USING A RADIOLOGY-BASED INFORMATICS SYSTEM TO IMPACT CLINICAL PRACTICE: A STUDY TO IMPROVE AND TRACK PATIENT ALIGNMENT IN COMPUTED TOMOGRAPHY

By

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CERTIFICATE OF APPROVAL

This is to certify that the MS Thesis of

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"… If you can talk with crowds and keep your virtue,
Or walk with Kings—nor lose the common touch,
If neither foes nor loving friends can hurt you,
If all men count with you, but none too much;
If you can fill the unforgiving minute
With sixty seconds' worth of distance run,
Yours is the Earth and everything that's in it,
And—which is more—you'll be a Man, my son!"

Excerpt from *If—,* by Rudyard Kipling

ABSTRACT

Introduction

Proper use of computed tomography (CT) imaging systems depends heavily on accurate patient positioning. Patient misalignment with respect to scanner isocenter generates deleterious effects on both the quality of the resulting image and the radiation output of the CT scanner. Alignment errors produce pixel intensity inaccuracies and increases in noise which degrade the quality of the image. In terms of radiation dose, distorted approximations of patient size emanating from improper positioning result in misallocations of radiation output. The mission of this study is to increase patient alignment accuracy in an effort to optimize CT dose and image quality through an education initiative.

Methods

A presentation on the negative effects of patient misalignment and the status of centering at Oregon Health & Science University (OHSU) was provided to CT technologists who perform diagnostic imaging exams on six CT scanners at OHSU. Imalogix™ informatics recording software was used to track changes in patient alignment and dose. Efficacy of the presentation was evaluated according to shifts in accuracy and average vertical displacement from isocenter. Radiation dose changes were evaluated in the context of patient alignment shifts.

Results

Vertical alignment increased toward isocenter by 0.49 cm on average following the presentation ($p < 0.0001$). Accuracy improved from 68.80% to 77.68%, which corresponded to a 30-percentile improvement in a peer ranking among other hospitals. Lateral alignment did not improve significantly with a shift of only 0.02 cm towards isocenter ($p = 0.35$). The alignment shifts were not large enough to significantly impact dosimetry. Modest increases of 1.37 mGy ($p = 0.14$) and 0.12 mGy ($p = 0.43$) were noted in $CTDI_{VOL}$ and SSDE, respectively, but were considered to be negligible.

Conclusions

Improvements in vertical positioning at OHSU proved that the presentation given to technologists was an effective quality improvement tactic. Lateral alignment shifts were minor since high baseline accuracy provided little room for improvement. Dosimetry gains were inappreciable from the small decreases in vertical displacement. The education initiative was successful in exacting a meaningful change in patient alignment at OHSU in support of improving radiation dose and image quality.

1 INTRODUCTION

Computed tomography (CT) is a widely used diagnostic imaging modality created in the early 1970's that produces 3-dimensional images in a clinical setting. Several advancements and technologies have been implemented for CT since its inception to make it a staple for quick and detailed medical imaging[1]. Proper use of these technological additions relies heavily on the ability of the technologist to prepare the patient for the scanning procedure. While the design of these technologies is meant to improve image quality and eliminate excess dose to the patient, improper patient alignment prior to scanning will cause these instruments to produce the opposite effects[2,3].

Large portions anatomy positioned off of the axial center line prior to the imaging exam can cause an over-attenuation of the X-ray signal. Studies have shown that images suffer a loss of pixel intensity accuracy when the X-ray beam is attenuated in such a way[4]. Spurious pixel intensities have been known to mislead radiologists when diagnosing patient conditions[2]. Over-attenuation from patient alignment can also increase the noise in CT images to undesirable levels. This noise can obscure essential portions of anatomy used for the proper evaluation of patient conditions[2].

Automated electronic systems aimed at reducing dose cannot operate effectively when patients are misaligned[3]. Large patient displacements toward the X-ray source causes these systems to increase dose rather than reduce it. Alternatively, displacements away from the source may reduce dose, but deprive the detector of the required number of X-rays to produce an image of sufficient quality[4,5].

Oregon Health & Sciences University (OHSU) uses a dose tracking software system known as Imalogix™ (Imalogix Incorporated, King of Prussia, PA, USA). This software tracks and evaluates alignment accuracy and dosimetry for the CT scanners at OHSU. Statistics provided by Imalogix uncovered a possible area for improvement in patient centering. Vertical positioning accuracy at OHSU is below that of the majority of hospitals that use Imalogix. Lateral alignment has been shown to be much more accurate than vertical alignment. Accuracy in the lateral direction is sufficient enough to not warrant much action. On the other hand, the deficit in vertical accuracy can be remedied as a method of optimizing patient dose and image quality.

This study aims to create a quality improvement program to increase alignment accuracy in CT exams at OHSU. Information on the impacts of alignment errors on image quality and patient dose will be provided to technologists to motivate the need for the best possible centering practices. Current performance and areas of improvement will also be demonstrated to the technologists as a way of prompting the implementation of superior positioning techniques. These topics will be discussed during a presentation at a staff meeting for CT technologists as a method for exacting change.

Progress in this endeavor will be tracked with the help of Imalogix. Information extracted from Imalogix will be used in this study to create characterizations of CT alignment performance as a way of discerning changes to patient doses and offsets. Since this is the first study to employ Imalogix at OHSU, the capabilities and ease of use of the software system will be evaluated for future use in quality improvement programs.

Misalignments in CT imaging generate negative effects on patient dose and image quality. This inhibits the capability of the diagnostic imaging department at OHSU to accurately diagnose conditions while impacting the ability of the system to deliver the right amount of radiation to the patient. OHSU's diagnostic imaging department is determined to capitalize on the opportunity for dose and image quality optimization by commissioning this quality improvement program. This project aims to inform technologists of the detrimental impacts of patient misalignment, and provide them with techniques for improving alignment accuracy for the mitigation of these centering errors. The mission of this study is to use this educational initiative to exact a meaningful change in patient positioning errors in an effort to optimize patient dose and image quality at OHSU.

2 BACKGROUND

2.1 COMPUTED TOMOGRAPHY UTILITY

CT was created in the early 1970's as a method of producing 3-dimensional radiographic images. Technological advances in CT technology have reduced scan times, improved image quality and drastically reduced radiation dose to the patient. These improvements have made CT a staple at most hospitals, and greatly increased throughput. Due to the variety and multitude of patients and conditions, CT technology is constantly improving and advancing to meet the demand[1].

Modern CT scanners image patients by rotating an X-ray source around the patient in a circular motion in what is designated as the x-y plane. X- and y-directions here refer to the horizonal and vertical components of this plane, respectively, with the isocenter designated as the origin. The radiation source, or X-ray tube, produces a beam of photons of a specific maximum energy and number which are referred to by tube voltage and tube current, respectively. As the tube rotates, the patient is translated through the opening in the z-direction which is perpendicular to the x-y plane, or bore of the instrument. X-ray photons pass through the patient and are subsequently detected by a semi-circular detector array which is mechanically fixed in its orientation to the X-ray tube. The signals received by the detector are reconstructed into a 3-dimensional image of photon absorption data corresponding to the spatial location of patient tissues and anatomy[1].

A number of technological advancements have been made to CT to adapt to the complexities of 3-dimensional imaging. Despite the prominent evolutions of CT imaging, the role of the technologist has remained relatively constant. Technologists are primarily responsible for preparing the patient and scanner for the scanning procedure in a way which optimizes quality of the image[1–3,6].

2.2 IMAGE QUALITY IN CT

Image quality in CT is defined by several quantities which describe positive and negative attributes of an image. These quantities are used to evaluate the success of the imaging procedure. The manner in which the CT technologist centers the patient within the bore of the scanner can have a great impact on several image quality attributes. The characteristics shown to have the greatest impact on image quality when a patient is placed off-center are noise and CT number accuracy[4,7]. These two features of an image are crucial in ensuring proper diagnosis by the radiologist. Successful patient alignment can minimize noise and ensure that the CT number in an image is accurate for measurements of tissue attenuation[2]. While these values do not rely wholly on patient alignment, their effects on image quality degradation from misalignment are notable and can be mitigated with proper patient alignment[4,7].

2.2.1 NOISE

Noise is a major characteristic of image quality in all radiological modalities. Increases in image noise are predominately associated with poor image quality since it can obscure relevant anatomy from the radiologist[2,4]. Noise can arise from variations in electronic baseline, scanner component non-uniformities and the probabilistic nature of photons traversing matter[1]. Often, in the context of CT imaging, noise is created by random photon scattering events in matter. In the diagnostic imaging range of X-ray energies, these scattering events are most commonly the result of Compton scattering[1,8]. The probability of the occurrence of these scattering interactions occurring can be modeled mathematically by the following equation.

$$P = 1 - e^{-\sigma l} \qquad \text{eqn. 1}$$

Where P is the probability of interaction, σ is the coefficient of Compton interaction for a given medium and l is the distance in which the photon of interest travels through the medium[1,8]. It should be noted that the probability increases with distance traveled through the medium and the ability of the medium to induce a Compton interaction.

Scattered X-rays travel at various angles relative to the tube-detector axis to ultimately be displaced from the normal linear path of most other photons. They appear as high spatial frequency pixel intensity variations across a predominately homogenous region in an image[1]. In CT, this scattering effect is caused by the patient and the filtration used. When a patient is misaligned, thicker parts of anatomy increase the probability of scattering events and increase noise[2,4].

2.2.1.1 NOISE MEASUREMENTS

As stated in the previous section, noise is a random process and is treated as such mathematically. Since the manifestation of noise is such a random process comprised of so many mechanisms, it is futile to attempt to derive such an equation from first principles to theoretically model noise as it appears in an image. Thus, noise must be measured as it appears in the image. Because noise appears as normal statistical variation, it can be modeled as a standard deviation of a region of pixels[4,7,9,10]. The equation for this is shown below.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i-\bar{x})^2}{N-1}} \qquad \text{eqn. 2}$$

Where σ is the standard deviation, N is the number of pixels in the measurement, $\bar{x}$ is the mean pixel intensity value and x_i is each individual pixel element[11].

Commonly a region of interest (ROI) is used to define an area of pixels in which to measure the noise of an image. This is done to omit regions which vary between scans and include consistent regions which help standardize measurements between images. Algorithms on CT scanners compile pixels within these regions to calculate a standard deviation. This method of measurement has been chosen by numerous studies to measure and evaluate the effects of patient misalignment on noise since it is a technology incorporated into many CT scanners[4,7,9,10]. In these studies, ROI’s are drawn in images around specified areas of patient anatomy in patient studies[4,7,10], or at very specific and consistent locations on certain phantoms in order to standardize measurements[4,9].

2.2.2 CT NUMBER ACCURACY

In computing, pixel intensity is based on bit values required to inform the system of how to display the image. While CT images are ultimately translated into bit value pixel intensities, it is also desired to derive an understanding of the radiological properties of the voxel imaged. Thus, the Hounsfield unit (HU) was developed to correlate the voxel intensity information in the image to the attenuation characteristics of the voxel relative to water[1,8]. The HU is defined by the following equation.

$$HU = 1000\left(\frac{\mu_{voxel}-\mu_{water}}{\mu_{water}}\right) \qquad \text{eqn. 3}$$

Where μ is the linear attenuation coefficient of either the voxel or water. As stated in the previous section, natural noise production can vary across the pixels of the ROI. HU values are normally calculated as an average of several pixels over a specific ROI. Thus, a ROI pixel intensity can be summarized by a Poisson statistical distribution with the CT number as the average and the noise variation as the standard deviation[4,7]. These two metrics are used to characterize the pixel intensity in a region and define a statistical model to demonstrate the image quality of a CT system.

2.2.3 PATIENT MISALIGNMENT EFFECTS ON IMAGE QUALITY

Misalignment errors have been shown to give rise to alterations in CT number and image noise in numerous studies. These studies demonstrate that the CT number of a given ROI can deviate from its true value the farther the ROI is from isocenter in either the x- or y-direction[4,7]. Further, some studies have mapped the increase in image noise at regions farther from isocenter compared to those closer[9].

Toth et. al. conducted a study using a cylindrical acrylic phantom to evaluate the noise distribution across an otherwise uniform area when the phantom was positioned at varying displacements from isocenter[9]. When the phantom was placed at isocenter, the noise was primarily concentrated in the center of the phantom since this area receives the most attenuated part of the beam as the source rotates. However, when the phantom was moved below isocenter, the top part of the phantom decreased in noise and the lower part of the phantom increased in noise. This showed that the noisiest part of the image manifests in the area farthest from isocenter. Overall, the noise across the entire circular cross-section of the phantom increased as much as 22% when the phantom was misaligned by 6 cm[9].

Another study utilized an anthropomorphic phantom to more accurately characterize the effects of misalignment on CT number and noise distribution. While a cylindrical acrylic phantom is a good quantitative way of noting image quality effects with few variables, it does not accurately mimic the more ellipsoidal cross-section of the patient which can have a more complex attenuation pattern. This study sought to show that these increases in noise and variation in CT number can be found in a reproducible anatomically correct phantom. Further, with this study as opposed to a patient study, the subject can be scanned multiple times without concerns over radiobiological effects. Changes in CT number observed in this study were over 20 HU when the phantom was moved from 10 cm above isocenter to 10 cm below. Standard deviations were also calculated to characterize changes in noise. Visible variations in noise were shown as the phantom was moved across table heights as shown in figure 1 below. This was confirmed by the doubling in voxel standard deviations from isocenter to maximum displacement[4].

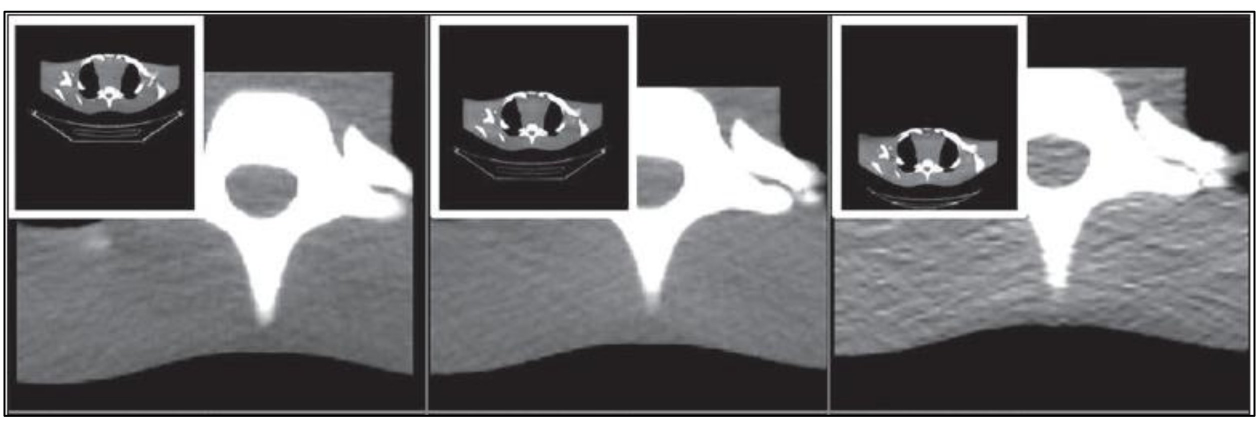

Figure 1: Szczykutowicz et al. fig. 3 (top row). Increases in noise due to misalignment. Left to right: above isocenter, at isocenter and below isocenter. Reprinted from the American Journal of Roentgenology with permission.

Due to the varying nature of patient tissues and anatomy, it is difficult to determine noise increases or CT number differences in patients. However, the phantom data is not always indicative of actual patient anatomy and corollary studies must bridge the gap between data in an acrylic phantom with a human. In order to create such a link, a retrospective study used ROI's placed by a physician in the liver and posterior fat deposits of patient images to study the effects of patient misalignment on CT number and noise. This study determined that there was a statistically significant increase in noise and change in CT number when the patient was placed off-center even by small distances. Similar noise distributions were found in the posterior and anterior measurements of the patient that were noted in the phantom studies[7].

2.3 DOSIMETRIC QUANTITIES IN CT

Due to the fact that CT scans involve a complex amalgamation of scanning parameters, it is difficult to provide a straightforward method of computing dose. Many methods have been developed that quantify the radiation dose received by a CT scan. Certain quantifications such as computed tomography dose index (CTDI), and size-specific dose estimate (SSDE) are used to approximate dose quickly after a scan has been completed. These quantities are used as the standard of dosimetric assessment in CT[1].

2.3.1 COMPUTED TOMOGRAPHY DOSE INDEX

The computed tomography dose index (CTDI) is the most basic index of dosimetry available. From it, all other dose indices mentioned here can be derived. It is important to note that this quantity is not a direct dosimetry method to assess dose to a patient. However, it is a practical approximation of the radiation used for a CT scan[1].

2.3.1.1 $CTDI_{100}$

CTDI is a broad category of quantities which were developed in series to more accurately evaluate dose from a CT scan. The most basic quantity is the $CTDI_{100}$ which is computed from a measurement of an ion chamber. At the most basic level, it is a ratio of the sum of the dose along a 100mm-length ion chamber to the width of the beam[12]. The equation which defines this parameter is shown below.

$$CTDI_{100} = \frac{1}{nT}\int_{-50\ mm}^{+50\ mm} D(z)\, dz \qquad \text{eqn. 4}$$

Where n is the number of detector elements in the z-direction, T is the thickness of each dexel, or detector element, and D(z) is the radiation dose at a particular point in the z-direction measured by the ion chamber. This quantity is measured with the ion chamber parallel to the z-direction at isocenter inside a cylindrical poly(methyl methacrylate) (PMMA) phantom. These phantoms come in two different sizes, 32 cm diameter to represent a torso and 16 cm diameter to represent an adult head or pediatric patient[1].

2.3.1.2 $CTDI_w$

The $CTDI_{100}$ is then used to derive the $CTDI_w$ which is used to compensate for the uneven dose distribution across the patient. Since the majority of dose is distributed along the surface of the patient, there is need for a metric which includes this effect. In order to obtain this quantity, the scan is performed twice with the ion chamber at isocenter in the phantom and again with the ion chamber 1 cm from the surface[1]. Two $CTDI_{100}$ measurements are taken, one at each ion chamber location. The two measurements are weighted and averaged together by the following equation to give the $CTDI_w$, or weighted CTDI[13].

$$CTDI_w = (2/3) \times CTDI_{100,periphery} + (1/3) \times CTDI_{100,center} \qquad \text{eqn. 5}$$

2.3.1.3 VOLUME CTDI

The final manipulation to the CTDI gives the $CTDI_{VOL}$ which is the most refined version of the CTDI and the dose index of choice for experiments which quantify changes in CT dose. The $CTDI_{VOL}$ compensates for pitch, which is defined as the ratio of the table translational distance to the z-directional width of the detector. This was a necessary change made when CT scanners switched from axial to helical image acquisition. Since the pitch is inversely proportional to dose and has a prominent effect on CTDI measurements, it was necessary to compensate in this way[1]. An equation for the calculation of $CTDI_{VOL}$ is shown below.

$$CTDI_{VOL} = \frac{CTDI_w}{pitch} \qquad \text{eqn. 6}$$

2.3.3 SIZE-SPECIFIC DOSE ESTIMATE

The size-specific dose estimate (SSDE) is another attempt to develop a more accurate dose index for CT examinations. Since the $CTDI_{VOL}$ is an approximation of the radiation received by a cylindrical acrylic phantom, it does not mimic actual human body types which are roughly ellipsoidal in cross-section. The SSDE provides a conversion factor to account for this which is based on tabular data that was developed as a part of task group 220 of the American Association of Physicists in Medicine (AAPM)[14].

Task group 220 advises that the patients anterior-posterior and lateral dimensions should be measured in order to compute the effective diameter of the patient which most closely approximates an ellipsoidal cross-section. The equation for such a calculation is shown below[14].

$$effective\ diameter = \sqrt{AP \times LAT} \qquad \text{eqn. 7}$$

Where AP is the anterior posterior diameter and LAT is the lateral diameter of the patient. This effective diameter is then used to look up a conversion factor from the table provided in AAPM report 220. The conversion factor is multiplied by the $CTDI_{VOL}$ to produce the SSDE[14].

Many are skeptical of the SSDE for its inaccuracies and assumptions, but it still remains one of the best dosimetric estimates short of monte carlo simulations. One of the largest pitfalls of the SSDE is that it relies heavily on accurate patient size measurements which are often measured on the scout image taken prior to CT scanning or on a cross-sectional image after the scan[5,14]. If the measurement is taken on the scout and the patient is positioned too close to the X-ray tube during the scout image, then the image will appear larger than the actual patient size due to magnification effects[1]. This, in turn, produces a larger effective diameter which throws off SSDE calculations. This effect is more pronounced for dual scout images taken of a patient who is positioned off of isocenter in both dimensions[5]. Measurements taken from a cross-section of the 3D image circumvent this pitfall.

2.3.4 PATIENT MISALIGNMENT EFFECTS ON CT DOSIMETRY

Changes in dose and dosimetric quantities due to patient misalignment come from a variety of different factors. Most studies conclude that alignment errors do cause noticeable variations in $CTDI_{VOL}$, SSDE and surface dose depending on the level of displacement from isocenter[5,9,10,15,16]. The degree by which a dosimetric quantity or radiation dose to the patient has been shown to be dependent on a number of different factors. Scanning algorithms used in automating scan parameters can differ between CT manufacturers which can create variation in dose metrics[5]. The protocols used to scan a patient can vary greatly between procedures and hospitals which can also influence the variability of output data[3,10,17]. Still a variety of measurement methods in several clinical and research contexts agree that patient misalignment can affect dose and dose indices.

Marsh and Silosky sought to determine the dosimetric effects of patient misalignment on both phantoms across several different scanners. The study noted the differences in the methods of acquiring scout images and pre-scan data as one such reason for the variability between scanners. The study found more than a 4-fold increase in $CTDI_{VOL}$ as the phantom was moved across from 16 cm below isocenter to 4 cm above isocenter towards the tube on one particular scanner, and an almost 3-fold increase in SSDE on the same scanner (“Scanner C”). Variations among other scanners were similar. One particular scanner, a Philips© Brilliance 64 (Koninklijke Philips N.V., Amsterdam, Netherlands), did not have a wide variation in $CTDI_{VOL}$ or SSDE. It was noted that this machine can only take planning images in one orientation. All other scanners in the study were capable of imaging in two orientations. It was speculated that the reason for the limited effects of misalignment on patient dosimetric quantities on this scanner were mitigated by this design. Graphs detailing this effect from the paper by Marsh and Silosky are shown below in figure 2 ("Scanner D" is a Philips Brilliance 64 scanner). This study determined a quantifiable change in $CTDI_{VOL}$ and SSDE linked to isocenter misalignment, then determined that the magnitude of this effect is also specific to certain scanners[5].

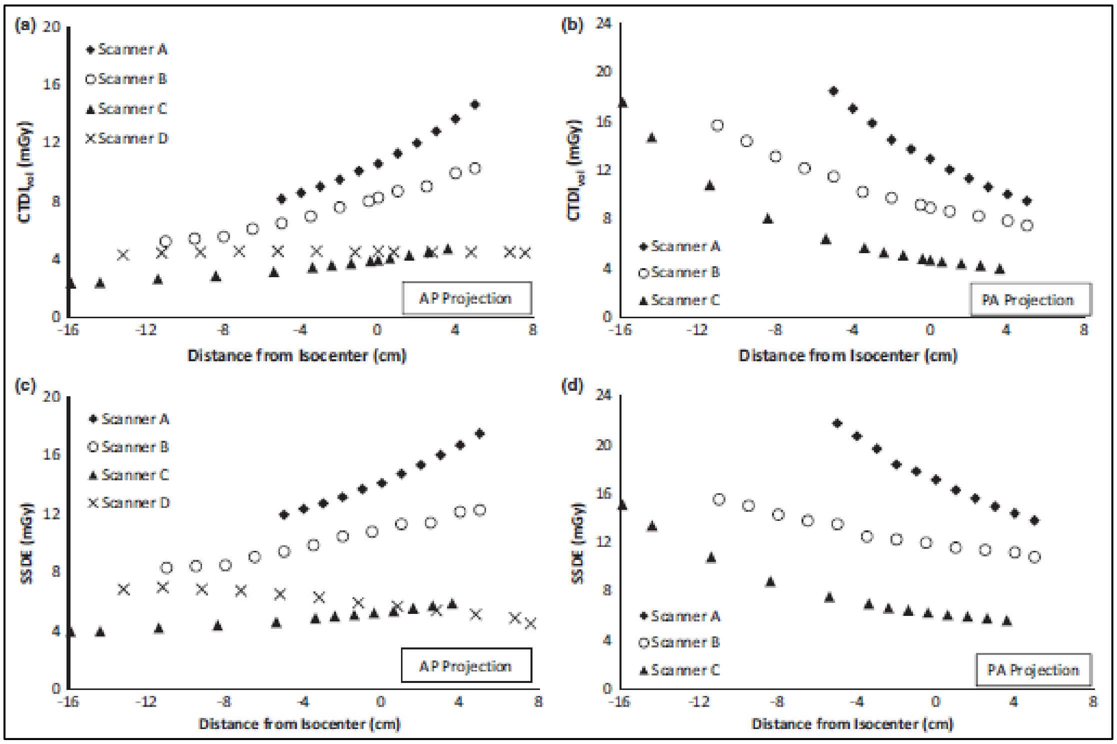

Figure 2: Marsh and Silosky fig. 7 a-d. Changes to SSDE and $CTDI_{VOL}$ due to phantom alignment. Reprinted from the Journal of Medical Physics with permission.

In order to correlate these dosimetric effects between a phantom and a human, another study analyzed both patients and an acrylic phantom. This study used an ACR approved CTDI phantom to find a correlation between patient misalignment and dose in a reproducible manner. Researchers noted an increase in surface dose of over 50% when the phantom was aligned 6 cm above isocenter compared to the value at isocenter. This surface dose skewed the measured dose indices in a similar fashion. In order to translate this data to a real patient scenario, the scientists in the study used $CTDI_{VOL}$ values tabulated after patient exams. Effects similar to what was observed in the phantom study were also noted in patient $CTDI_{VOL}$ values with an increase up to 21.9% from an average misalignment of 2.1 cm below isocenter[10].

Other studies were unable to discern a notable overall change in dose caused by patient alignment errors in certain instances. One such study demonstrates that there is actually an alteration of dose distribution within the patient caused by misalignment. This distribution arises when the X-ray tube is at a minimum and maximum distance from the surface of the patient. At a maximum distance, the X-ray beam is allowed to spread out and does not distribute a large enough dose to the patient with the opposite being true for the minimum distance. The decrease in dose on one side and increase on the other offsets the overall dose the patient receives, but creates an uneven distribution of dose. These studies did not advise treating this data any differently, because elevated radiation dose is usually not a good outcome in diagnostic imaging even in small localized areas[9].

Another study which sought to distinguish these effects on both a phantom and human subject noted a similar effect in dose distribution. Peripheral and surface doses in both the patient and phantom increased with distance from isocenter. In the phantom study, there was not a notable increase in $CTDI_{VOL}$ measurements. The study described this lack of change as an averaging of the peripheral and center measurements used in calculating the $CTDI_{VOL}$. Since the center measurement stayed relatively consistent due to shielding from the periphery of the phantom, it kept the average somewhat constant[15].

A set of researchers sought to determine the effects of patient misalignment during a CT scan for planning an image guided radiotherapy (IGRT) regimen in breast cancer patients. This study used thermoluminescent dosimeters (TLD) to measure the actual surface dose received by an anthropomorphic phantom. Most other studies of this nature use dosimetric quantities to describe dose, which is subject to several approximations and assumptions. In this study, researchers sought to more accurately characterize surface dose changes due to misalignment. The researchers noted an increase in surface dose along the contour of the breast in a phantom when the object was positioned 3 cm above isocenter prior to the scan. During radiotherapy, patients already receive a large amount of radiation dose and excess amounts can potentially be detrimental to the treatment[16].

2.3.5 LIMITATIONS OF $CTDI_{VOL}$ AND SSDE IN ALIGNMENT STUDIES

Radiation dose from a CT exam is not only difficult to quantify, but can also be difficult to measure especially in alignment studies. For this reason, studies that seek to determine dosimetric impacts of misalignment must either commit to a laborious and time-consuming direct measurement or defer to using output calculations from the scanner. Of these two, the latter is by far the most commonly used among studies of this nature for its relative simplicity.

When measuring $CTDI_{VOL}$ the phantom is centered exactly at isocenter to reduce the differences in periphery quantities at various locations around the edges. If this condition is satisfied, the dose reading will remain relatively constant throughout the tube rotation when the ion chamber is placed in the center of the phantom. During the measurement at the periphery, the dose reading will naturally fluctuate as the tube rotates around the phantom. These dose fluctuations are similar at all points along the periphery of the phantom when it is placed at isocenter due to the radial symmetry of the tube rotation and phantom. As the phantom is moved farther from isocenter, the dose readings at different periphery locations vary more greatly from one another. Measurements closer to isocenter will be more constant, while measurements farther from isocenter will have larger variations due to the differences in the distance from the ion chamber to the source throughout the rotation of the source.

Measurements are required at only one location on the periphery to measure the $CTDI_{100,\ periphery}$ when the phantom is positioned at isocenter. When the phantom is placed off of isocenter, measurements must be taken at multiple locations on the periphery and averaged to compensate for the variations. For this reason, researchers often default to using the $CTDI_{VOL}$ calculations provided by the scanner software to evaluate dosimetric impacts of misalignment. This value from the scanner is only valid for patients or objects placed at isocenter and does not account for off-center placements. Measurements off of isocenter could differ considerably from those produced by the scanner. Studies which use $CTDI_{VOL}$ measurements to characterize dosimetry effects almost exclusively use scanner output quantities. The dose indices reported by studies which use these values are subject to the uncertainties caused by the assumptions of the scanner and should be viewed with that in mind. Other studies use dosimeters placed on or in the phantom to gather location specific measurements of exact dose, but are unable to gather large volume dose information.

2.4 ATTENUATION COMPENSATION IN CT

Modern CT systems come with a substantial amount of software and hardware designed to obtain the highest quality images while optimizing dose to the patient. Pressure to reduce radiation dose in CT prompted the advent of tube current modulation as a method of reducing unnecessary tube output[1,3,17]. In response to the early CT scanners which utilized large toroidal water phantoms to compensate for attenuation differences across the beam profile, bowtie filters were created to reduce dose from low energy X-rays and provide an even distribution of radiation exiting the patient[2]. Despite the effort to reduce dose, these advances in CT design have also put a greater responsibility on the technologists who use these systems. Improper use of these devices can have a detrimental effect on the image quality and an increase in dose[2,5,9].

2.4.1 TUBE CURRENT MODULATION

Tube current modulation (TCM) is a method of varying the number of photons produced by the X-ray tube as it moves through the scan area. TCM gathers information on attenuation and patient size from the scout image. In areas where the patient is large or heavily attenuating, the TCM system raises the tube current in the X-ray tube to emit more photons while the tube is in that position during the scan. This is often the case when the beam profile is projected across the patient laterally or near a heavily attenuating area such as the mediastinum. Likewise, the tube current is lowered in areas of low attenuation like the lungs. In this way, the TCM system is able to only produce as much radiation as needed to properly expose the detector. This method maintains proper image quality while keeping the radiation dose to the patient as low as possible[1].

Because the algorithm which dictates the TCM function relies heavily on the data received from the scout image, it is imperative that the scout be performed correctly with the patient central axis aligned with isocenter. Misalignments from isocenter have been shown to increase the $CTDI_{VOL}$ and SSDE, and skew dose distributions[5,9,10,15,16].

2.4.1.1 SCOUT IMAGE

Scout images are taken at the beginning of the imaging exam to gather data about patient attenuation characteristics and provide the technologist with an image on which to plan the scanning procedure. During the scout image, the tube does not rotate as the table translates the patient through the bore at a constant rate. The detector acts like a planar X-ray radiographic detector. As the image data is gathered, the detector stitches together the series of imaging data into a 2-dimensional X-ray image. This image is then sent to the TCM algorithm software, which measures and analyzes the pixel intensities to develop a function used to vary current during the scan. Scout images are often taken with the tube positioned above or below the patient. Scanning protocols requiring two scout images usually take the second scout with the tube-detector axis parallel to the x-axis. This second scout provides the TCM algorithm with attenuation data for an additional dimension and helps the technologist plan the scan[1].

2.4.1.2 WIDTH MEASUREMENTS

TCM algorithms depend greatly on width measurements taken from scout images. Attenuation of a X-ray beam is an exponential decay function of distance travelled within a medium[1,8]. The equation which mathematically governs this is shown below.

$$I = I_o e^{-\mu x} \qquad \text{eqn. 8}$$

Where I is the intensity or number of photons after the beam has passed through the medium, I_o is the intensity of the beam prior to entering the medium, μ is an attenuation coefficient of the medium based on the effective energy of the beam, and x is the distance travelled in that medium. Thicker media will more drastically reduce the number of photons than thinner media[1,8].

TCM algorithms are thus programmed to compensate for this effect. These algorithms use the measurements obtained from the scout image to develop an idea of how much tube current is needed to properly expose the detector after it leaves the patient. If a patient is misaligned towards the tube during the scout image, the TCM algorithm measures the patient as larger than actual due to magnification effects. This causes the TCM system to produce a higher than necessary current to traverse the deceptively larger patient. The elevated beam current contributes to a higher dose[3,17].

To the contrary, a patient positioned farther from the X-ray tube will appear deceptively smaller in size. Following the same logic, this will lower the current in the TCM system to compensate for seemingly thinner anatomy. While this would seem ideal to lower the dose, it is actually detrimental to the image quality. When a patient appears small, the TCM algorithm lowers the tube current in an attempt to reduce unnecessary radiation entering the patient. The exposure at the detector is consequentially lower than is required to produce a proper image. This has a two-fold impact on image quality. The lower signal does not permit the reconstruction algorithm to accurately assign CT numbers to pixels and lack of signal allows noise to enter the image unobscured. Both of these effects make it difficult for physicians to assess images[2,4].

2.4.2 FILTRATION

The purpose of filtration in CT is similar that of general radiography. It is mainly designed to remove lower energy X-rays from the beam that will normally be attenuated by the time they reach the detector. These photons serve no diagnostic benefit, but contribute largely to dose as their energy is almost entirely deposited in the patient. Much like general radiography, filtration is meant to lower dose while preserving diagnostic potential[1,8].

2.4.2.1 BOWTIE FILTERS

CT filters also have the added effect of conforming the beam profile to the roughly ellipsoidal cross-section of a patient. These filters are referred to as bowtie filters based on their shape, and are also described as beam-shaping filters. Since patients are predominately thicker and thus more attenuating in their center, the bowtie filter was developed to preferentially attenuate the incident beam in the center of the profile less than on the edges. The resultant beam coming out of the patient is roughly equal in attenuation across the detector surface. Variations in attenuation of the beam profile are therefore only caused by anatomical tissue differences within the patient rather than the thickness of the patient cross-section. This has a wide range of benefits for image detection and reconstruction[1,2].

2.4.2.2 PATIENT MISALIGNMENT EFFECTS OF BOWTIE FILTERS

Bowtie filters are also very sensitive to patient misalignment. The thinner center of the bowtie filter is designed to be superimposed over the thickest part of anatomy which is typically at the center of the patient. When a patient is positioned off of isocenter in any direction in the scanning plane, the thicker part of the bowtie filter becomes superimposed over thicker parts of the patient cross-section. Thus, an attenuated beam exiting the edges of the bowtie filter is further attenuated by the thicker cross-section leaving a lack of X-rays at the detector in that area. Conversely, the part of the beam that exited the center of the bowtie filter passes through a thinner part of the patient cross-section and thus has a relatively higher intensity. Figure 3 below demonstrates this attenuating effect for patients misaligned laterally[2,6].

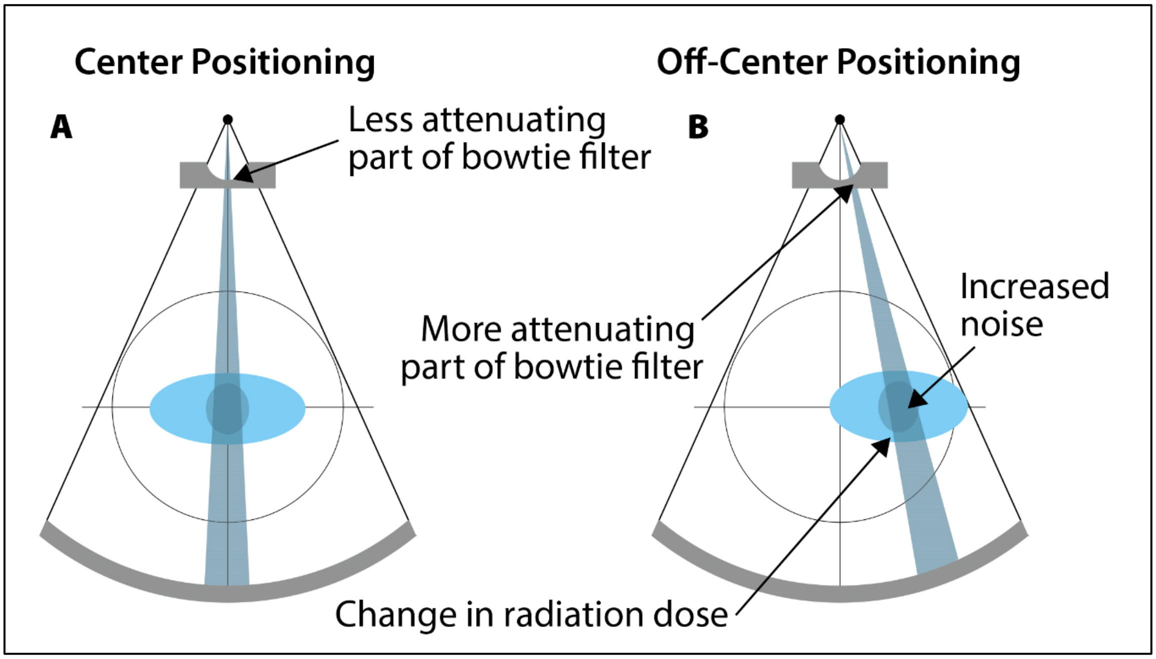

Figure 3: Zhang et al. fig. 7 a and b denoting effect of bowtie filter. Reprinted with permission from the American Society of Radiologic Technologists for educational purposes. ©2016. All rights reserved.

As stated earlier, a lack of X-rays at the detector fails to average out noise and produces a false CT number. Further, the larger amount of medium the beam travels through, the higher probability of Compton scatter that ensues[1,8]. Areas with a lack of attenuation due to misalignment have a stronger signal at the detector which can also manifest as an incorrect CT number for the voxels affected. While the noise level will be slightly lower in the region of low attenuation, this does not improve the quality of the image. The differences in attenuation create a variability in noise across the entire image[4]. This can make exams which involve thick portions of anatomy difficult to read. Comparisons between paired and symmetrical anatomy can prove to be difficult if one section of the image is obscured and the other is not. This effect has occasionally been known to lead to misdiagnosis[2].

2.5 UTILIZING DOSE MONITORING SOFTWARE TO ANALYZE PATIENT CENTERING PERFORMANCE

Tracking the effects of patient misalignment proves to be a data intensive and laborious task. The number of metrics impacted by off-center patient placement can be quite large and difficult to manage. CT instruments have also been outfitted with a number of technological developments which have turned a previously lengthy exam into a procedure that lasts a few minutes per patient. Consequentially, hospitals have pushed radiology departments to adopt a high throughput of patients in an effort to provide diagnoses as quickly as possible. Due to the accelerated workload, it is very difficult for technologists to keep up with manual data recording. This sort of data collection is prone to error and loss of data points, and is not ideal for large studies containing multiple variables. Methods to automate this process are highly sought after.

Imalogix is an internet-based software service which is used to automate data extraction from a variety of radiological procedures. Scan parameters are automatically uploaded and analyzed by the program. Each scan is tagged with a time and date stamp along with a patient identification number. Scout images, dosimetric properties and protocol parameters are attached to each data point to specifically archive all necessary data for the exam. Added automation like this permits larger scale dose monitoring.

Imalogix extracts and calculates specific vertical and lateral isocenter alignment data along with all of the exam parameters from the scout images and exam parameters. Data can then be sorted and analyzed based on subcategories influenced by patient misalignment. Correlations can be drawn between technologist errors and machine outputs.

Data can be downloaded in comma-spliced-variable format for review and manual data analysis. The Imalogix graphical user interface compiles data and displays statistical visualizations of trends automatically as an alternative to manually data manipulation. An example of the graphical summary statistics is shown in figure 4 below.

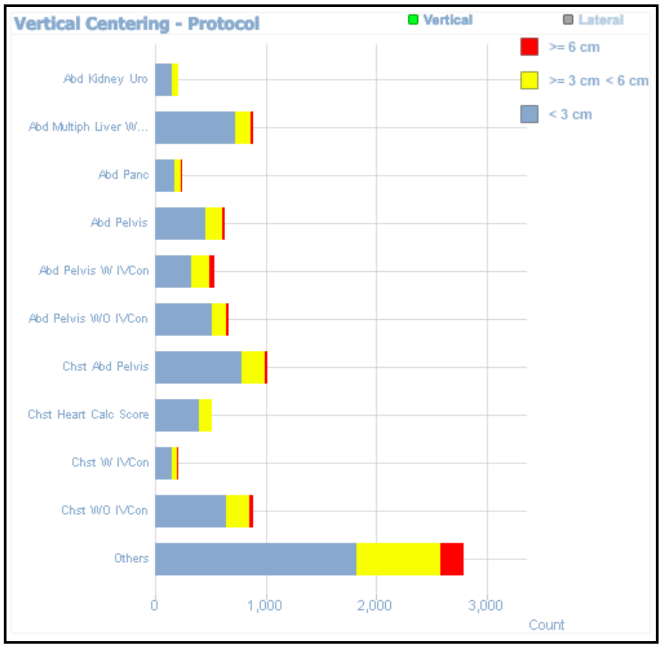

Figure 4: Graphical representation of statistical analysis on Imalogix.

OHSU hospital has six CT scanners devoted exclusively to diagnostic imaging at its main location in Portland, OR. Combined, these scanners see thousands of patients every week. The quantity of data produced by this number of scans can be staggering. Requesting the technologists to record data required by this study would be unnecessarily onerous. As a result, this study seeks to determine if Imalogix can be utilized for tracking quality improvements in the radiology department at OHSU. Since this is one of the first studies to use Imalogix in such a context, the level of productivity provided by this software will be assessed for future quality improvement endeavors. From the sufficient levels of automation programmed into the Imalogix system, it can be considered a convenient alternative to manual data extraction for this patient misalignment study.

3 MATERIALS AND METHODS

3.1 CT SCANNERS AND DATA TRACKING

Patient scan data from six CT scanners at OHSU were used in this study. These scanners are located on OHSU main campus and are operated by the same group of technologists. The scanners are enumerated to provide a simplified naming convention at the hospital. All of these names along with the make and model of the scanners are given here in the table 1 below.

Table 1: CT names, makes and models of scanners in the study.

Scanner ID	Make	Model
CT 1	Philips	Brilliance 16p
CT 2	Toshiba	Aquilion ONE VISION
CT 3	Philips	iCT 128
CT 4	Philips	Ingenuity 64
CT 5	Philips	Brilliance 64
CT 6	Philips	iCT 256

These scanners provide a variety of tools and technologies to the diagnostic radiology department at OHSU. They are all staffed by the same team of CT technologists who rotate between them. The scanners are spread out through the OHSU Main Hospital and the Center for Health and Healing (CHH) at locations near the patients they serve. Each CT has its own dedicated use for a specific patient population which may or may not be shared by another scanner. Occasionally, scanners are recruited to share the workflow of another machine.

All six scanners transmit their exam data to Imalogix. Parameters from each patient scan are grouped together and listed in a tabular format. Imalogix stores these tables and patient scan data, then provides fundamental analysis for quick reference. For data analysis which is not provided by Imalogix, the data can be exported into a comma-separated value (CSV) format. Data for this study was exported as a CSV file then analyzed using Excel (Microsoft® Corporation, Redmond Washington, USA). Prior to exporting from Imalogix, data was separated into specific categories which included, CT scanner, protocol, dosimetric parameter and size of patient.

Imalogix compiles data from other institutions and hospitals which use its service. Rankings are formulated as a percentile based on individual hospital performance among its peers. This data was used to compare metrics at OHSU to other similar facilities. It is important to compare rankings not as a method of competition, but as a comparison to help OHSU determine the standards in the industry it should pursue. An example image of this metric as viewed on the user interface is shown below in figure 5.

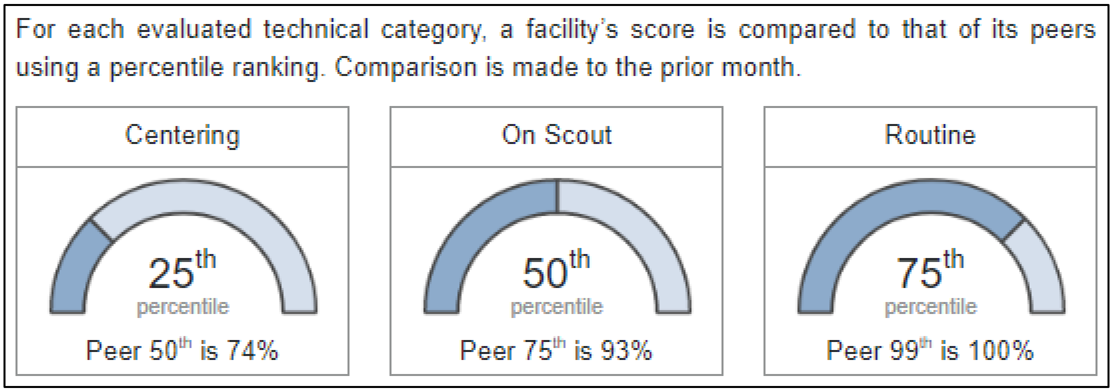

Figure 5: Imalogix graphical display of statistics with accuracy and peer ranking.

3.2 TECHNOLOGIST PRESENTATION

In order to improve isocenter alignment at OHSU, it was determined that the best course of action was to draft a presentation for the technologists. This presentation was intended to show CT technologists the current state of misalignment errors at OHSU, offer opportunities for improvement and provide information on the detriment to image quality and dosimetry incurred by misalignment. This presentation was the result of a combined effort by the three diagnostic imaging physicists involved in the study with consultation provided by the CT technologist supervisor. Technologists were not informed of the presentation or the content involved prior to the meeting to preserve the CT alignment *status quo* for data comparison. A copy of the presentation is included in Appendix A.

The presentation discusses a number of imaging issues stemming from alignment errors supported by findings in peer-reviewed journal articles. These articles note that changes in CT number and increased noise, which stem from alignment errors, contribute to degraded image quality. Alterations to dosimetric quantities, such as $CTDI_{VOL}$ and SSDE, are presented as dose effects of misalignment on CT. These effects were used to form a narrative which would motivate the technologists to improve isocenter alignment.

In the latter part of the presentation, case studies were included to further show the impact of these negative effects. One case study involved a patient who was misdiagnosed due to image artifacts brought on by poor patient alignment. Cases of alignment errors from OHSU were discussed to provide relevant examples. These anecdotal examples provided the technologists with more relatable incidents that demonstrate how the error could arise if care is not taken.

At the end of the presentation, a screenshot taken from Imalogix of vertical alignment accuracy at OHSU was shown to the technologists. This was followed by a discussion among the attendees at the meeting about improvements that could be made to remedy the deficit in proper alignment. Before the meeting adjourned, the technologists were informed that there would be a follow up meeting to show whether or not there was a significant improvement, so they could be encouraged by the impact of their efforts.

This presentation was meant to be the crux of the study. As a result, significant time and effort was put into the slideshow to ensure that it was motivating enough to exact a change. Content and verbiage in the presentation was catered towards an audience of CT technologists. All technologists associated with the six CT scanners were given the presentation to be sure that everyone could contribute to the quality improvement study. Multiple presentation sessions from February 8th to the 12th, 2019 were given to include technologists at all different work schedules. The data before and after these presentations was then analyzed to determine the effects of the presentation on patient alignment in the clinic.

3.3 STATISTICAL ANALYSIS

Three basic date ranges exist for the data produced in this study. The first date range was from January 1st to September 10th, 2018 and establishes a baseline characterization of the status of patient alignment before any technologists were informed of it. The second date range begins on September 11th, 2018, which was the day after technologists were informed by their supervisor that patient alignment was an area that required improvement at OHSU. This range continues until February 7th, 2019, which was the day before the technologists were given the quality improvement presentation on patient alignment. This presentation was given several times over the course of four days from February 8th to the 12th, 2019 to ensure all technologists received the information. The third and final date range started after the presentation, February 13th, and ended on April 26th, 2019 when the final data was extracted from Imalogix.

Data in the date range from January 1st to September 10th, 2018 is referred to as the baseline data. It was not grouped in with the subsequent date range, because there was a small but noticeable improvement in patient alignment accuracy after the technologists were informed by their supervisor, which does not allow the proper characterization of the impact from the presentation. The data belonging to the second date range is referred to as data taken before the presentation and should not be confused with the first date range even though they both occurred before the presentation. The data belonging to the third date range is referred to as data taken after the presentation. Both the before and after data were extracted at the same time and analyzed together to make a comparison which would determine the efficacy of the presentation.

Data remained separated in vertical and lateral offset cohorts. Total offset was not used in this study, because it does not properly isolate factors stemming exclusively from offset in one particular dimension. In general, vertical offsets above isocenter are considered positive, while those below isocenter are considered negative. Lateral offsets are either positive when the patient center is to the right of isocenter, and negative when the patient center is to the left of isocenter. It is important to note that lateral directions are defined when the bore of the scanner is viewed from the end of the table at the patient's feet. This means that the left side of the patient from their point of view is actually defined as the right side of the image. This convention is used by most radiologists and technologists in the clinic, so it will be used here.

3.3.1 2018 BASELINE DATA

CT data across all CT scanners from the year 2018 was exported from Imalogix into a CSV file. This set was used to produce a characterization of misalignment errors prior to the presentation given to the technologists. Data produced before and after the presentation was compared to this 2018 data set to determine the extent of the presentation's efficacy. Data from this set was restricted to only include those scans taken between January 1st, 2018 and September 10th, 2018.

After the date was restricted, the data were further refined to eliminate biases and exclude redundancies. Data points belonging to the same patient and visit were combined. Scout images, localizer scans and full CT scans were pooled together to provide a general set of data variables belonging to one data point per exam. Patient identification information was removed to reduce the spread of personal data. Many scans for which Imalogix could not extract quantitative alignment data were not included in this data analysis. Imalogix does not take alignment offsets for extremity, head, and neck scans, because these scans cannot be used to calculate size-specific dose estimates. The data and methods for calculating SSDE measurements for these types of scans are not available at the current time. Imalogix determined that this was a necessary step to provide accurate data for dosimetry.

Data taken from heart exams were excluded from protocol data analysis. Heart scans, despite being imaged with the same protocol, often include a variety of supplemental anatomy as requested by the physician. Some exams include the heart only, while others include other regions of the torso. Since these exams can have different alignment landmarks and procedures, they were considered too inconsistent to be analyzed in the same ways as the other data.

The remaining data points were grouped into several categories to gain insight into reasons for errors made during patient alignment. Data sets for each CT scanner were produced and analyzed. Data was further separated by scanning protocol used. These protocols were refined further to produce a set of scanning regions. For example, the protocols “Chst Abd Pelvis” and “Chst Abd Pelvis Angio” were grouped together into a category titled “Chest-Abdomen-Pelvis,” or “CAP,” to obtain all data for patients scanned across the entire torso. The scanning regions were intended to represent protocols with similar alignment landmarks and techniques. Only the most utilized protocol categories for both lateral and vertical alignment were analyzed. An arbitrary cutoff point of 10 data points was used to distinguish the top protocols from the others. This was justified by the desire to reduce the number of categories with large statistical variations due to low numbers that may have skewed analysis results. Further, the top categories included in the analysis were well above the 10-scan threshold. There was no differentiation made on the type of scan, but rather how many scans of that type were taken during the time period.

All the data was combined to produce characterizations of the data as a whole in 2018. Calculations of accuracy and averages were used to evaluate alignment performance. Accuracy calculations are tabulated as a percent of scans within 3 cm of isocenter. Histograms were formed with half centimeter bins. Bar graphs and line graphs were used to display numbers relative to one another. Separations were made to categorize data and compare among the categories. Certain protocol categories were compared to one another to determine the specific errors made in aligning certain body parts. All CT scanners were compared to each other to identify scanner technology which may have contributed to alignment errors.

3.3.2 PRESENTATION EFFICACY AND DOSE CHANGES

In a similar way to the baseline data, the before and after data were retrieved from Imalogix and formatted to one exam per patient per visit. Patient identification numbers were removed to reduce the spread of private information. Heart, extremity, head, and neck exams were removed for the same reasons as the baseline data. Differences between the before and after data were noted by accuracy and average offset in both lateral and vertical data. Percent accuracy calculations were defined as the fraction of patient exams aligned within 3 cm of isocenter to the total number of exams in the category. Histograms were graphed together to demonstrate changes in data. All graphs were formatted with different colors for different offsets and date ranges. Bar graphs were used to compare changes and relative values to one another.

Protocols were also grouped in the same way as the baseline data with the same categories. Torso protocols were taken separately from the rest of the protocols for further analysis. These protocols were chest, abdomen, pelvis, abdomen-pelvis and chest-abdomen-pelvis. All five of these categories represent different parts of the torso or the whole torso. Since this is cross-sectionally the largest part of the body, it receives the largest doses from the higher output of the tube current modulation system.

Data were also grouped by CT scanner for an analysis by scanner technology. CT2, the only Toshiba (Toshiba Corporation, Tokyo, Japan) scanner, was compared to all the others which are of Philips make to determine if the technology employed by either company has any impact on positioning or the changes made in the study. In the article by Marsh and Silosky a Philips Brilliance 64 (scanner D) just like CT5 was used to demonstrate scanner differences[5]. The other scanners in that paper were Siemens and General Electric, which are brands not used in this study. No Toshiba scanners were used in the study by Marsh and Silosky, so data from the Toshiba were used to compare to scanners in the paper and this study.

Imalogix performs its own statistical analysis to display on its user interface. The software program calculates percent accuracy for quick evaluations. This accuracy only includes vertical offsets and does not include head, extremity or other exams which do not have a SSDE or vertical offset data. It also calculates a peer review ranking for hospitals that also use Imalogix. These rankings are displayed as monthly statistics on the dashboard of the graphical user interface. Both the accuracy and peer review rankings for each month were extracted and analyzed as a whole and by CT scanner. The date ranges for these were rounded to the nearest month (e.g. the baseline data included data from January to September, not January 1st to September 10th).

SSDE and $CTDI_{VOL}$ were also exported with each data point. These data provided a basis for determining dosimetric changes based on patient alignment. While other dosimetric parameters for CT exist, they are not as robust as SSDE or $CTDI_{VOL}$ for detecting changes since they are also dependent on other variables that vary separately from displacements. Dosimetric change evaluations were based only on SSDE and $CTDI_{VOL}$. Changes in dose were evaluated for the data as a whole and for each data category.

Since radiation dose depends largely on the patient and attributes of the CT exam, the data was restricted by a number of methods to eliminate any factors which may cause unforeseen variations in dose. First, the data was tabulated as a change in $CTDI_{VOL}$ or SSDE based on CT scanner. Each CT has its own technology which is used in exams for which it is best suited. For example, CT6 is used almost exclusively for cardiology exams since it has technological additions used to image the heart. These data were used to determine the effects of various scanner technologies on dosimetric changes.

Data were then categorized by protocol. Each exam protocol is specifically calibrated with the inputs required to properly image the region of anatomy requested by the physician. These parameters have a notable impact on the $CTDI_{VOL}$ that a patient receives. These protocols also cover the same area of anatomy which further reduces variation caused by factors other than offset.

Radiation dose and tube current modulation correlate with patient size. Larger patients receive a higher radiation output from TCM systems and as a result receive larger doses than smaller patients. Data were extracted from Imalogix according to patient size to reduce variation caused by the cross-sectional width of patients. Imalogix characterizes patient size as XXS, XS, S, M, L, XL and XXL. Information on the measurements that define these categories can be found below in table 2. Size measurements are taken from the scout image and are measured by Imalogix. These categories were each extracted with both $CTDI_{VOL}$ and SSDE measurements. These data were further categorized by protocol to determine the changes in dose due to vertical offset for each patient size and region of the body imaged.

Table 2: Measurement ranges used by Imalogix to define patient sizes. Values in centimeters.

Body Region	XXS	XS	S	M	L	XL	XXL
Chest	<24.0	24.0 - 26.6	26.6 - 30.1	30.1 - 33.3	33.3 - 36.5	36.5 - 39.6	>39.6
Waist	<19.0	19.0 - 21.8	21.8 - 25.0	25.0 - 28.2	28.2 - 31.7	31.7 - 34.9	>34.9
Hips	<24.0	24.0 - 26.6	26.6 - 30.1	30.1 - 33.3	33.3 - 36.5	36.5 - 39.6	>39.6

As a final restriction, lateral offset data was not included in the evaluation of dose changes. It was determined that lateral offsets mostly impact image quality, and do not have a known or distinguishable impact on dosimetry. Vertical offsets alone were used to show correlations between patient dose and alignment errors. Dosimetric changes were demonstrated as changes in average $CTDI_{VOL}$ or SSDE for each category or CT scanner described. These were compared to the average vertical offset for their respective categories.

Both offset and dosimetry changes were analyzed using a two-tailed t-test with a test statistic of 0.05. Statistical significance was determined by a p-value which was compared to the test statistic. T-tests were performed in Microsoft Excel using the data analysis tool kit. The hypothesized mean difference was determined to be 0, or no change. Equal variances were assumed since there was only a slight change in standard deviations between the two data sets involved. The extent of changes and those associated with separate categories were demonstrated by graphical data.

4 RESULTS

4.1 2018 BASELINE DATA

A total of 13,632 vertical alignment data points and 14,349 lateral alignment data points from CT scans during the period between January 1, 2018 and September 10, 2018 were extracted from Imalogix and analyzed. The average vertical offset across all data points was 2.05 ± 2.45 cm below isocenter. The average lateral offset across all data points was 0.23 ± 1.51 cm to the left of isocenter. The percent accuracy defined by scans made by aligning patients within 3 cm of isocenter was 64.13% vertically and 94.17% laterally.

Vertical offset averages were farther from isocenter and had a larger standard deviation. The average vertical offset was almost 9 times that of the lateral offset. The accuracy was about 47% percent better for lateral offset than it was for vertical offset. Histograms are shown below in figure 6 depicting this discrepancy. The vertical offset bell curve is farther to the left and wider at the full-width half-max than the lateral curve reflecting the greater offset and larger variation respectively.

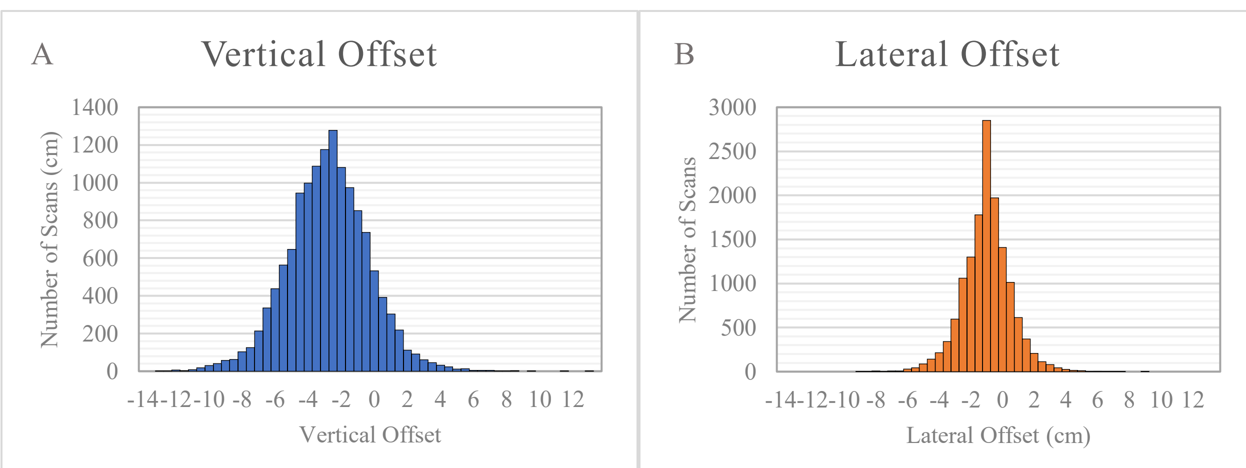

Figure 6: A) Vertical offset histogram. B) Lateral offset histogram.

All data were sorted by CT scanner and analyzed according to the vertical and lateral offset. The total number of scans for each CT scanner and the summation of the total scans are shown in the graph below, figure 7. CT2 and CT4 were the most utilized scanners during this time period, but CT5 had the most lateral and vertical offset data points. CT6 was the least utilized scanner during this time period.

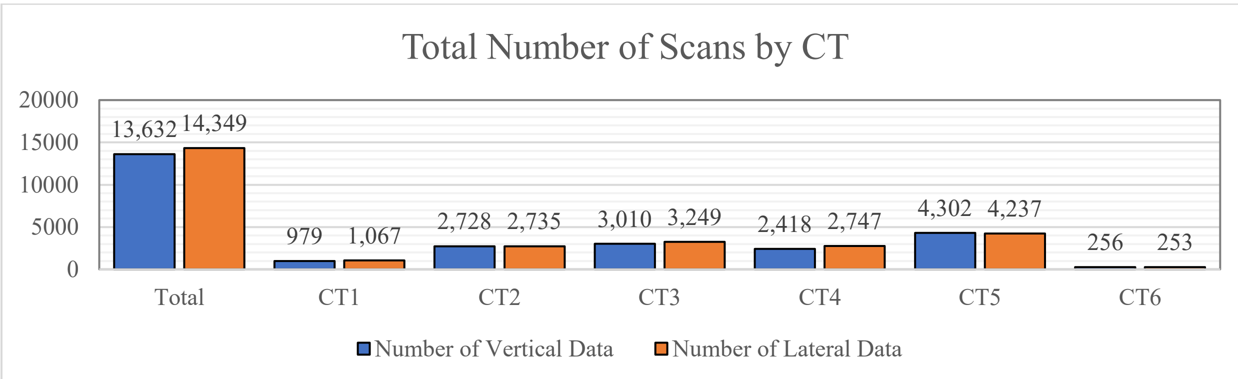

Figure 7: Total scans of each CT scanner from January 1, 2018 to September 10, 2018.

Exams on CT3 had the largest average vertical offset of all scanners, while exams on CT5 had the largest lateral offset. All scanners had vertical offset averages below isocenter. Most lateral offset averages were to the left of isocenter with the exception of CT1 and CT3. Bar graphs detailing the average misalignments of each scanner are shown below in figure 8. Negative values represent averages which were below or to the left of isocenter, while positive values denote averages above or to the right of isocenter when viewing the patient from the foot to the head. These averages have been included at the ends of the bars. Total values have been added to the graphs to compare each CT to the data as a whole.

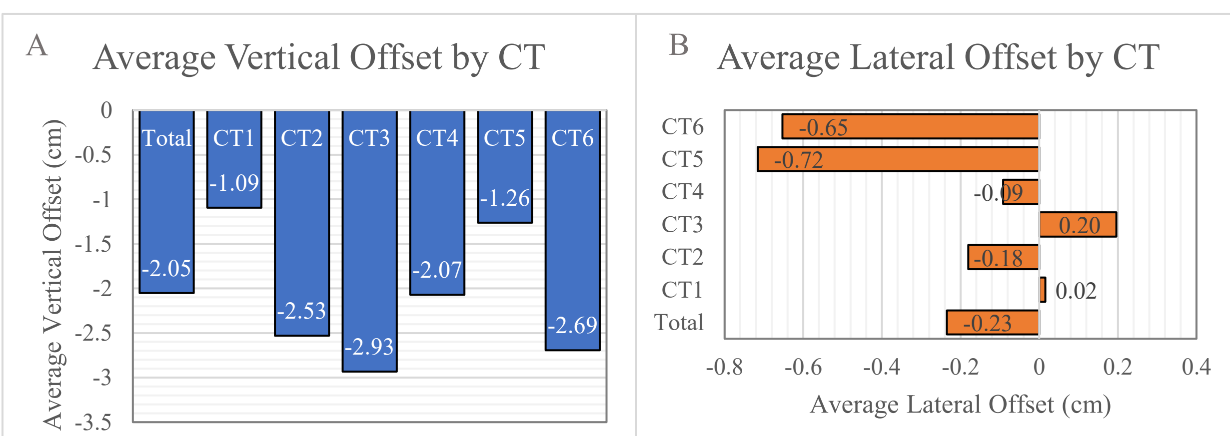

Figure 8: A) Average vertical offset for each CT scanner. B) Average lateral offset for each CT scanner.

When data were separated by protocol, pelvic scans demonstrated the farthest average offset from isocenter in the vertical direction with an average of 2.82 cm below isocenter. Lumbar spine (L Spine) scans tended to be the most accurate by average at 1.10 cm below isocenter. These exams were nearly half a centimeter better than thoracic spine (T Spine) protocols on average. None of the vertical alignment averages were above isocenter. A graph of each protocol's vertical alignment average is shown below in figure 9.

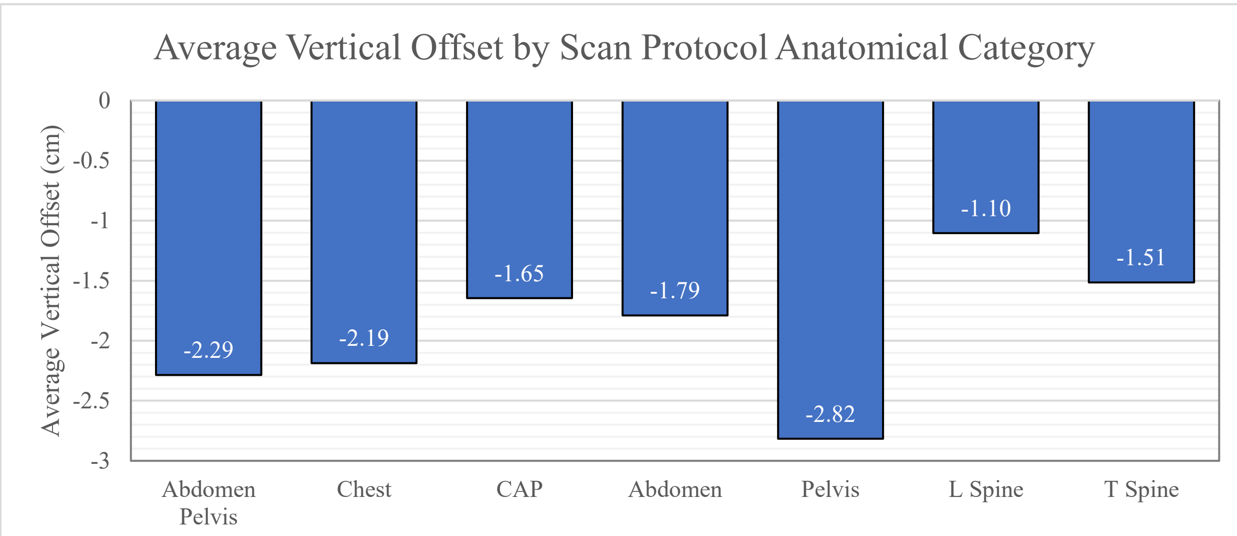

Figure 9: Average vertical offset for each protocol.

In most protocols patients were positioned laterally to the left of isocenter with the exception of pediatric chest-abdomen-pelvis, pediatric abdomen and pediatric chest. Chest screening protocols were on average, the farthest from isocenter at 0.43 cm to the left of it. Thoracic and lumbar scans were comparable in average lateral offset. Pediatric protocols varied considerably from adult protocols. Most of these protocols were to the right of isocenter while their adult counterparts were to the left. Pelvic scans were comparable between adult and pediatric scans and on the same side of isocenter. A graph of each protocol's Lateral alignment average is shown below in figure 10.

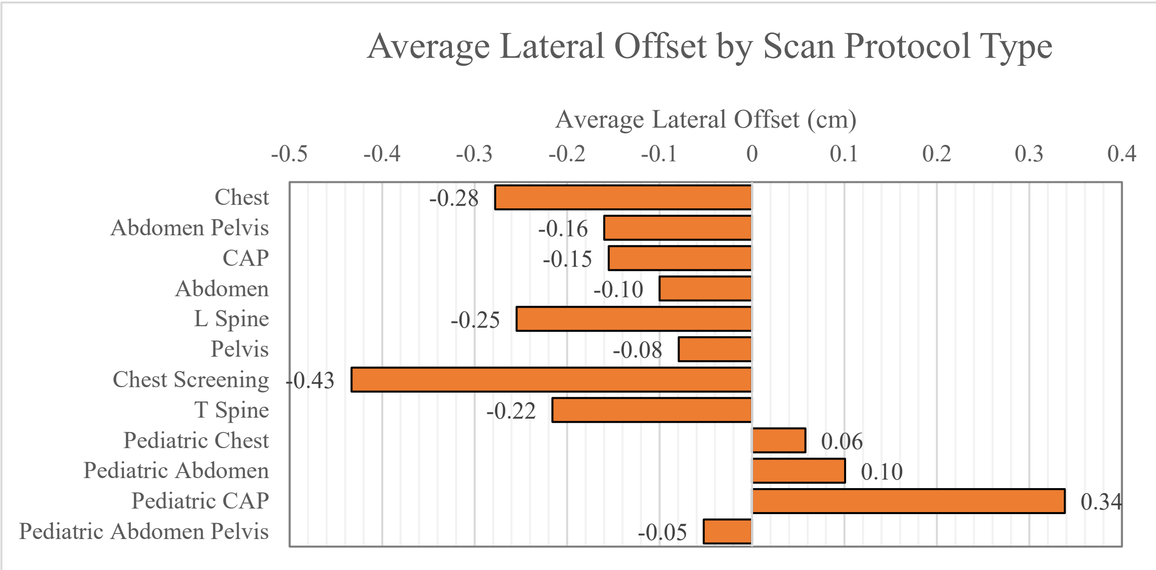

Figure 10: Average lateral offset for each protocol.

Five of the most utilized protocols which included the same part of the body, the torso, were separated out and analyzed. These selected categories include chest-abdomen-pelvis (CAP), abdomen-pelvis (AP), chest, abdomen, and pelvis. AP protocols were the most utilized of the data obtained. Pelvic exams were the least common of these data.

CAP categories were separated from the rest of the data to help determine parts of the torso which were difficult for technologists to align. The CAP category tended to be more accurate than its constituents, abdomen-pelvis (AP), chest, abdomen, and pelvis. From what was observed in the vertical offset data, pelvic scans had the largest percentage of scans over 6 cm from isocenter. Other protocol categories were similar to CAP, but ultimately did not have as good of accuracy. Percent of total values for 3 cm accuracy is higher in CAP than any other protocol category. The percent of scans over 6 cm was smaller than any other category.

Lateral data showed a similar story, but with an accuracy that was much better than in the vertical data. Only a handful of scans were over 6 cm from isocenter. There were no pelvic scans that were off-center by more than 6 cm. Still, pelvic scans had relatively low accuracy in other offset categories. CAP remained the most accurate category in lateral alignment of those shown. These protocol categories along with the percent of total accuracy distributions are shown in table 3 below.

Table 3: Percent accuracy by offset category for vertical and lateral offset.

Vertical Offset					
Top Exams	Totals	0-1 cm	1-3 cm	3-6 cm	6+ cm
Abdomen Pelvis	3608	20.84%	39.66%	33.81%	5.68%
Chest	3171	22.80%	40.96%	31.03%	5.20%
CAP	2953	25.87%	43.82%	26.85%	3.45%
Abdomen	1701	23.75%	41.68%	30.51%	4.06%
Pelvis	168	9.52%	33.93%	36.90%	19.64%
Lateral Offset					
Abdomen Pelvis	3611	59.04%	35.06%	5.73%	0.17%
Chest	3206	50.25%	43.11%	6.39%	0.25%
CAP	2981	62.29%	34.08%	3.52%	0.10%
Abdomen	1717	60.28%	35.88%	3.79%	0.06%
Pelvis	193	48.70%	35.75%	15.54%	0.00%

4.2 PRESENTATION EFFICACY

In total, there were 7,908 exams in the vertical offset cohort between September 11, 2018 and February 7, 2019, and 4,050 exams between February 13 and April 26, 2019. Average vertical offset before the presentation was 1.70 ± 2.48 cm below isocenter. After the presentation, the average vertical offset was closer to isocenter at 1.21 ± 2.33 cm below isocenter. A two-tailed t-test assuming equal variances showed that the decrease in distance from isocenter of 0.49 cm was highly significant ($p < 0.0001$).

Data for lateral offset analysis included 8,304 exams between September 11, 2018 and February 7, 2019, and 4,234 exams between February 13 and April 26, 2019. Lateral offset before the presentation was at 0.18 ± 1.52 cm to the left of isocenter. After the presentation, lateral offset remained roughly the same, but was ultimately closer to isocenter at 0.16 ± 1.46 cm to the left. This 0.02 cm shift was not a significant change in the mean as demonstrated in a two-tailed t-test ($p = 0.35$).

Bell curves detailing the change in offset are shown below in figure 11. These charts show the percent of all exams that were aligned in the given vertical or lateral offset bins. There are two prominences on the vertical offset curves. The peak to the right of the larger one indicates the percentage of scans performed at isocenter in the vertical direction. The lateral offset curves did not shift by much and are thus superimposed slightly.

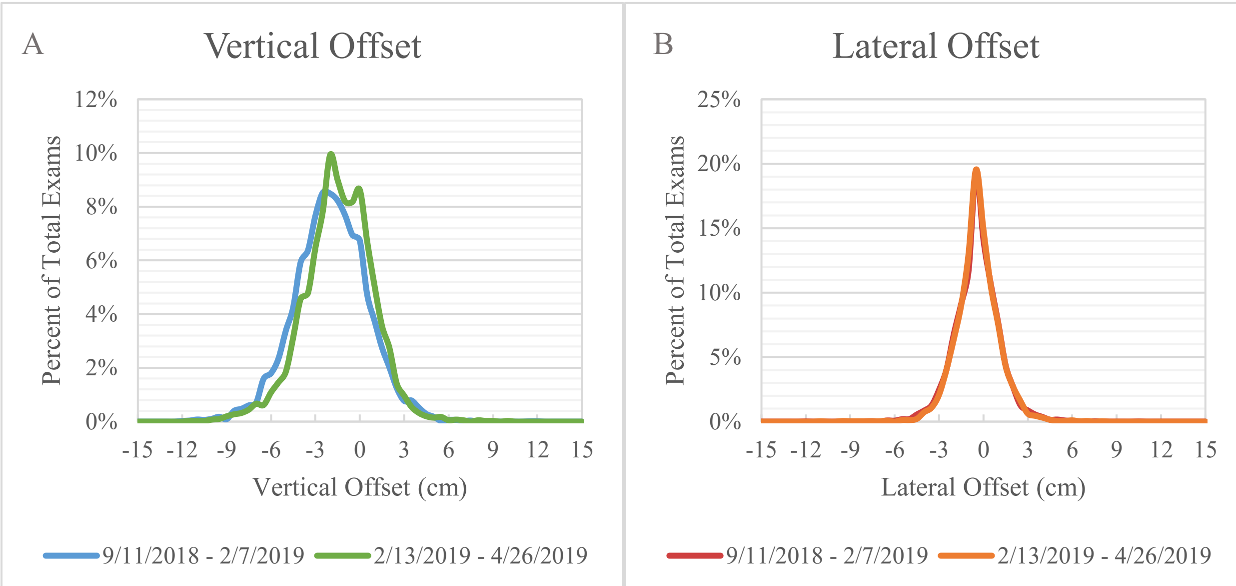

Figure 11: A) Vertical offset histograms and B) lateral offset histograms for before and after the presentation.

Accuracy as defined as the percentage of exams aligned within 3 cm of isocenter was 68.80% vertically and 94.41% laterally prior to the technologist presentation. After the presentation, accuracy was 77.68% vertically and 95.73% laterally. Accuracy improved by 12.91% from the initial value in vertical alignment, and only 1.40% from the initial value in lateral alignment.

Data produced by Imalogix also showed an increase in accuracy for the September and February technologist discussions. From the Imalogix rankings among other hospitals, the peer ranking averaged in the 28th percentile between January 2018 and August 2018. This average ranking improved to 34th during the second date range, September 2018 to January 2019. After the technologist presentation the peer ranking averaged 55th from February to April in 2019. Graphs of both the accuracy, as calculated by Imalogix, and the associated peer ranking of that accuracy are shown below in figure 12.

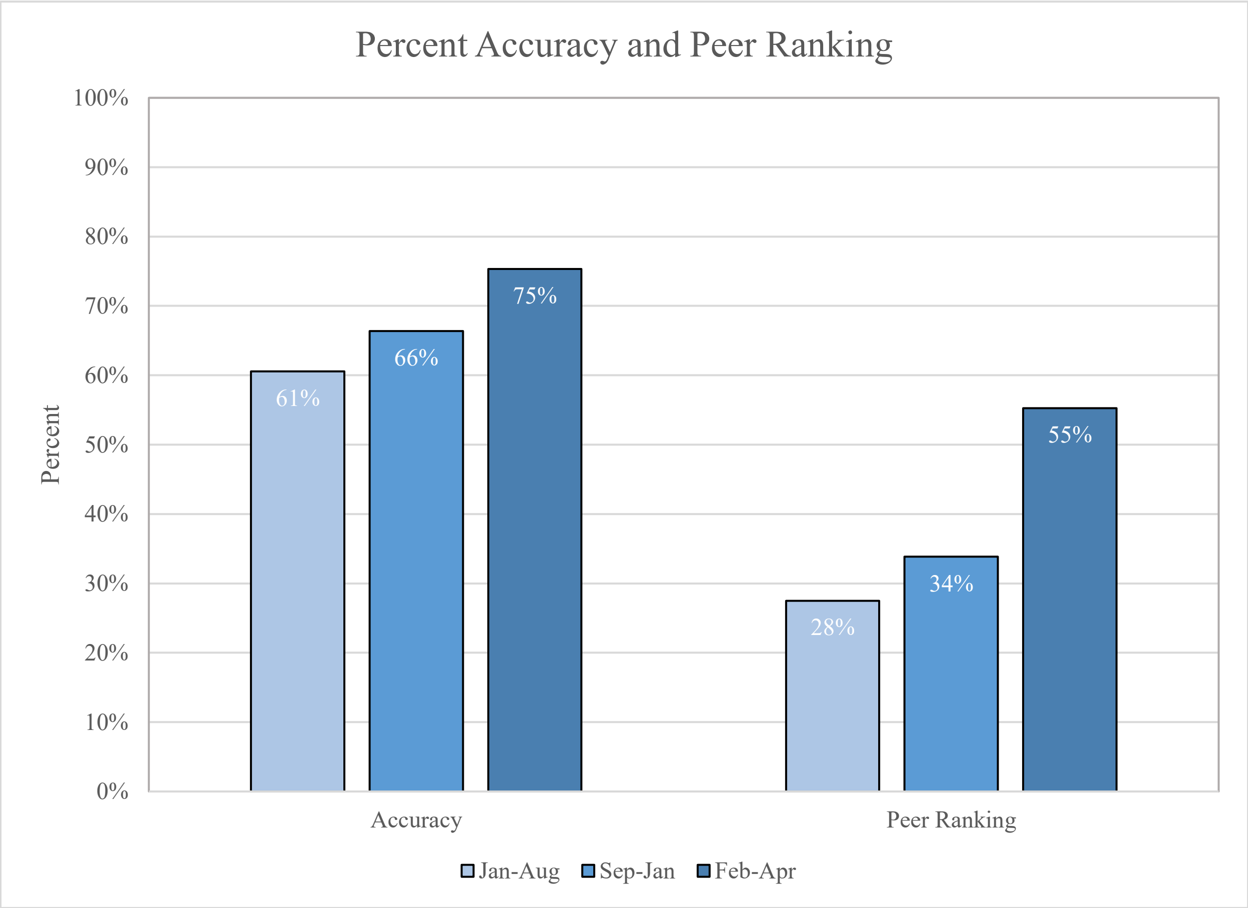

Figure 12: Percent accuracy and peer ranking for each scanner.

The accuracy and peer ranking data for each CT is shown below in figure 13. All scanners showed improvement in both categories across all date ranges. The change in peer ranking and accuracy was much greater for the January-February transition when the presentation occurred than the August-September one when the technologists were informed of the less than optimal patient alignment status at the hospital. CT6 made one of the most dramatic improvements, while CT1 made the smallest improvements. CT5 had the best peer ranking and accuracy for all date ranges, while CT3 had the worst. All CT scanner accuracies and peer rankings improved.

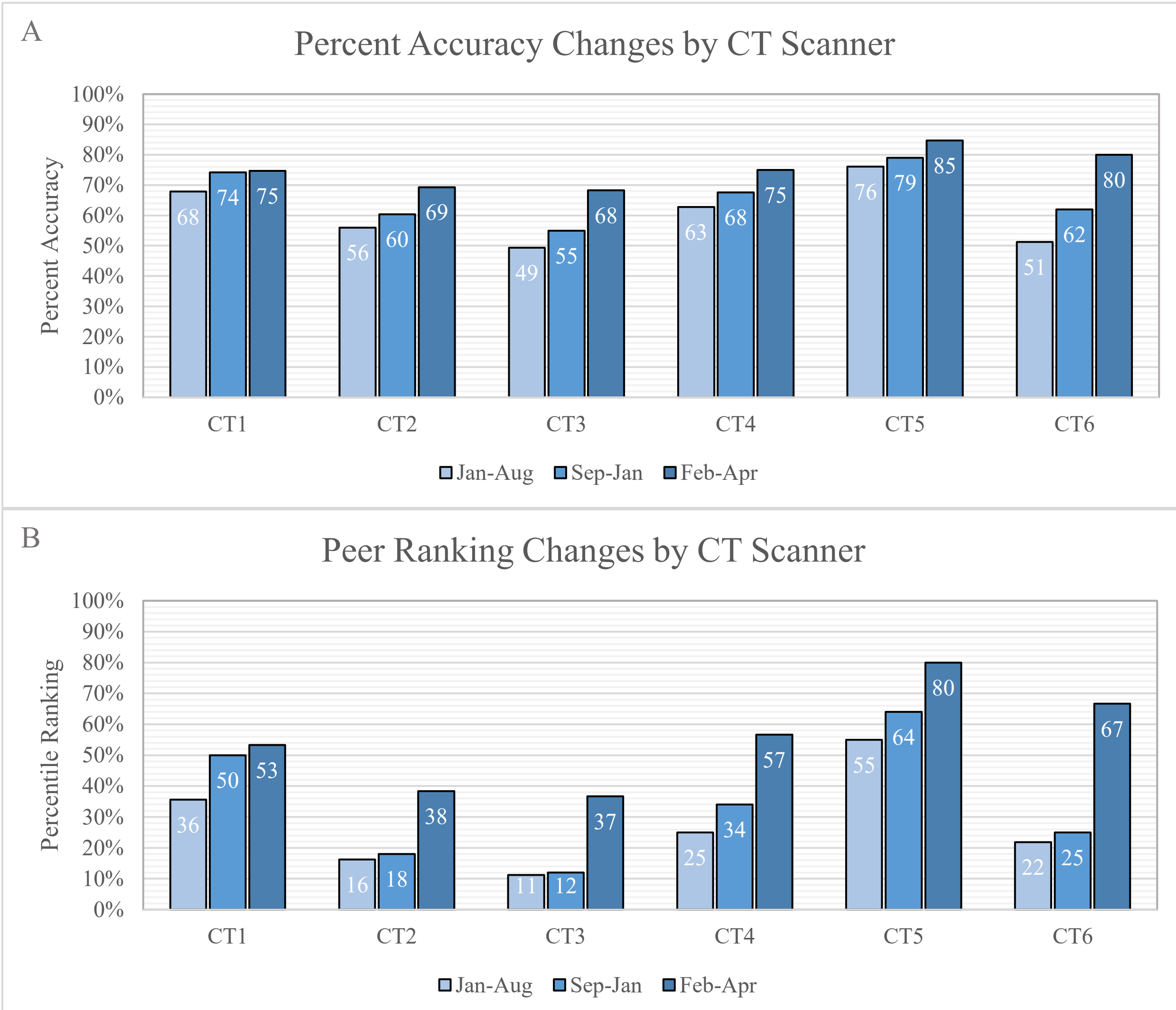

Figure 13: A) Percent accuracy and B) peer ranking changes across all date ranges for all CT scanners.

Average vertical offsets from after the presentation improved over the offsets from before for all scanners. All scanners remained below isocenter for both date ranges despite prominent improvements in average vertical offset. CT6 had the largest change in average vertical offset with a 1.22 cm increase towards isocenter. CT5 had the closest vertical offset to isocenter after the presentation at 0.39 cm below it. Changes in average vertical offset for each scanner can be seen below in figure 14. Each average is shown at the ends of the columns in the bar graph.

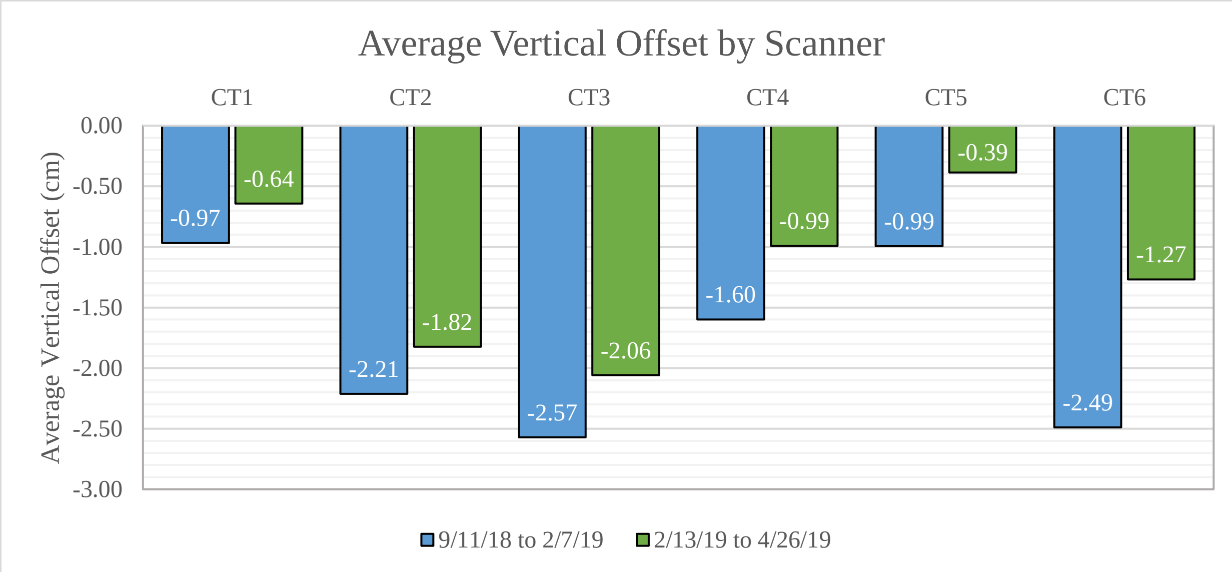

Figure 14: Average vertical offset for each CT scanner.

Average lateral offset improved on some scanners and worsened on others. The largest lateral offsets decreased while smaller offsets shifted farther from isocenter. CT6 had the greatest decrease in distance from isocenter at 0.5 cm which corresponds to a 66% reduction. A graph demonstrating these changes is shown below in figure 15.

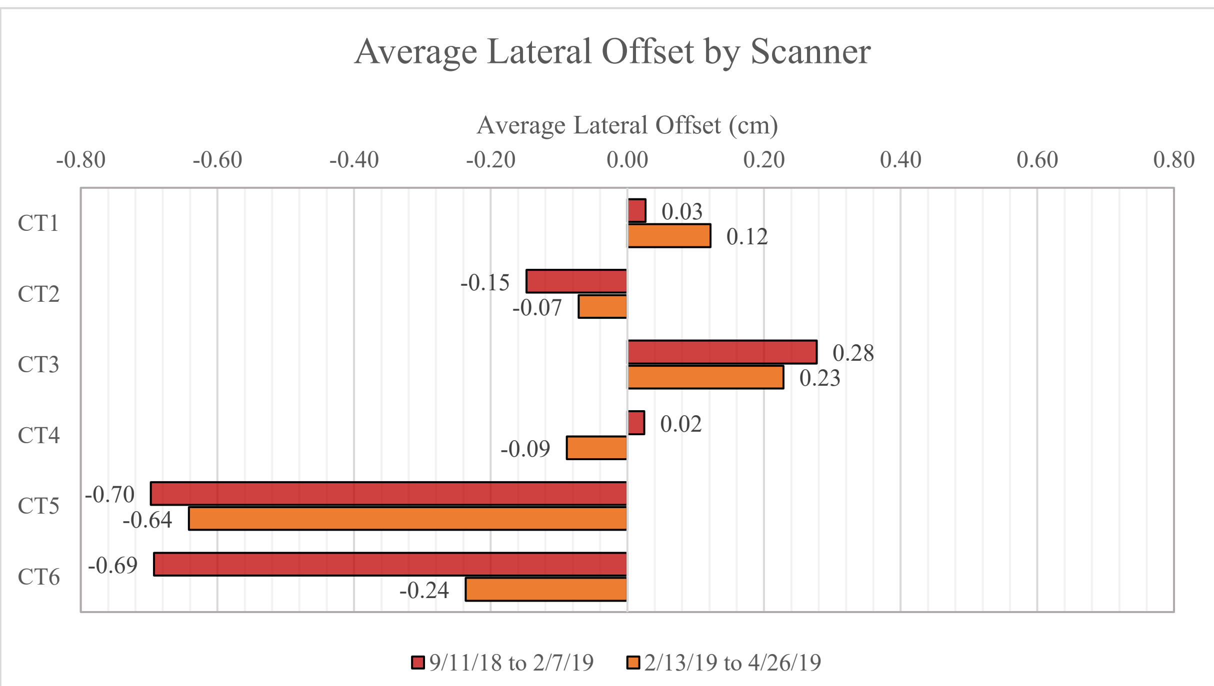

Figure 15: Average lateral offsets for each CT scanner.

While vertical offset improved in all CT scanner categories, it did not improve in all protocol categories. Lumbar and thoracic spine exams were aligned more poorly after the presentation than before. Other protocols demonstrated decreases in vertical distance from isocenter. Abdomen protocols produced the most dramatic improvement in vertical offset, while pelvis had the smallest decrease in distance from isocenter. Despite this, all average offsets were below isocenter for both date ranges. This can be seen below in the following graph, figure 16. Averages are included in the ends of the columns for convenience.

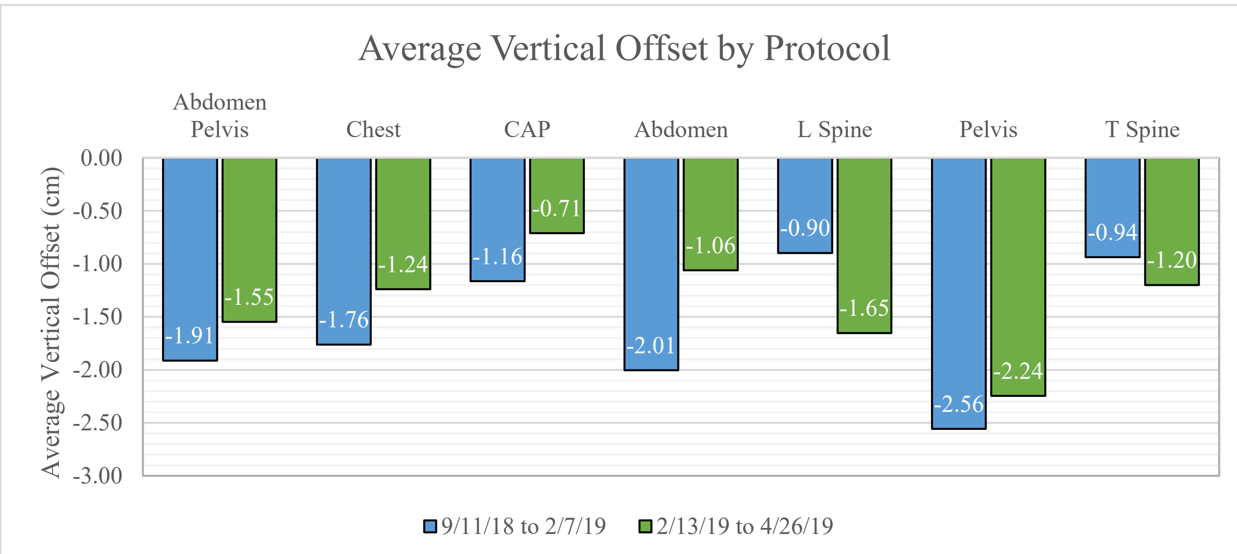

Figure 16: Average vertical offset for each protocol.

Improvement of lateral averages for each protocol varied. Some protocols were aligned better while others were aligned more poorly or remained the same. In fact, the majority of offsets were worse after the presentation. Abdomen-pelvis, chest, abdomen, lumbar spine, and pediatric abdomen protocols were the only exams for which lateral alignment improved. Pediatric abdomen protocols had an average vertical offset of 0.0 cm which was the only datum that improved to perfect alignment in the entire study. Average lateral alignment statistics are shown in figure 17 below with numerical data shown at the ends.

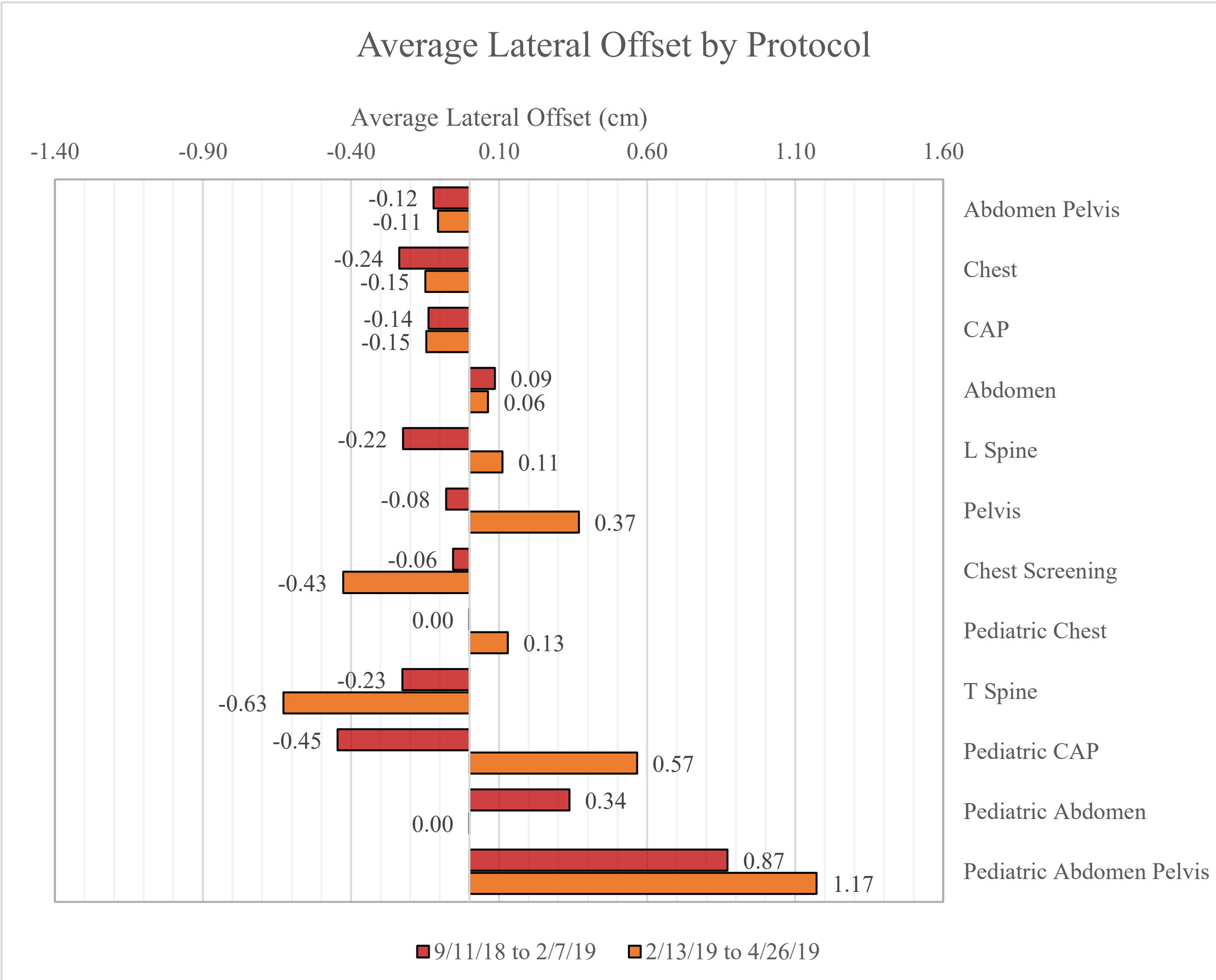

Figure 17: Average lateral offset for each protocol.

CAP protocol improvements were tracked by categorical accuracy in addition to average offsets. Vertical accuracy groupings are shown in the bar graph below in figure 18. The percentage of scans over 6 cm decreased in all categories, with pelvis protocols having the largest decrease in value at 8.16%. Pelvic accuracy within 3 cm did not change and remained at 50%. The largest increase in accuracy came from abdomen protocols which improved 11.73%. With the exception of pelvic exams at 3 cm, all CAP protocols showed signs of accuracy improvements at all levels.

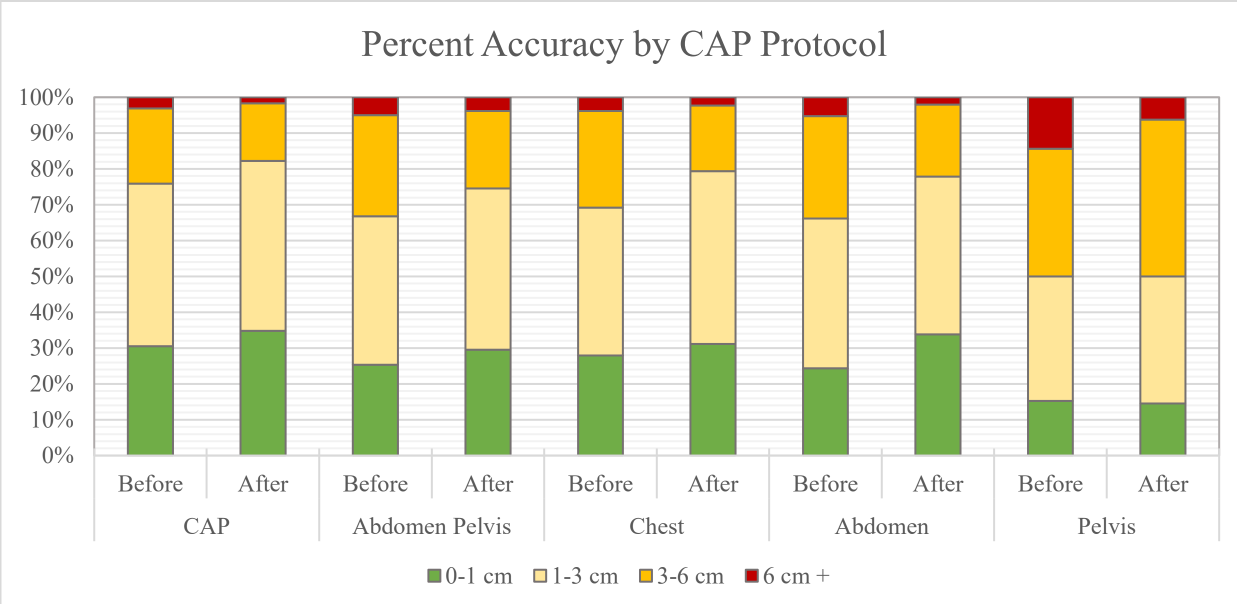

Figure 18: Percent accuracy by offset category for each torso protocol.

4.3 DOSIMETRIC EFFECTS FROM ALIGNMENT CHANGES

$CTDI_{VOL}$ and SSDE measurements are used to demonstrate changes in dosimetric data due to alignment shifts. In total, there were 14,528 data points for $CTDI_{VOL}$ between September 11, 2018 and February 7, 2019, and 7,339 exams between February 13 and April 26, 2019. The average $CTDI_{VOL}$ in the first date range was 21.71 ± 17.69 mGy. In the second date range, the $CTDI_{VOL}$ average shifted up to 22.08 ± 18.44 mGy. The increase in dose of 1.37 mGy was deemed not a significant difference in the mean as demonstrated by a two-tailed t-test ($p = 0.14$).

Exams for which there was SSDE data totaled 8,308 between September 11, 2018 and February 7, 2019, and 4,235 between February 13 and April 26, 2019. The average SSDE before the presentation was 12.93 ± 8.11 mGy, while the average after was 13.05 ± 9.03 mGy. This 0.12 mGy shift was also not deemed a significant difference in the mean in a two-tailed t-test ($p = 0.43$).

In general, $CTDI_{VOL}$ and SSDE changed in similar ways. When $CTDI_{VOL}$ increased or decreased, SSDE had the same reaction. Changes in SSDE were smaller than $CTDI_{VOL}$. SSDE values were generally smaller than those of $CTDI_{VOL}$.

Across all scanners, the average $CTDI_{VOL}$ and SSDE increased in value. The most dramatic change came from CT6, where $CTDI_{VOL}$ increased by almost 2 mGy or 17.28%, and SSDE increased by 0.40 mGy or 3.87%. The smallest change came from CT1 which had a $CTDI_{VOL}$ increase of 0.35% and a SSDE increase of 0.61%. Graphs in figure 19 below show the average changes in $CTDI_{VOL}$ and SSDE for each scanner.

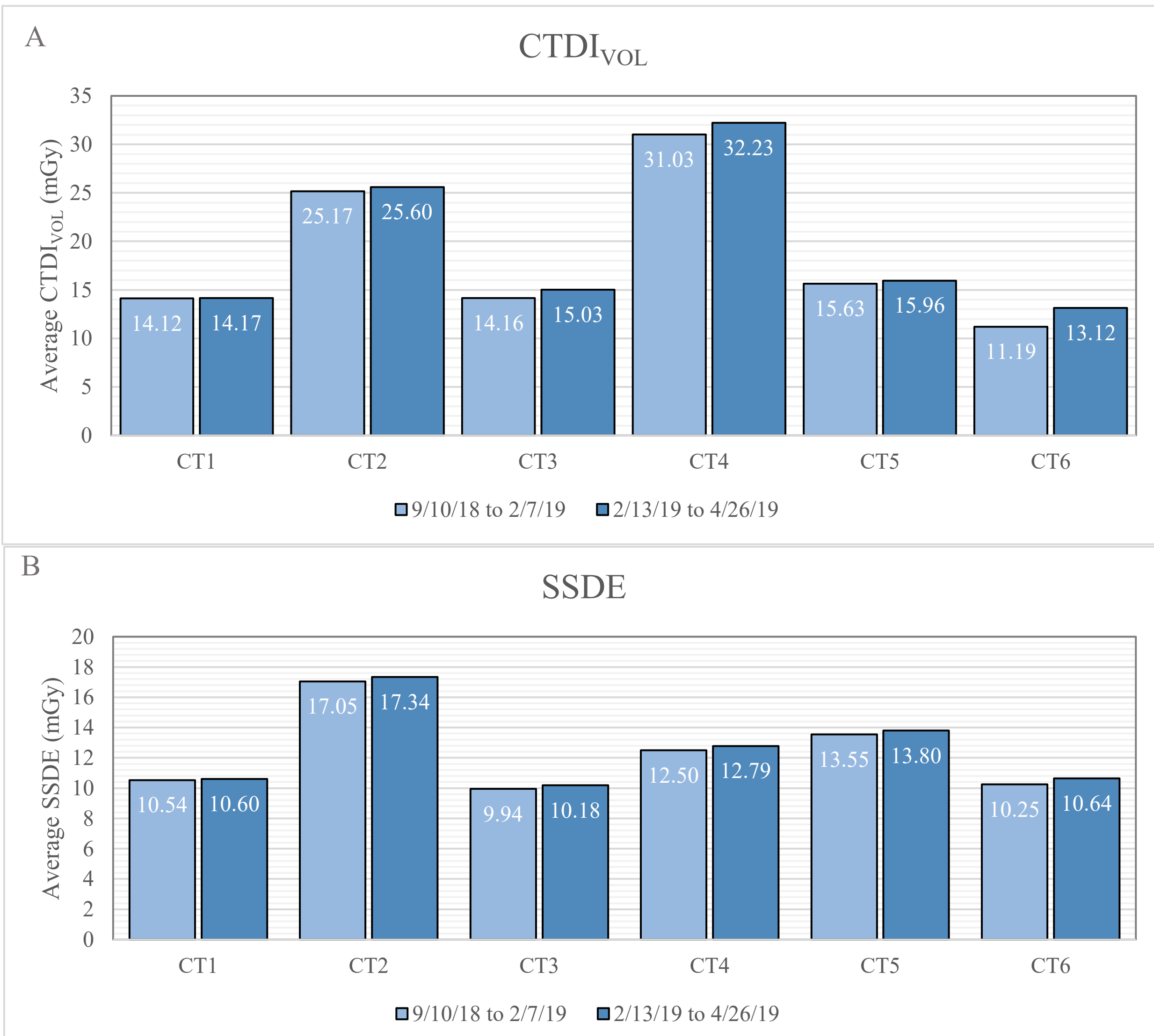

Figure 19: A) $CTDI_{VOL}$ and B) SSDE for each CT scanner.

Average $CTDI_{VOL}$ and SSDE measurements were calculated on a per protocol basis. Whether or not the $CTDI_{VOL}$ or SSDE increased for a given protocol varied. Some protocols increased, while others remained roughly the same or decreased. In general, spinal protocols had the greatest dose and large changes in $CTDI_{VOL}$ and SSDE between the two date ranges. CAP and its constituent protocols had the least change in $CTDI_{VOL}$ or SSDE with the exception of abdominal protocols. Figure 20 demonstrates the magnitude of change for each protocol.

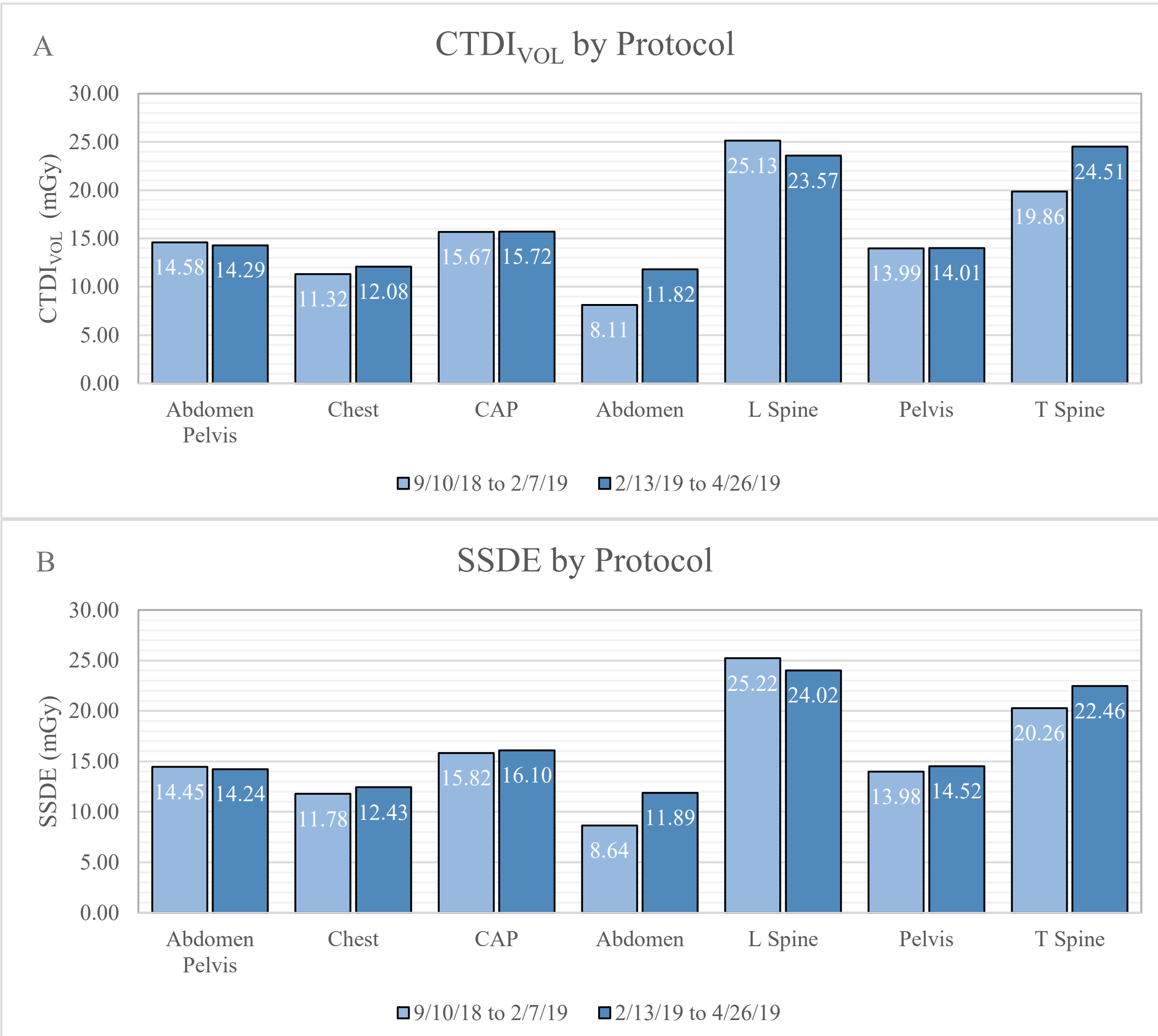

Figure 20: A) Average $CTDI_{VOL}$ and B) SSDE for each protocol.

SSDE and $CTDI_{VOL}$ graphs grouped by size are shown below in figure 21. These dosimetric measurements were taken for all three date ranges to demonstrate any changes resulting from the September 10th, 2018 meeting. A notable trend of larger doses for larger patients is shown in the graph by the increasing bar height from left to right over the seven size categories. In both the SSDE and $CTDI_{VOL}$, there is not an apparent trend from one date range to the next. Some values increase, some decrease and some remain roughly the same.

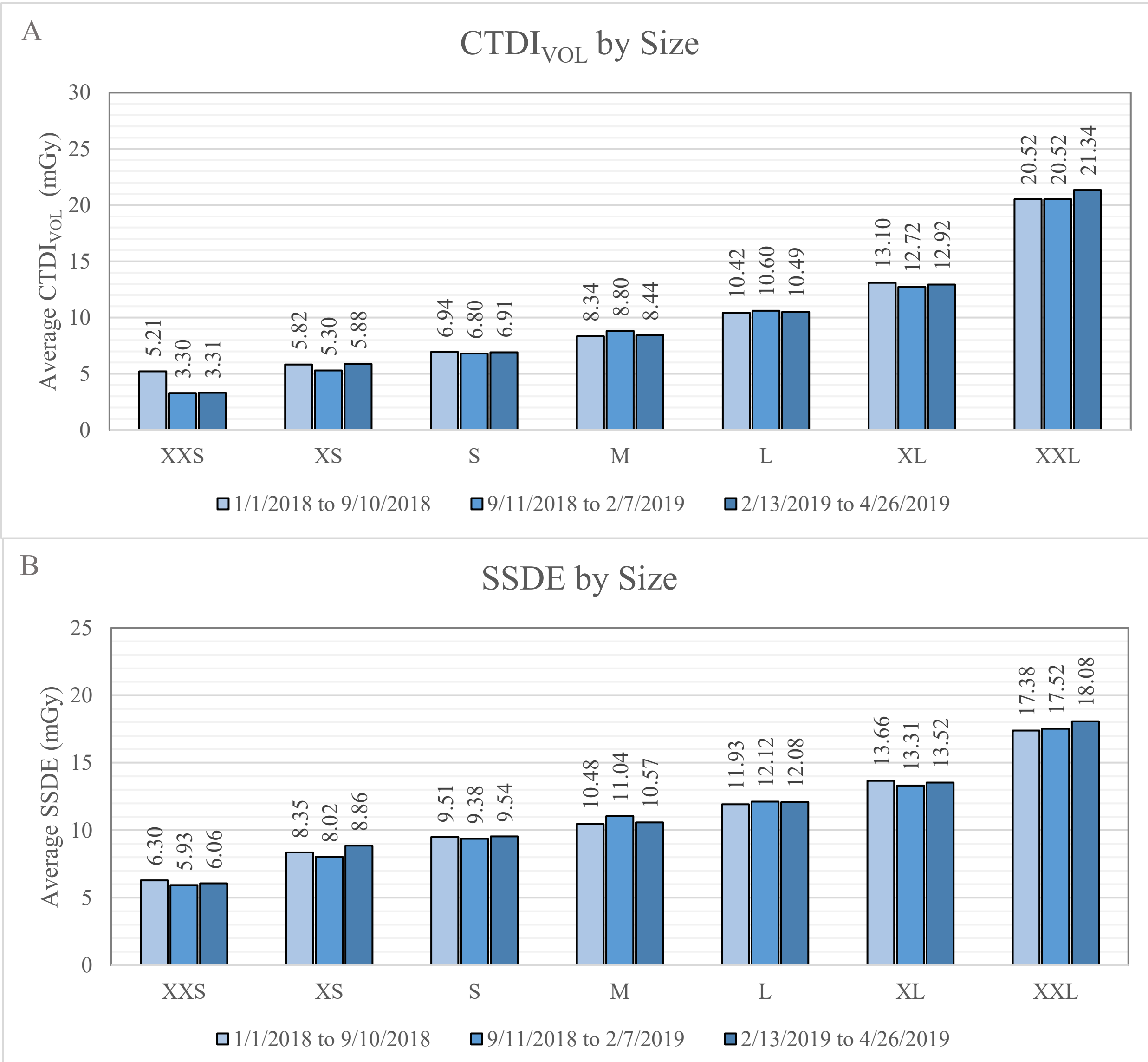

Figure 21: A) Average $CTDI_{VOL}$ and B) average SSDE for each size category.

5 DISCUSSION

5.1 2018 BASELINE DATA

Data from the 2018 cohort of CT scans provided several key insights into the state of patient alignment prior to the September 10th meeting. These takeaways provide a basis on which to inform technologists of techniques for better patient alignment and observe quality improvement changes. Certain scanners and protocols which had a deficit in alignment accuracy were the major focus when formulating a strategy for improving patient alignment. Data that showed adequate patient positioning were used as benchmarks to demonstrate proper positioning techniques.

The first and most notable insight provided by the 2018 data was presented in the differences between lateral and vertical alignment detailed in figure 6. Lateral alignment was considerably better than vertical alignment in 2018 prior to the September 10th meeting. This coincided with the initial hypothesis. Lateral alignment landmarks are more easily visible than vertical landmarks due to the symmetry of the human body across the vertical midline. Further, the changing body habitus of patients in the z-direction and the curvature of the table make vertical positioning challenging.

Imalogix algorithms define the center of the patient to be at the center axial image slice of the entire patient length in the scout image in the respective dimensions. Currently, technologists use the average midline of the patient width in the scanning area along the z-direction to define the center of the patient for positioning. This difference in the way the patient center is defined contributes to decreases in vertical offset accuracy.

Another insight came from the differences in accuracy of each CT scanner. CT2 was observed closely in this context, because it is the only scanner of the six that is not Philips brand. CT2 is the newest CT scanner and the only Toshiba brand device included in the study. This scanner has extra positioning capabilities that are not included in the other five Philips brand scanners. CT2 is able to adjust the table laterally and vertically after the scout while the other CT scanners can only adjust vertically.

CT2 ranks fourth in average vertical offset and third in average lateral offset as seen in figure 8. This indicates that technologists are not taking advantage of the extra features available on this scanner in their workflow. Since all other scanners do not have this capability, technologists are not used to implementing this realignment technology in their workflows. Better workflow integration of this step will likely improve average offsets and accuracies.

CT2 is located in the emergency department where its extra technological features help image patients with a wide variety of acute conditions. As a trauma scanner, mistakes are often made on this machine when technologists must position patients with conditions that limit their ability to be properly aligned. This is compounded by the celerity required when imaging patients with life-threatening afflictions. This CT also has a wider bore than the other scanners in the study. Occasionally, bariatric patients, who are difficult to position, are scanned on this device. Another scanner, not included in this study, is also recruited for bariatric imaging, but its primary use and location limit its ability to be used as often as CT2 for diagnostic exams.

One insight brought up in the 2018 results was the discrepancy between the offsets of lumbar and thoracic spine protocols and those of protocols for abdomen and chest, respectively. Prior to the presentation, technologists aligned the anatomy to be scanned at isocenter rather than the region of the body. In this case, spine exams were aligned on the lumbar or thoracic spine instead of the abdomen or chest, respectively. Technologists were raising the table to align the spine at isocenter during spinal exams and lowering the table to align the entire section of the torso at isocenter during torso exams. This was noted in the data in figure 9 by an average vertical offset of 1.1 cm and 1.5 cm below isocenter for lumbar and thoracic spine scans, respectively. However, average vertical offsets for abdomen and chest protocols were 1.79 cm and 2.19 cm below isocenter, respectively.

It was hypothesized that both spine protocols would on average be lower than their respective protocol counterparts, because the technologists are instructed to align along the spine and not the center of the patient. However, the thoracic spine and lumbar spine protocols were closer to isocenter than the chest and abdomen protocols, respectively. In order to remedy this, the technologists were instructed to align spine protocols at the center of the patient during the presentation meeting. Alignment averages of spinal protocols were expected to improve to coincide with abdomen or chest protocol averages after the presentation.

The graph below, figure 22, shows the percent accuracy of torso protocols at different distances from isocenter. This graphical display is extracted from the data in table 3. Among the torso protocols, chest-abdomen-pelvis was the most properly aligned of all the protocols.

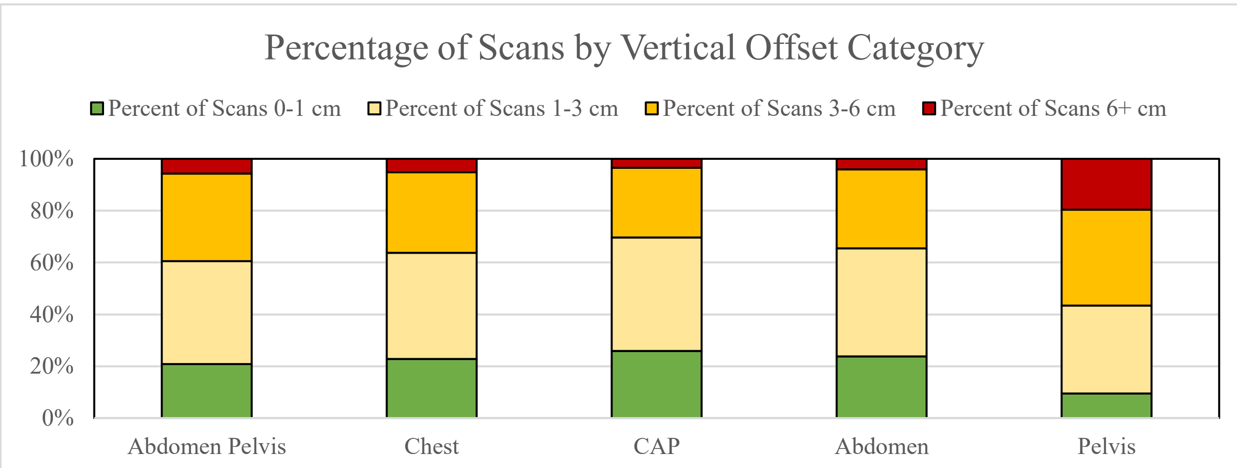

Figure 22: Percent accuracy by offset category for each torso protocol.

Since CAP is a combination protocol, variations in sectional anatomy width across the scan length were predicted to throw off accuracy. It was expected that the single protocols, chest, abdomen and pelvis, would be better aligned. However, pelvic scans had the most alignment errors, while CAP exams had the least by percent. It is assumed that this is a result of the curvature of the CT table. This curvature obscures the lower region of anatomy which is used to establish the center of the patient. Technologists were attempting to align patients based on the region of anatomy that is visible, putting the patient center lower than the table.

Further complications arose in the manner in which patients were aligned in individual regions of the torso. Technologists were only focusing on aligning the region of anatomy to be scanned, ignoring surrounding regions. However, the scout image sometimes covers more than the anatomy to be imaged. As a result, anatomy that is not relevant to the procedure, but which is included in the scout image, can affect the alignment offset as calculated by Imalogix. Technologists should be aware of how sections of anatomy impact the image analysis algorithms and cause deviations in offset measurements, then adjust mitigate these errors.

5.2 TECHNOLOGIST PRESENTATION EFFICACY

The presentation was effective in improving vertical alignment errors. There was a notable and highly significant improvement by 0.49 cm toward isocenter. Accuracy within 3 cm of isocenter improved from 68.8% to 77.68%. The presentation was not effective in changing the status of lateral alignment. Lateral offset did shift towards isocenter, but the change in mean of 0.02 cm to the right from left of isocenter was so small that the difference was deemed insignificant in a two-tailed t-test. Lateral accuracy within 3 cm only improved by a little over one percent.

Vertical positioning standard deviations lowered as seen in figure 11 by the shrinking histogram width despite having fewer exams in the data cohort following the presentation. Technologists were more consistent with patient alignment and actively sought to put the center of the patient at isocenter. Further, there was a marked increase in the percentage of scans aligned exactly at isocenter in the y-direction from 6.74% to 8.62%. Technologists not only focused on finding patient center points, but were able to align them exactly on the laser alignment tool on the scanner. Still, the average vertical alignment is below isocenter and the percentage of scans at isocenter is a far cry from the ideal goal of 100%. There is a lot of room to further optimize patient positioning.

Percent accuracy values calculated by Imalogix also demonstrated large gains as shown in figure 12. There was a notable 5% gain at the beginning of September when the technologists were informed by their supervisor that alignment required improvement. This correlated to a 6 percentile gain in peer ranking average before the presentation. Gains after the presentation were substantially larger. The presentation brought accuracy up 9%, which resulted in a 21 percentile gain in peer ranking. This demonstrates that accuracy not only got better at OHSU, but alignment improved over other hospitals which use Imalogix. The presentation improved accuracy to higher than half of these hospitals.

Figure 13 showed that accuracy and average alignment in vertical offset improved for all CT scanners. Percent accuracy as calculated by Imalogix also improved across all three date ranges. For most scanners, accuracy improved more after the presentation than after the September 10, 2018 short discussion with technologists. More emphatic, targeted and intentional solutions are required to exact a larger improvement in alignment.

CT6 made the largest improvement in vertical accuracy, peer ranking and alignment. This is likely due to its lack of throughput. Since it is the least utilized scanner for patient exams, technologists are not as concerned about the risk of pushing back appointment times by spending extra time on each patient. They then have more time to spend aligning patients prior to their exams.

CT5 had the best alignment accuracy in all date ranges. This scanner is located in the same outpatient clinic as CT6. It sees almost as many patients as CT3 and serves a similar purpose. However, since it does not service inpatients, CT5 images fewer patients with severe disorders and mobility impairments. There are fewer patients imaged on this scanner that have conditions which would interfere with alignment procedures.

CT1 had the least improvement from the technologist presentation as demonstrated in figure 14, likely due to the fact that its alignment was better than most other scanners prior to the presentation. It images fewer patients than most scanners, but more than CT6. CT1 is primarily used for biopsy studies which require very accurate alignment and repositioning. CT2 and CT3 did not improve by as much as other scanners. Both of these scanners have very high throughput. CT2 is a trauma scanner, which gives technologists limited time to align patients due to the haste required to image patients with life-threatening complications. In some cases, patients must use a lift system to be placed on the table. When a lift system is used it is difficult for technologists to reposition the patient after they are placed on the table. CT3 has one of the highest throughputs and is used for the widest variety of patient exams. Alignment on this scanner is therefore difficult on this scanner in the same way as CT2.

Five of the scanners used in this study were Philips brand, CT2 was the only scanner that was of a different make, Toshiba. Alignment was generally better for Philips scanners than Toshiba before and after the presentation. Patient positioning on Philips scanners was better than on the Toshiba scanner as shown in the cumulative percentage histogram below in figure 23. The shifts to the right for both brands after the presentation indicate an improvement in vertical alignment. Philips brand scanners had better alignment before and after the presentation. The positioning after the presentation for the Toshiba scanner was worse than the positioning before the presentation from the Philips scanners, albeit minimally. This shows that Toshiba did not perform better despite the requests at the presentation for technologists to use the extra capabilities of the scanner to better align patients.

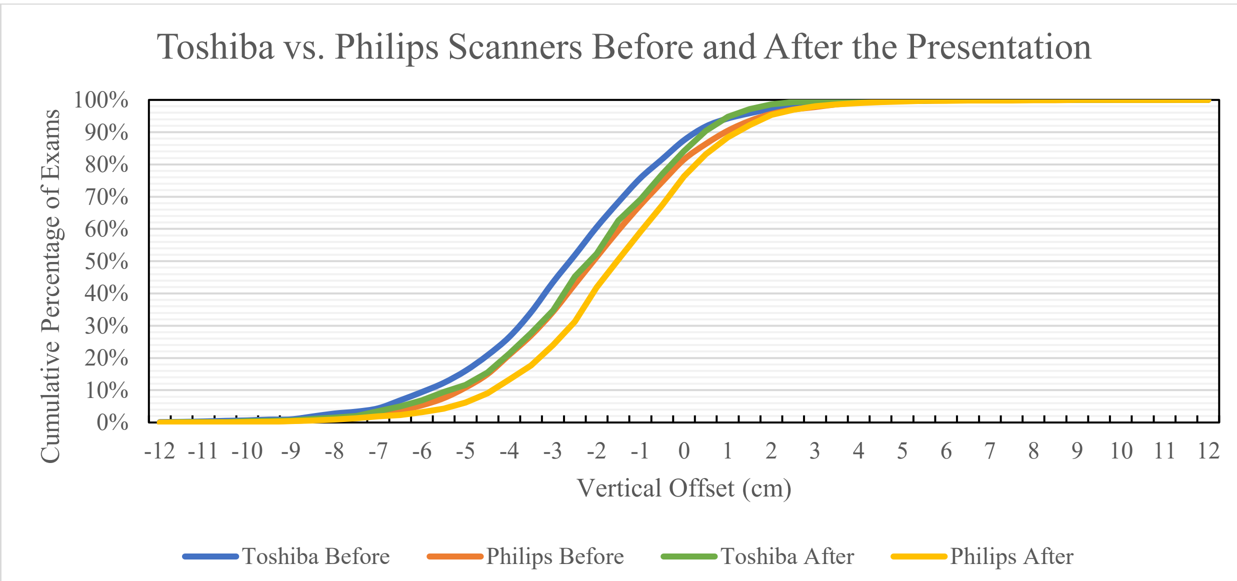

Figure 23: Cumulative percentage histogram for Toshiba and Philips scanners before and after the presentation.

Most protocols showed improvements in average alignment. These changes can be seen in figure 16. Spinal protocols were the only exception to this change. Abdomen protocols had the largest gains in average vertical offset. Prior to the presentation abdomen exams had some of the worst offsets, but after the presentation they improved to have the second-best offset average. This shows that the technologists realized that abdomen scans were some of the most challenging exams to align, then focused on taking the proper corrective actions to improve it.

Lumbar and thoracic spine exams were positioned worse after the presentation as shown in figure 16. However, they did reach values that more closely resemble scans from that same part of the torso. Chest and thoracic spine exams were at 1.24 cm and 1.20 cm below isocenter after the presentation, respectively. This indicates that technologists moved away from the previous instruction of aligning spinal exams on the spine and adopted the instructions provided by the presentation to align patients at the center of their body. At the presentation meeting, technologists were instructed to position the abdomen or chest at isocenter instead of the lumbar or thoracic spine when preparing spinal exams. This demonstrates that the presentation was effective in broadcasting its message despite the reduction in proper positioning.

CAP and its constituent protocols all improved in average vertical alignment. CAP was the most accurate protocol of the five before and after the presentation. It was the only protocol with an average vertical offset within 1 cm of isocenter. In combination protocols like CAP, technologists will align the entire patient body. In individual protocols, there is only a desire to align the specific portion of anatomy to be scanned. There is little desire to include other regions. If the image includes more than that portion of anatomy, then there will likely be an alignment error if all of the anatomy in the scout image is not aligned.

All CAP protocols improved in vertical accuracy which can be noted in figure 18. Far fewer pelvic exams were aligned greater than 6 cm which was a large improvement in a category beset with low accuracy prior to the presentation. Average vertical alignment did improve, but not substantially. The pelvis is where a lot of individual's bodies store fat and an area in which large portions may be obscured by the table curvature. Technologists are instructed to align pelvic scans with the vertical center point at the greater trochanter of the femur. Unless the technologist palpates to find these landmarks, it is very difficult to align at this point especially in patients with a lot of adipose tissue surrounding the pelvis.

Lateral alignment did not improve in accuracy or average offset as a result of the technologist presentation. The shift of 0.02 cm was small due to variation seen in analysis categories. Since accuracy was already high, there was little room for improvement. Protocol and scanner average changes varied as detailed in figures 15 and 17. Some improved while others worsened or stayed the same. There was not a discernable trend in changes for any category of lateral offset analyzed.

Lateral offsets and accuracies were not expected to change much. Total average offset was already below 2 mm prior to the technologist presentation, which was sufficiently good. Accuracy percentages were over 95% by the end of the study. This reflects the relative ease in determining the center of the patient laterally. Since the human body is symmetrical about a vertical midline, landmarks are easy enough to find that improvements are not often sought in this category. Further, lateral offsets have been shown to have minimal to no effect on patient dosimetry[5,9,15].

Image quality was not assessed as a metric of improvement in CT alignment. The steps required in analyzing image quality were beyond the limits of this study. There were, however, improvements in alignment that likely would improve image quality. Szczykutowicz et al. noted gains in CT number accuracy and reductions in noise which correspond to alignment accuracy for both vertical and lateral positioning, which can be viewed in figure 1[4]. Kim et al. backs this up with patient studies that demonstrate the same effect[7]. Foundations for this cause and effect are rooted in the bowtie filter effects for patient misalignment. Zhang et al. describes this as an over- or under-attenuation caused by the superposition of the thickest part of the filter over the thicker parts of the patient cross section. A visualization of this effect is available in figure 3[2]. It is expected that average alignment improvements will result in gains in image quality. Further investigation is required to back up this claim in the context of this study at OHSU.

5.3 DOSIMETRIC EFFECTS FROM ALIGNMENT CHANGES

CT doses primarily increased when average vertical offset increased, and decreased when average vertical offset decreased. These changes were, however, small. There were no significant changes in any dosimetric parameter or analysis category in this part of the study. The differences in the means for $CTDI_{VOL}$ and SSDE were so small that changes were neither significant nor substantial enough to attribute to a change. P-values did indicate that there was a notable shift, but not at a 95% confidence level.

Marsh and Silosky explain that as a patient moves towards the tube, their body appears larger in the scout image due to projection imaging magnification effects. Because of the tube current modulation system design, this causes an increase in dose. Marsh and Silosky demonstrated this effect on an anthropomorphic phantom and displayed their results in figure 2. The particular Philips scanner that was used in this study was a Philips Brilliance 64 (Scanner D), which is the same scanner as CT5. This scanner showed very minimal changes in $CTDI_{VOL}$ and SSDE for different vertical offsets[5]. Further, Philips uses a special design for tube current modulation software which limits the reaction of the system to changes in patient width as measured on the scout image[18]. From this information, only large changes in average vertical offset would be expected to induce a notable change in dose. A change of 0.49 cm in average vertical offset was not enough to induce this change.

SSDE and $CTDI_{VOL}$ are closely related by a conversion factor which is determined by patient width measurements and a table formulated in TG-220[14]. Due to the reliance on patient width, it was expected that there would be a more drastic change in SSDE than in $CTDI_{VOL}$, because of the effect of skewed width measurements from improper vertical alignment. However, this was not the case. The SSDE was developed to circumvent over- or under-estimation of the dose by reducing the reliance on approximations of body shape made in calculating $CTDI_{VOL}$. Small patient widths correspond to larger conversion factors, while larger correspond to smaller conversion factors. This correction is made to counter the effects of patient size on dose calculation[14]. As a result, this reduced the impact of vertical offset on SSDE.

Data were initially restricted by CT to find out if a difference in scanner technology along with changes in vertical offsets could demonstrate a significant change in radiation dose. There was none such change in dose as shown in figure 19. CT1 experienced a change of less than one tenth of a milligray. This result echoes the findings of the Marsh and Silosky study. The Philips scanner in that study produced the smallest dose changes as the phantom was moved across the range of vertical offsets. In that study, $CTDI_{VOL}$ changed by a factor of 1.03 when the phantom was moved almost 9 cm. The SSDE changed by a factor of 1.53 when moved by over 11 cm[5]. In a study which vertical offsets changed by only 0.49 cm on average, it would be difficult to detect a change even as subtle as the ones noted in the Marsh and Silosky paper. Even the Toshiba scanner, a brand not included in the Marsh and Silosky study, did not observe a significant enough change in dose.

It was originally hypothesized that separating $CTDI_{VOL}$ and SSDE into size categories would be restrictive enough to eliminate variation that might obscure statistical shifts. Still, this size restriction did not lower p-values sufficiently enough to exact a change in the mean. The same correlation in which increases in vertical offset towards isocenter increased SSDE and $CTDI_{VOL}$ was noted in most cases. These shifts can be observed in figure 24 below which shows average vertical offsets, and figure 21 which shows dosimetric changes. XXS and XS size categories should be viewed with caution since they had the lowest numbers and averages contain prominent variations. Still, the changes from average vertical offset were too small to exact a significant change in dosimetric values.

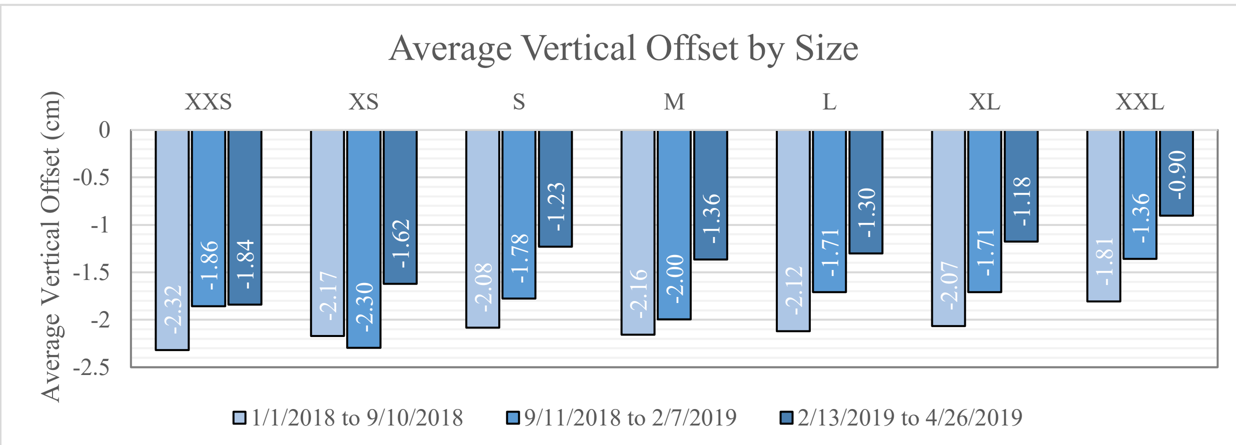

Figure 24: Average vertical offsets for each size category.

Analyzing the data on a per protocol basis was also hypothesized to eliminate unwanted variation, because protocols use similar imaging parameters that often have an impact on the radiation output of the scanner as noted in two studies by Cheng, and Gudjonsdottir[3,17]. Figure 14 demonstrates the average vertical offset changes for each protocol, and figure 20 represents the dosimetry changes. Again, dosimetry changes usually increased and decreased for respective increases and decreases in average vertical offset. No change in offset was substantial enough to exact a meaningful difference in $CTDI_{VOL}$ or SSDE. Thoracic spine and abdominal exam doses did change considerably compared to other protocols. Since other protocols did not change with the same magnitude, it is difficult to attribute dose shifts to changes in vertical offset. Further, thoracic spine protocol vertical offset averages decreased, but $CTDI_{VOL}$ and SSDE increased, which does not coincide with the majority of data trends. It is suspected that these variations are attributed to some unknown factor, not vertical patient alignment.

Finally, the data were separated by both protocol and size. A table of these data can be found in Appendix B. Similar correlations were found to that of the categorical analysis of protocol, size and CT data. Changes were more prominent, but still too small to discern a significant change. Even restricting and categorizing the data down to a few patients per category could not draw out a significant change.

Much larger vertical offset changes are required to observe a distinct shift in the mean of dosimetric values. While it is always beneficial to lower radiation dose, it is not always feasible. In this case, the dose started to trend towards the appropriate dose for the scanning procedure, which is to say the dose received at isocenter. This is a step in the right direction, but not a large enough one to consider it a definitive improvement to CT dosimetry caused by vertical offset changes.

5.4 STUDY LIMITATIONS

One of the most notable limitations of this study was the inability to evaluate image quality gains resulting from alignment improvements. A study by Kim et al. described a method of evaluating CT number and noise in patient images taken at different alignments. The patient images were viewed retrospectively by radiologist who placed regions of interest on specific, relatively uniform tissues within the image. The CT number and standard deviation of the ROI's were compared to the offset position to determine a trend. This study was also aimed at observing changes for a very specific subset of exams[7]. In comparison to the Kim et al. study, this project was determined to view more general changes in image quality across a wide variety of patients and exams. Further, this study sought to reduce the spread of patient information, which meant that acquiring patient images was not an option. Lastly, a radiologist was not available for ROI placement on these patient images. For these reasons, it was considered unwise to pursue an image quality evaluation.

Imalogix was a crucial part of the analysis in this study. Its automated features were a necessary part in the data extraction and compilation. However, with the help of automation, there is always a risk of computer error. Imalogix gathers patient alignment information from the scout image. The image analysis algorithm assesses the patient border by analyzing the light intensity of the image. Occasionally, the algorithm will assume artifacts in the image are part of the patient border which can skew the alignment data. Imalogix also uses the entire scout image to determine patient center. Anatomy which is not a part of the scanning procedure but is included in the scout image must be aligned properly for accurate analysis.

This study also relied on the dosimetric quantities calculated by the scanner and Imalogix. While the $CTDI_{VOL}$ values produced by the scanner were not tested and calibrated specifically for this study, OHSU employs a rigorous quality control and accreditation testing protocol which ensures that these values are within the acceptable range set by the American College of Radiology. Still, uncertainty may pervade the CT scanner software, but this is monitored to guarantee errors are minimal.

SSDE values were calculated according to the patient width measurements from scout images. Traditionally, SSDE is calculated from measurements taken of the cross section of the patient image in two dimensions. Because the software only had access to the scout image, these measurements were taken in one dimension. Further, they are subject to errors of the image analysis algorithm.

Limitations and errors were kept to a minimum where it was possible to control them. The few errors that did propagate through the data did not contribute considerably due to the large sample sizes. Any effects caused by errant performance of the technology used in this study were sufficiently averaged out in the statistical analysis.

6 SUMMARY AND CONCLUSIONS

6.1 FUTURE DIRECTIONS

While this study was successful in impacting patient alignment, there are still opportunities available to further increase positioning accuracy. The insights and observations from this quality improvement program have been preserved to aid in the intent of future studies to continue ameliorating patient alignment errors. Part of the design of this project was to provide future studies with data to aid in their endeavors.

A wealth of knowledge is available in the analysis of the 2018 baseline data. Several protocols and CT scanners were identified that require improvement in alignment accuracy. Technologists were not shown this data to limit the scope of this project and provide other studies with tools to expand on this design. As an example, since lateral alignment was already sufficiently accurate, it would be inadvisable to pursue this as an area of improvement. Pelvic scans on the other hand were not accurately aligned initially, but made prominent gains. By focusing on pelvic vertical alignment, there is a greater chance of reducing offsets than focusing on bettering lateral alignment. Future studies should focus on scanners and protocols which had discernably poor alignment, figure out what may be causing the large offsets, and enact a method of fixing it with the appropriate tactic.

Changes brought by the technologist presentation are a small glimpse at how technologists reacted to quality improvement actions. In comparison to the September 10^{th} mention of positioning errors at OHSU, the presentation exacted larger gains. This demonstrates that a more emphatic presentation or discussion will likely produce a more substantial change than a brief mention. Imalogix also has the capability to sort data by individual technologist, which can be used as a more targeted approach to address technologists separately. Future studies should consider an approach that gathers information more specifically and conveys it more clearly to a smaller audience to produce a greater change.

This study could not provide conclusive evidence of the dosimetric impacts of misalignment. Studies that were able to show these impacts were subject to errors made by the scanner assumptions. A study using the direct measurement of $CTDI_{VOL}$ based on location from isocenter rather than the scanner outputs is required to provide more accurate insights into the impacts of patient alignment on dose indices. This study as well as future studies would benefit from the insights provided by direct measurement.

In reality, alignment accuracy will never be 100% and average offsets will never be 0.0 cm. Technologists are constantly dealing with environments and patient conditions which inhibit proper positioning. Several medical device companies are attempting to implement automated alignment systems to mitigate positioning errors. While this technology is expected to drastically reduce the number of errors, there will always be environments, patient conditions and computer errors which will prevent 100% accuracy. These technologies currently do not exist at OHSU, but until that time comes, quality improvement projects in patient alignment will be centered on the technologist's role.

6.2 CONCLUSIONS

This study sought to improve patient alignment as a method of optimizing image quality and radiation dose. The primary strategy was to use a presentation informing technologists about the need for improvement in patient positioning. Progress on this endeavor was tracked through Imalogix and analyzed statistically to determine the extent of the changes made. Data separated by scanner technology and protocols sought to demonstrate efficacy of the presentation and areas that needed improvement.

Average vertical alignment and accuracy improved in almost every category. There was a statistically significant shift in the mean offset towards isocenter, and more exams were performed at isocenter. Technologists were on the whole more consistent and made fewer significant mistakes. Lateral offsets did not improve like vertical offsets did. There was not a discernable change in the average or accuracy. Still, lateral accuracy was very good to begin with and maintained that level throughout the study. The gains in vertical offset with the sustained accuracy in lateral alignment demonstrate that the presentation was effective in broadcasting its message and generating a beneficial change.

No significant shifts in radiation dose were observed, because vertical offset changes were small. There was a slight indication that this dose shift was likely a result of the gains in patient positioning. However, shifts were too inconsequential to demonstrate that the presentation had a prominent effect on altering doses. To note prominent changes, data would have to be analyzed on a pairwise basis between the two of the same exams on the same patient with different alignment offsets at different times.

Tracking of image quality effects was beyond the scope of this quality improvement project. CT number accuracy and noise were noted to improve with reduction in alignment errors by many articles referenced in this study. From the results gathered in those articles, it was assumed that image quality did improve for exams aligned closer to isocenter, but the change was subtle like that of $CTDI_{VOL}$ and SSDE.

Imalogix proved to be a useful system for tracking and analyzing the data in this study. Its automated design provided a more efficient alternative to manual entry. Most, if not all, data points were recorded with little error. Data were easily exported and analyzed with a computer, allowing large sample sizes to pinpoint subtle differences. This study likely would not have been as feasible or practical without the use of Imalogix.

The presentation given to the technologists was deemed effective in reducing displacements from isocenter. It was less effective in its ability to promote a notable change in radiation dose or lateral offset. Imalogix proved to be an advantageous tool in observing impacts of the presentation. When combined with the utility of Imalogix recording software, a presentation given to CT technologists was an effective quality improvement tool for creating a meaningful and beneficial change in patient alignment.

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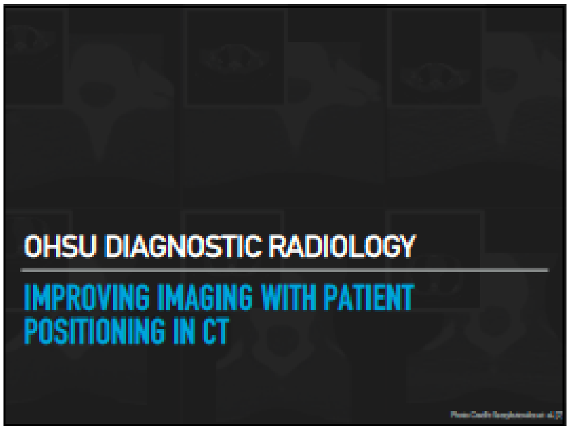
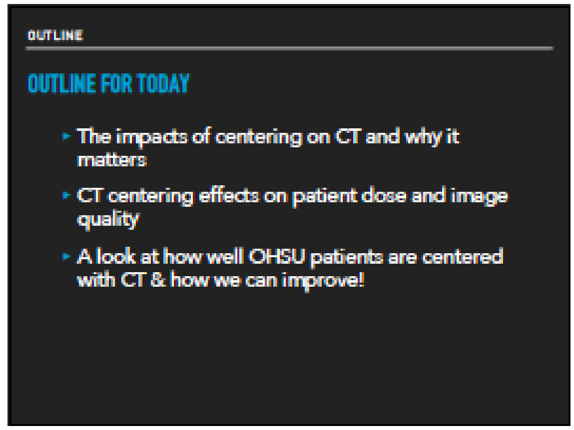
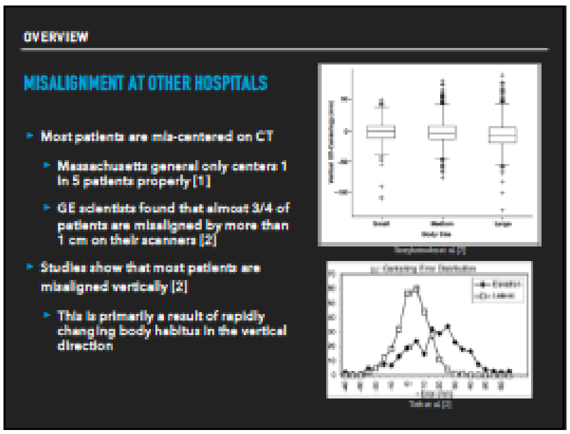
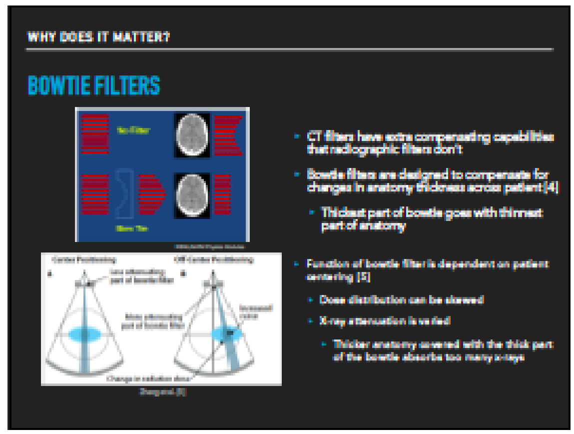
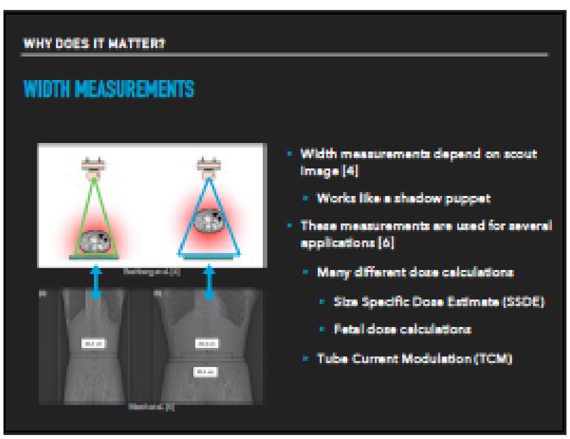
APPENDIX A: TECHNOLOGIST PRESENTATION

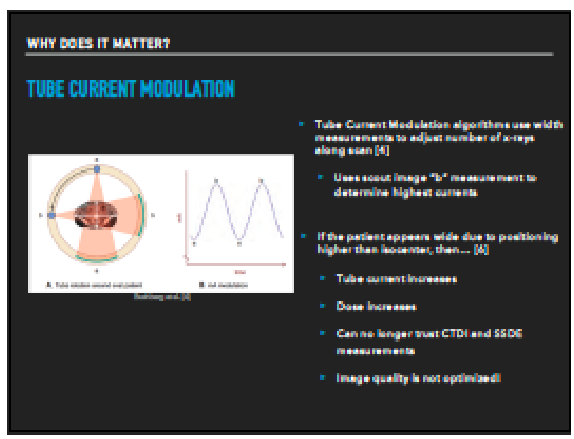












EFFECTS OF MIS-CENTERING

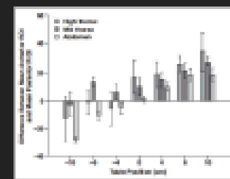
OFF-CENTER IMAGES HAVE POOR IMAGE QUALITY

- Increased x-ray attenuation on edges of bowtie filter [4]
  - Lack of "good" x-rays at detector
  - More "bad" x-rays at detector
- Contributes to image artifacts [7]
  - Noise obscures anatomical features
  - Degrades contrast
  - Interferes with radiologist readings

EFFECTS OF MIS-CENTERING

MIS-CENTERING CHANGES CT NUMBER

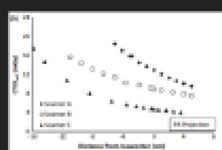
- Can vary up to 25 HU on average [7]
- Creates difficulty for radiologist in evaluating conditions which are noted by changes in HU
- Radiological research studies rely on CT number data
- Some dose calculation software programs rely entirely on CT number [8]



EFFECTS OF MIS-CENTERING

MISALIGNMENT CAN INCREASE DOSE

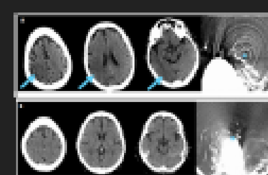
- CTDI can change by factor of 4.4 from below isocenter to above [6]
  - One scanner had CTDI of 17.52 mGy at the closest to the tube, and 4.0 mGy farthest away (Scanner C on PA scout) [6]
  - Surface dose can increase by 50% relative to anatomy at isocenter [9 and 10]
- When the patient is farther from the x-ray tube there is a decrease in dose and increase when closer to the tube [6]
- Proper alignment can drastically improve patient dose.



CASE STUDY

MISDIAGNOSIS OF NEURAL INFARCT [5]

- Patient: 66 y/o with altered mental status, sepsis and atrial fibrillation.
- Misalignment: Arrows point to area of low attenuation caused by mis-centering.
- Diagnosis Error: Radiologist was unaware of alignment error and diagnosed this as acute ischemic infarct.
- Result: Patient was rescanned 2 days later. Radiologist confirmed no infarct.
- Fallout:
  - Unnecessary fear caused by misdiagnosis
  - Wasted expenses in treating non-existent infarct
  - Double the dose from repeat scan
  - Hospital under fire from patient and family



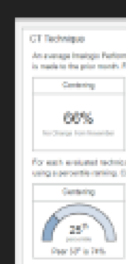
SO, WHY ARE WE HERE AGAIN?

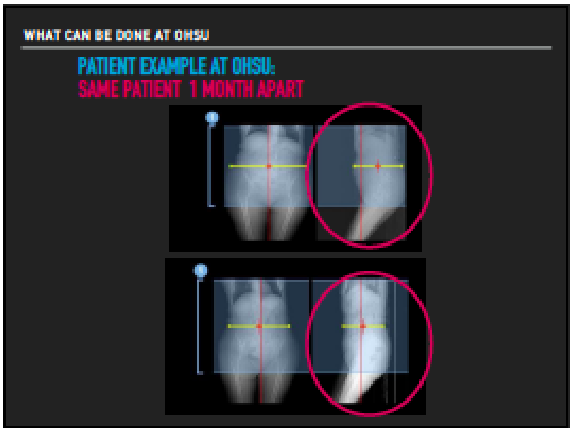
... because we are going to implement a quality improvement project to easily optimize patient dose and improve image quality through better patient alignment

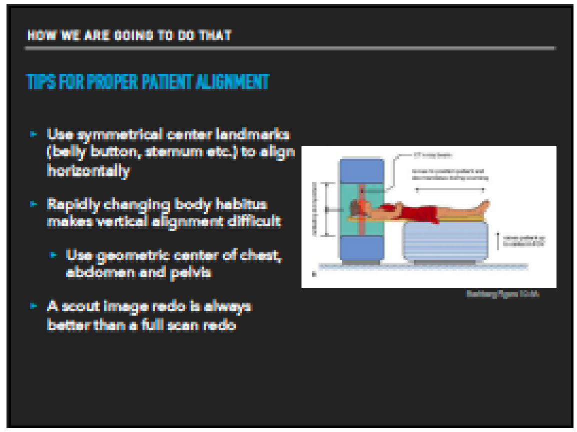
WHAT CAN BE DONE AT OHSU

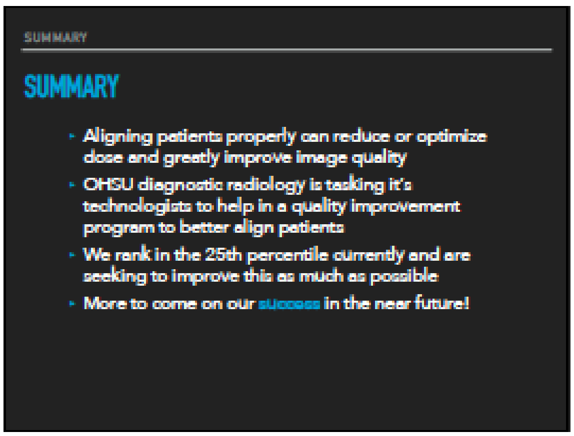
HOW DO WE RANK IN CENTERING?

- We are currently in the 25th percentile in patient centering
  - Only 66% of our patients are aligned within 3 cm of isocenter
- The median accuracy of all hospitals is only 74%
- By improving accuracy by only 8% we can improve our ranking by at least 2-fold
- We will come back and review how we have done to show you the strides we have made in improving patient care

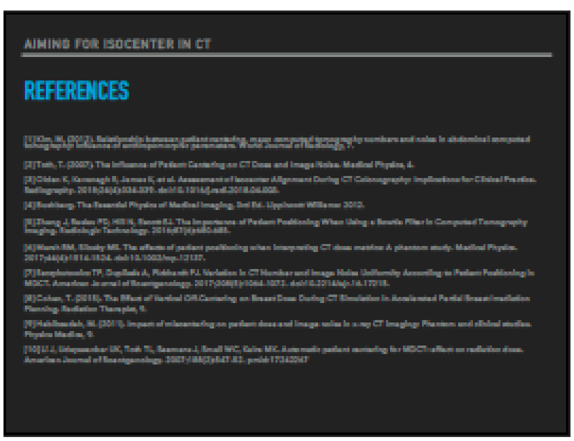



WHAT CAN BE DONE AT OHSU
PATIENT EXAMPLE AT OHSU:
SAME PATIENT 1 MONTH APART


HOW WE ARE GOING TO DO THAT
TIPS FOR PROPER PATIENT ALIGNMENT
Use symmetrical center landmarks (belly button, sternum etc.) to align horizontally
Rapidly changing body habitus makes vertical alignment difficult
Use geometric center of chest, abdomen and pelvis
A scout image redo is always better than a full scan redo


SUMMARY
SUMMARY
Aligning patients properly can reduce or optimize dose and greatly improve image quality
OHSU diagnostic radiology is tasking it's technologists to help in a quality improvement program to better align patients
We rank in the 25th percentile currently and are seeking to improve this as much as possible
More to come on our success in the near future!


QUESTIONS?


AIMING FOR ISOCENTER IN CT
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APPENDIX B: DOSIMETRIC DATA BY SIZE AND PROTOCOL

XXS									
	1/1/2018 to 9/10/2018			9/11/2018 to 2/7/2019			2/13/2019 to 4/26/2019		
Protocol	**Average Vertical Offset (cm)**	**Average** CTDI$_{VOL}$ **(mGy)**	**Average SSDE (mGy)**	**Average Vertical Offset (cm)**	**Average** CTDI$_{VOL}$ **(mGy)**	**Average SSDE (mGy)**	**Average Vertical Offset (cm)**	**Average** CTDI$_{VOL}$ **(mGy)**	**Average SSDE (mGy)**
Abdomen	0.15	3.50	6.91	-0.59	1.20	2.28	No Data	No Data	No Data
Abdomen Pelvis	-2.62	5.72	6.28	-2.33	3.20	6.41	-2.25	2.93	6.02
CAP	-3.00	4.14	5.02	-2.14	2.08	4.06	-4.32	2.30	4.43
Chest	-2.23	4.93	6.64	-1.48	3.99	6.57	-0.93	4.89	7.90
L Spine	-2.22	2.02	3.94	No Data	No Data	No Data	1.81	2.48	4.61
Pelvis	-1.03	3.00	5.31	-1.51	4.22	6.94	-4.11	4.50	7.40
T Spine	-1.56	2.96	3.70	-0.52	3.08	5.29	-3.44	3.95	6.38
XS									
Abdomen	-2.63	4.57	8.01	-1.09	4.45	7.67	-4.10	3.60	6.05
Abdomen Pelvis	-2.41	6.26	9.23	-2.73	5.14	8.91	-2.57	6.35	10.95
CAP	-2.82	8.26	10.70	-1.76	4.87	8.36	-1.31	6.72	11.47
Chest	-2.06	5.18	7.39	-1.94	5.02	7.30	-1.52	5.24	7.58
L Spine	-0.87	8.02	13.82	-3.86	9.30	16.15	2.64	7.20	12.51
Pelvis	-3.02	8.87	12.68	-3.56	6.80	9.83	-3.98	6.00	8.55
T Spine	-1.32	8.67	11.81	-0.95	8.04	11.27	-1.71	9.45	13.70
S									
Abdomen	-2.25	5.33	8.32	-2.02	4.99	7.71	-0.95	4.92	7.58
Abdomen Pelvis	-2.67	6.66	10.07	-2.14	6.62	10.22	-1.69	6.36	9.86
CAP	-1.69	7.95	12.24	-1.24	8.07	12.32	-0.61	7.28	11.18
Chest	-2.00	6.96	8.97	-1.79	6.83	8.86	-1.36	7.36	9.53
L Spine	-2.48	11.43	17.49	-1.52	9.85	15.26	-1.05	9.49	15.03
Pelvis	-2.01	9.91	12.86	-2.81	8.31	10.69	-2.29	9.39	12.16
T Spine	-1.80	10.89	14.07	-2.41	14.69	18.96	-3.90	27.50	35.24
M									
Abdomen	-1.95	6.36	8.87	-2.26	6.34	8.80	-1.20	6.41	8.94
Abdomen Pelvis	-2.66	7.88	10.82	-2.43	7.77	10.85	-2.09	7.79	10.84
CAP	-1.79	9.01	12.44	-1.45	9.39	12.90	-0.87	9.37	12.78
Chest	-2.15	8.89	10.23	-1.86	9.85	11.40	-1.40	9.49	10.96
L Spine	-1.46	14.57	20.06	-1.97	12.02	16.60	-4.77	13.96	19.29
Pelvis	-2.60	13.47	15.76	-3.27	11.16	12.91	-1.13	14.60	16.63
T Spine	-1.64	16.36	19.05	-1.06	18.14	20.82	-2.07	15.27	17.62

L									
Abdomen	-2.20	7.60	9.44	-1.88	7.63	9.41	-1.27	7.49	9.31
Abdomen Pelvis	-2.51	9.60	11.74	-2.11	9.52	11.76	-1.79	9.39	11.60
CAP	-1.71	11.37	13.92	-1.31	11.68	14.33	-1.13	11.34	14.03
Chest	-2.16	11.79	12.25	-1.58	12.24	12.72	-1.08	13.05	13.51
L Spine	-0.80	18.19	22.34	-0.53	20.67	25.31	-2.30	15.66	19.16
Pelvis	-3.51	15.85	16.42	-3.30	16.09	16.57	-2.92	13.62	13.97
T Spine	-0.49	27.18	27.48	0.39	22.33	23.25	0.91	17.85	18.45
XL									
Abdomen	-1.78	9.78	10.77	-1.51	10.05	11.06	-1.26	10.10	11.05
Abdomen Pelvis	-2.20	12.16	13.31	-2.05	12.23	13.37	-1.78	12.22	13.34
CAP	-1.66	14.39	15.71	-1.23	13.73	15.01	-0.74	14.65	16.03
Chest	-2.44	15.22	14.15	-1.76	14.19	13.26	-0.87	14.76	13.81
L Spine	-1.57	22.91	25.14	-1.96	22.19	24.12	-1.48	25.32	27.19
Pelvis	-3.67	24.19	22.20	-2.46	16.52	15.69	0.46	17.54	16.37
T Spine	-2.68	39.06	35.30	-3.83	20.44	18.86	-1.46	18.30	17.46
XXL									
Abdomen	-1.60	16.26	14.12	-1.45	16.61	14.29	-0.76	17.23	14.96
Abdomen Pelvis	-2.02	22.41	18.64	-1.53	21.57	18.17	-1.05	22.06	18.26
CAP	-1.50	21.86	19.04	-0.91	21.70	19.14	-0.33	22.87	19.92
Chest	-2.30	18.09	14.81	-1.88	18.22	15.24	-1.40	20.67	17.11
L Spine	-0.65	32.53	27.20	0.16	36.10	30.51	-1.48	34.66	30.04
Pelvis	-1.02	24.37	20.25	-0.13	30.27	21.95	-3.80	40.50	32.53
T Spine	-2.33	45.31	35.03	-0.52	36.35	28.74	-2.21	62.84	47.02