	A / 2	76	2.7	1.18
	A / 2	71	2.2	0.65
	A / 2	71	2.2	0.65
	A / 3	72	2.3	0.73
	A / 3	73	2.4	0.87
	A / 3	73	2.4	0.78
	A / 2	73	2.5	0.91
DD	A / 3	71	2.3	0.72
EE	A / 3	71	2.2	0.68
FF	B	70	2.6	0.62
	A / 1	64	2.6	1.65
	A / 2	74	3.4	1.27
	A / 2	74	2.4	0.84
	A / 3	73	2.5	0.83
GG	A / 3	75	2.7	0.87
HH	A / 2	79	2.0	0.72
	A / 1	73	2.5	1.54
II	A / 3	74	2.6	0.94
	A / 1	71	2.3	1.25
JJ	A / 3	72	2.4	0.69
	A / 3	72	2.4	0.81
KK	A / 2	71	2.3	0.76
	A / 2	74	2.5	0.92
	A / 2	74	2.4	0.79
	A / 2	74	2.5	0.77
	Average	71.2	2.9	1.12
	Stnd. Dev.	4.5	1.0	0.58
	Max. Diff.	22	4.1	3.05

Table A2. Manufacturer and Model Specific Data.

Man. / Model	kVp	mA	Exposure Rate (R/min)
A / 1	72	2.3	1.49
A / 1	78	2.9	2.41
A / 1	70	2.2	1.18
A / 1	70	2.2	1.39
A / 1	72	2.3	1.32
A / 1	70	2.1	0.81
A / 1	73	2.4	1.26
A / 1	81	3.0	0.53
A / 1	71	2.3	1.40
A / 1	70	2.2	1.13
A / 1	73	2.5	1.54
A / 1	71	2.3	1.25
Averages	72.6	2.4	1.31
Standard Deviation	3.48	0.28	0.45
A / 2	72	2.4	0.71
A / 2	73	2.5	0.74
A / 2	76	2.7	0.97
A / 2	72	2.4	0.88
A / 2	78	2.9	1.35
A / 2	75	2.5	0.92
A / 2	81	3.1	1.37
A / 2	71	2.3	0.83
A / 2	74	2.5	0.98
A / 2	81	3.1	1.51
A / 2	71	2.2	0.98
A / 2	80	3.1	1.47
A / 2	71	2.2	0.63
A / 2	75	2.6	1.05
A / 2	72	2.3	0.84
A / 2	77	2.7	1.24

A / 2	73	2.4	0.88
A / 2	74	2.4	0.84
A / 2	76	2.7	1.18
A / 2	71	2.2	0.65
A / 2	71	2.2	0.65
A / 2	73	2.5	0.91
A / 2	74	3.4	1.27
A / 2	74	2.4	0.84
A / 2	79	2.0	0.72
A / 2	71	2.3	0.76
A / 2	74	2.5	0.92
A / 2	74	2.4	0.79
A / 2	74	2.5	0.77
Averages	74.4	2.5	0.95
Standard Deviation	3.04	0.32	0.25
A / 3	70	2.2	0.64
A / 3	73	2.4	0.88
A / 3	71	2.3	0.72
A / 3	71	2.3	0.90
A / 3	71	2.3	0.76
A / 3	72	2.3	0.73
A / 3	73	2.4	0.87
A / 3	73	2.4	0.78
A / 3	71	2.3	0.72
A / 3	71	2.2	0.68
A / 3	73	2.5	0.83
A / 3	75	2.7	0.87
A / 3	74	2.6	0.94
A / 3	72	2.4	0.69
A / 3	72	2.4	0.81
Averages	72.1	2.4	0.79
Standard Deviation	1.36	0.14	0.09
B / 1	66	3.6	0.78
B / 1	66	3.5	0.77

B / 1	65	3.2	0.64
B / 1	59	4.3	0.75
B / 1	66	2.1	0.46
B / 1	59	4.7	0.77
B / 1	65	3.3	0.69
B / 1	68	4.0	1.35
B / 1	69	3.4	0.72
B / 1	70	2.6	0.62
B / 1	71	2.6	0.59
B / 1	77	2.8	0.84
Averages	66.8	3.3	0.75
Standard Deviation	4.94	0.75	0.22
C / 1	66	3.0	1.56
C / 1	76	2.3	0.95
C / 1	66	2.8	2.02
C / 1	65	2.7	1.37
Averages	68.3	2.7	1.48
Standard Deviation	5.19	0.29	0.44
D / 1	68	6.0	2.67
D / 1	65	6.0	2.56
D / 1	64	6.0	2.99
D / 1	63	6.0	2.61
D / 1	67	6.0	2.48
D / 1	66	6.0	2.79
D / 1	72	5.9	3.51
D / 1	61	5.6	2.05
Averages	65.8	5.9	2.71
Standard Deviation	3.37	0.14	0.42

Table A3. C-arm fluoroscopy exposure data with variable attenuation.

Site	Manufacturer	4" lucite (R/min)	6" lucite (R/min)	8" lucite (R/min)
1	D	0.61	1.32	2.53
2	A	0.61	1.12	2.15
	A	0.35	0.68	1.13
	A	0.36	0.69	1.20
3	A	0.40	0.83	1.53
4	A	0.31	0.59	1.18
	A	0.35	0.79	2.01
5	A	0.35	0.65	1.15
6	A	0.35	0.63	1.14
7	A	0.40	0.80	1.43
8	A	0.60	1.22	2.12
9	A	0.47	0.85	1.54
	A	0.56	1.00	1.99
10	D	0.87	1.79	3.18
	D	1.00	2.07	3.39
11	A	0.39	0.74	1.36
	A	0.36	0.65	1.18
	A	0.33	0.61	1.14
	A	0.69	1.23	2.39
12	D	0.94	1.91	3.29
	A	0.29	0.58	1.12
13	A	0.48	0.91	1.67
	A	0.32	0.59	1.08
14	A	0.70	1.24	2.26
15	A	0.61	1.17	2.20
	B	0.22	0.48	1.10
	B	0.19	0.46	1.01
16	A	0.30	0.57	1.07
17	A	0.50	0.94	1.91
	A	0.25	0.48	0.99
18	A	0.30	0.59	1.04
	A	0.25	0.49	0.93
	A	0.25	0.49	0.95
	A	0.22	0.45	0.90
19	A	0.32	0.61	1.09

	A	0.41	0.76	1.49
	A	0.33	0.60	1.11
	A	0.37	0.65	1.2
20	A	0.29	0.57	0.98
21	A	0.64	0.88	1.63
	A	0.41	0.81	1.44
22	A	0.26	0.47	0.90
	A	0.22	0.43	0.79
	Averages	0.43	0.82	1.53
	Standard Deviation	0.20	0.39	0.67