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Automatic Exposure Control During Computed Tomography Scans of the Head: Effects on Dose and Image Quality

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ABSTRACT

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Automatic exposure control (AEC) is effective at reducing potentially harmful radiation doses without sacrificing image quality for many types of computed tomography (CT) scans. However, there is a need for more information regarding the use of AEC for CT head scans. This study was conducted at Johnson County Community Hospital in Mountain City, TN. Preexisting adult CT head scans (*n*)60 were randomly selected to form 2 stratified samples, (*n*)30 each. One sample used a standard protocol, and the other used a protocol with a mA-modulated AEC system, Siemens CARE Dose 4D. Causal-comparative analyses were conducted, and it was determined that AEC was effective at maintaining subjective image quality while reducing radiation doses an average of 38% for adult CT head scans. It was concluded that using AEC was an effective tool to optimize radiation doses for adult CT head scans in one particular setting, but more research on this topic is needed.

DEDICATION

I dedicate this thesis to my family. I owe a special gratitude to my beloved wife, Cherie. Her wise advice was consistently helpful. Cherie's encouragement and belief in what I was doing helped me to believe in myself and to persevere. I also owe thanks to my adult children, who encouraged me and found it not strange to have a middle-age dad who was still in school. My hope is that I have set an example for them to work hard and to always keep learning.

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Health's Research Policies and Procedures; more specifically, they taught me to view this project from the perspective of a researcher rather than a CT technologist. I am thankful to my imaging department's team leader, Wilma Perdue, who supported me throughout this project and provided me with a randomized list of participants. Heather Perkins, who was responsible for making protocol changes to our CT scanner, helped me in many ways. Theresia Cannon, from ETSU's IRB, gave great assistance by providing me with vital research protocol input.

And finally, my gratitude goes to Dr. Adam Wallace who gave me permission to use the image quality scoring criteria that he and others used in their 2015 article titled *Evaluation of the use of Automatic Exposure Control and Automatic Tube Potential Selection in Low-Dose Cerebrospinal Fluid Shunt Head CT*.

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CHAPTER 1

INTRODUCTION

Both radiography and computed tomography (CT) require the use of x-rays, a type of ionizing radiation, to produce diagnostic images. However, CT requires significantly more x-rays than radiography to produce an image (Bushong, 2017). Radiation exposure to humans can result in two types of harmful effects. *Deterministic* effects are early manifestations from exposure to high amounts of radiation; examples of these effects include hair loss, skin burns, and death (Bushong, 2017). S*tochastic* effects are random, late effects, such as cancer, which can be caused by any amount of radiation exposure. There is a direct linear relationship between exposure to ionizing radiation and stochastic effects, and although the associated risk of developing radiation-induced malignancy from CT is low, it is not zero (Bushong, 2017). Therefore, occupational workers must strive to keep patients' and others' exposures reasonably low (Bushong, 2017; Long, Rollins, & Smith, 2016; Naseri et al., 2014; Valentin, 2007).

Wide dose variation exists among CT imaging facilities and among different types of CT scanners (Aldrich, Bilawich, & Mayo, 2006; Sadri, Khosravi, & Setayeshi, 2013). While CT technologists frequently increase the radiation exposures of larger patients, they often do not decrease the exposures on smaller patients. Therefore, smaller patients are more prone to receiving unnecessary overexposures during CT scans (Aldrich, Chang, Bilawich, & Mayo, 2006). However, automatic exposure control (AEC) is a feature that can be used to control radiation exposure in radiography and CT. Although AEC has been used in radiography for decades, its use in CT began in the early 2000s (Kalender et al., 2008). AEC systems do not free technologists from selecting appropriate CT scan parameters, but they have become an important tool to moderate dose and image quality (Valentin, 2007). Unfortunately, there is a paucity of literature regarding the use of AEC during routine adult CT head scans. Therefore, the consequences of using AEC when scanning this particular region are unclear.

Furthermore, CT has become an important diagnostic tool. As a result, its use has increased over the years, and this trend has been predicted to continue. As radiation doses per capita rise, increased efforts to reduce CT scan doses are needed (Kalender, 2008).

Naseri et al. (2014) studied the relationship of radiation dose and image quality in CT using acrylic phantoms. Rather than altering their protocols using AEC, they manually altered the scan parameters for their study. The researchers concluded that chest, abdomen, and brain images with acceptable quality and reliable detection ability could be obtained using smaller doses of radiation than those commonly used.

In a study in which the use of AEC was evaluated for pediatric cerebrospinal fluid shunt CT scans, Wallace et al. (2015) concluded that AEC reduced doses about 40% while maintaining diagnostically acceptable image quality; this finding is consistent with Kalender et al.'s (2008) statement that, when compared to CT scans with constant tube current, AEC reduces overall doses 10-60%. However, Wallace et al.'s pediatric protocol also used a voltage modulating system. Furthermore, the protocol being studied was for the evaluation of brain shunts and the ventricles; these are examples of high contrast structures which, when compared to low contrast structures in the brain, can be evaluated with CT using less radiation and higher noise levels (Valentin, 2007).

According to Naseri et al. (2014), CT image quality is often higher than what is needed for accurate diagnoses. As a result, CT scans may be performed using more x-rays than are necessary to produce adequate images. On the other hand, lowering the dose too much results in inadequate image quality. There are many aspects of CT that affect radiation exposures, and

AEC has become an important tool to effectively manage patient dose (Valentin, 2007; Yu et al., 2009). However, manufacturers and users need more information in regards to defining quality reference levels for various diagnostic tasks (Dixon, 2007; Kalender, 2008). Even though the American College of Radiology (ACR) has established dose reference levels for various CT scans (American College of Radiology, 2017), technologists need additional criteria such as target noise levels to ensure a proper balance between dose and image quality (Aldrich, Chang, et al., 2006).

Raman et al. (2013) stated that many radiologists and technologists do not fully understand CT dose-reduction systems, and therefore, fail to take advantage of their scanners' dose reduction capabilities. In 2010, an AEC-equipped CT scanner was installed at the hospital where I am employed. While the manufacturer recommended that AEC should be used on most scans, they recommended that AEC *should not* be used on CT head scans; as a result, the scanner was programmed to use a manual technique on these scans. However, in 2017, while attempting to decrease patients' radiation doses, the technologists did some comparison tests on the CT head protocol using the standard technique without AEC and the same technique with AEC. Before AEC was used on patients, it was tested on an acrylic phantom and promising results were observed (increased noise and decreased dose). Then- after receiving approval from the supervising radiologist, the protocol with AEC was used on some adult patient scans. The results of these informal pilot tests were promising in that the patients' radiation doses were significantly reduced, and image quality appeared to be maintained. Therefore, the supervising radiologist reviewed the radiation doses and images of the patient scans with AEC and instructed the technologists to add the use of AEC to the adult CT head protocol (H. Perkins, personal communication, November 21, 2017).

The protocol change described above has provided a comprehensive population from which I have formed two patient-scan samples to study: one without AEC and one with AEC.

Purpose Statement

The increased use of CT and frequent, excessive radiation exposures from CT warrants greater attention when forming CT protocols. The purpose of this study was to analyze some of the effects AEC had on adult CT scans of the head, and perhaps more importantly, to determine if diagnostic image quality was maintained while using AEC during routine adult CT scans of the head.

Research Questions

The following questions guided this project:

1. Is there a significant difference in radiation dose between adult CT head scans performed without and with AEC?
2. Is there a significant difference in objective image quality between adult CT head scans performed without and with AEC?
3. Is there a significant difference in subjective image quality between adult CT head scans performed without and with AEC?
4. Is there a relationship between head size and radiation dose when AEC is used in adult CT head scans?
5. Is there a relationship between head size and image noise when AEC is used in adult CT head scans?

Delimitations

Patient-scan image data collected for this research was delimited to existing adult CT head scans performed during the years 2017 and 2018 that were generated using a 16-slice multi-detector computed tomography (MDCT) scanner at Johnson County Community Hospital in Mountain City, Tennessee. CT scans that were degraded by motion, metal artifact, or other artifact were excluded from the study.

Limitations

CT images that were used to perform noise, attenuation, and distance measurements were retrieved from a GE Centricity™ PACS system. No other PACS systems were available to perform measurements.

Assumptions

It was assumed that measurements obtained from PACS were reliable. It was also assumed that that subjective image quality scores were a reliable indicator of image quality.

Operational Definitions

- Automatic exposure control (AEC) – Feature that automatically determines radiation exposure (Bushong, 2017)
- CTDI vol – Dose value for an average slice in MDCT where vol represents the volume of tissue irradiated (Bushong, 2017)
- Diagnostic confidence – Acceptable image quality for a given diagnostic task (Valentin, 2007)
- Dose Length Product (DLP) – Product of CTDI vol and slice thickness (Bushong, 2017)
- Effective mAs- mAs divided by pitch (Valentin, 2007).
- Hounsfield units – Scale of CT numbers used to assess the nature of tissue (Bushong, 2017)

- Ionizing radiation – Radiation capable of removing an orbital electron from an atom (Bushong, 2017)
- Milliampere-seconds (mAs) – Product of exposure time and x-ray tube current; measures of the total number of electrons (Bushong, 2017)
- Milligray (mGy) – Gray (Gy) is the name for the SI unit of absorbed dose and air kerma (1 Gy = 1000 mGy) (Bushong, 2017).
- Millisievert (mSv) – Sievert (Sv) is the unit of effective dose which is used to express radiation exposure of populations (1 Sv = 1000 mSv) (Bushong, 2017).
- Multi-detector computed tomography (MDCT) – Imaging modality that is capable of using two or more detector arrays to produce simultaneous multiple helical slices (Bushong, 2017)
- Noise – Grainy or uneven appearance of an image caused by an insufficient number of primary x-rays (Bushong, 2017)
- Picture archival and communication system (PACS) – A system used in diagnostic imaging to interpret, store, and network digital images (Bushong, 2017)
- Radiation – Energy emitted and transferred through space (Bushong, 2017)
- Region of interest measurements (ROI) – A ROI is an area of a structure on a reconstructed digital image as defined by the operator using a cursor (Bushong, 2017).
- Subjective image resolution – A subjective, 5-point image quality scoring system adopted for this study to compare CT head images relative to the ability to visually distinguish one object from another (Bushong, 2017; Wallace et al., 2015).

CHAPTER 2

REVIEW OF LITERATURE

Introduction

AEC has been proven effective at moderating doses in many types of CT scans (Valentin, 2007). However, the literature is incomplete regarding the effects of using AEC during CT scans of the head. Much research has been published on optimizing patients' doses from CTs while maintaining diagnostic confidence, but more research is needed to provide technologists with target reference values (Aldrich, Chang, et al., 2006).

Sources of Ionizing Radiation

X-rays are formed by converting electrical energy into a specific type of electromagnetic radiation. Visible light is another form of electromagnetic radiation, but unlike visible light, x-rays are capable of removing orbital electrons from other atoms; this type of energy is called ionizing radiation, hereafter referred to as radiation. It is the ionizing capability of x-rays that can result in tissue damage in humans (Bushong, 2017; Long et al., 2016).

However, x-rays and other man-made sources of radiation are not the only types of radiation. Natural radiation exists in the form of cosmic rays, terrestrial radiation, internally deposited radionuclides, and radon. For example, trace amounts of radon, which is the largest source of natural radiation, are present in earth-based materials such as concrete, bricks, and gypsum wall board. Since the beginning of their existence, humans have been in the presence of naturally occurring radiation, and many believe that human evolution has been influenced by it (Bushong, 2017; Long et al., 2016).

The Increased Use of CT

CT scan use has increased and has resulted in increased radiation exposure to the global population (Bushong, 2017). Berrington de Gonzalez et al. (2009) stated that much attention has been given to the increased risks from pediatric CT scans. However, the authors estimated that because of the high frequency of use, the potential impact to public health was greater for 35 to 54 year old adults.

In 1990, natural radiation accounted for an annual average of about 3 millisieverts (mSv) per person in the US, and man-made radiation, which includes medical radiation, accounted for 0.6 mSv per person. However, in 2008, while natural radiation remained constant, man-made radiation exposure increased to an average US annual dose of 3.2 mSv. This change was primarily attributed to the increased use of CT, nuclear medicine, fluoroscopy, and other diagnostic sources (Bushong, 2017). When compared to radiography, MDCT is much higher in radiation dose and yields significantly more diagnostic information. Despite the higher radiation dose, it appears that MDCT is progressively replacing radiography (Dixon, 2007; Yu et al., 2009). One estimate is that 25-30% of trauma imaging is performed with CT scans (Karla, Rizzo, & Novelline, 2005). In some countries, CT accounts for 70% of the population's radiation dose from medical procedures (Valentin, 2007).

As the number of CT scans performed has risen and continues to increase, efforts to reduce dose per scan have been somewhat successful; this success is largely due to technologies such as AEC. However, even when AEC is available, optimizing scan parameters is not a simple task. The imaging community should continue in their efforts to ensure the use of judicious CT parameters by evaluating the available tools and implementing their use into their protocols based on different diagnostic tasks (Kalender et al., 2008).

Effects of Ionizing Radiation

Radiation exposure to humans can result in two different types of harmful effects. Deterministic effects are short-term manifestations such as epilation (hair loss), erythema (skin redness), and death, which occur relatively soon after receiving *high* radiation exposures. In contrast, stochastic effects may result in harm to people months or years following *any* amount radiation exposure. Stochastic effects may be manifest as leukemia, various cancers, and other tissue damage, including damage to the lens of the eyes (Bushong, 2017; Long et al., 2016).

Although the link between medical radiation and cancer is somewhat controversial, one estimate is that around 29,000 future cases of cancer will result from 70 million computed tomography (CT) scans that were performed in the US in 2007; 4000 of these predicted cancers were attributed to CTs of the head (Berrington de Gonzalez et al., 2009).

In the US, one out every four deaths is due to cancer, and following heart disease, cancer is the second leading cause of death. Also in the US, 1,596,486 new cases of cancer were diagnosed, and 591,686 people died from cancer in 2014 (CDC, 2017). By one estimate, cancer care in the US cost about $145 billion in 2010 (Lee, Roehrig, & Butto, 2016). However, despite the link between medical radiation and cancer, when a CT scan is medically necessary, the benefits of having a scan outweigh the risks involved. Nevertheless, judicious CT parameters that ensure diagnostic quality at a reasonable radiation dose are important in minimizing potentially harmful radiation-related effects from CT during each scan (Valentin, 2007).

Another controversy within the radiological profession is that of radiation costs verses benefits. Some radiological scholars promote the practice of routinely performing low dose scans in order to keep patients' and others' radiation doses as low as reasonably achievable (Kalra, Rizzo, & Novelline, 2005). However, others advocate the concept of obtaining the maximum amount of possible information during any initial CT scan (Dixon, 2007). Exacerbating the matter is the fact that CT scans, particularly CTs of the head, are frequently performed unnecessarily (Owlia et al., 2014).

Radiation Safety

Radiography, fluoroscopy, and CT require x-rays to produce diagnostic images. Wilhelm Röntgen was experimenting in the physics laboratory at Würzburg University in Germany when he accidentally discovered x-rays in 1895. In 1896, using a gas-filled Crooke's tube, Röntgen produced and published the first medical radiograph of his wife's hand. In the same year, the first medical radiograph in the US was produced in the physics laboratory at Dartmouth College, New Hampshire (Bushong, 2017).

Shortly after Röntgen's discovery of x-rays, some of x-ray's harmful effects began to be realized. In 1898, Thomas Edison developed the fluoroscope which uses x-rays to produce moving images. However, Edison abandoned his x-ray research after his assistant and long-time friend, Clarence Dally, was severely burned on both arms during an experiment. As a result of the injury, both of Dally's arms were eventually amputated, and he died in 1904. Dally's death was the first known x-ray fatality in the US (Bushong, 2017).

In the early days of x-rays, physicians and, more commonly, patients frequently suffered injury from x-rays. In radiological science, electrical voltage is measured in kilovolt peak (kVp), and electric current is measured in milliamperes (mA). Using the Crookes tube, which was limited to about 3 mA and 50 kVp, it was not uncommon to make radiographic exposures to last 30 minutes or more. The long exposure times and low energy x-rays frequently resulted in radiation injury in the form of burned skin, epilation (hair loss), and anemia (Bushong, 2017).

Intensifying screens, double-emulsion film, collimation, and filtration were among the first advancements used to reduce x-ray exposures and some of the associated hazards such as skin burns. Fluorescent intensifying screens reduce exposure by converting x-rays to light. Therefore, fewer x-rays can be used to produce an image. The use of double-emulsion film enhanced radiographic images and allowed exposures to be reduced by 50%. X-ray beam collimation restricts the useful beam to the anatomy of interest. Thin layers of aluminum or copper filtration in the x-ray tube absorb lower energy x-rays which have little, if any, diagnostic value (Bushong, 2017).

Around the turn of the 20th century, technological advancements led to the Snook transformer and the Coolidge x-ray tube which, when combined, allowed the operator to vary electrical voltage and amperage independently. The use of the Snook transformer and Coolidge x-ray tube, which also allowed much shorter exposure times and higher x-ray energies, greatly reduced the frequency of superficial radiation injuries. Modern x-ray tubes, which are high performance versions of the Coolidge tube, commonly use up to 150 kVp and 1000 mA, allowing for exposure times ranging in the milliseconds. Nevertheless, current protective measures are to keep x-ray exposure as low as reasonably achievable (ALARA). The ALARA principle is largely based on the linear non-threshold concept that even low radiation doses may result in a small incidence of latent harmful effects (Bushong, 2017).

In addition to radiation injuries to patients, occupational exposure is also a concern in the radiological sciences. Early in the 20th century, radiologists were more likely than other physicians to develop leukemia and aplastic anemia. This led to the development of lead-impregnated protective apparel and other protection devices for occupational use, as well as personnel radiation monitoring devices. Modern ALARA precautions for patients and radiological workers focus on time, distance, and shielding (Bushong, 2017).

CT Image Production

CT was the first diagnostic imaging modality to produce digital images. In 1970, using mathematical algorithms developed by Alan Cormack, Godfrey Hounsfield was the first to demonstrate a CT system. CT images are produced by directing a rotating, collimated x-ray beam 360 degrees around a patient. As an x-ray beam penetrates a patient, internal anatomical structures attenuate (absorb) x-rays relative to the structures' mass densities and effective atomic numbers. Digital detectors, located opposite the x-ray tube, receive the post-patient attenuated x-ray beam (Bushong, 2017; Long et al., 2016).

The detectors used in CT are particularly critical, and their size and concentration affect a scanner's spatial resolution (the ability to differentiate objects that are close together), and their efficiency affect a scanner's signal-to-noise ratio. Modern detectors are 90% efficient in that they are small and tightly placed adjacent each other allowing about 90% of the remnant beam to be converted to an output signal. Detectors, which are usually made from cadmium tungstate and have a dynamic range of 4096 gray levels, emit an analog signal that is proportional to the attenuated beam intensity received at the detector. The signal is amplified and converted to a quantified digital signal. Signal amplification, in conjunction with effective beam collimation, allows CT to exhibit exceptional contrast resolution. Using an array processor and a 512 x 512 matrix, the CT computer simultaneously applies algorithms to solve as many as 250,000 equations to produce high-contrast cross-sectional images based on the attenuation pattern of the x-ray beam. The array processor allows faster image reconstruction, and the 512 x 512 matrix configuration allows the display of 262,144 pixels of information. Each pixel is a two-dimensional representation of a specific tissue volume and is also quantified into CT numbers, which are also known as Hounsfield units (HU). The brightness in which each pixel is displayed represents anatomy, with light shades representing dense structures and vise-versa (Bushong, 2017; Long et al., 2016).

Dose Versus Quality

There are many aspects of CT that affect patient dose including mA, kVp, rotation time, and pitch factor (Bushong, 2017). In their study conducted with phantoms, rather than patients, Naseri et al. (2014) concluded that images with acceptable quality and reliable detection ability could be obtained using smaller doses than protocols commonly used. However, unlike the phantoms used in Naseri et al.'s study, patients are of different sizes and densities. The authors also concluded that sequential (also known as step-and-shoot and/or axial) scanning, when compared to volume helical scanning, yielded significantly lower doses. However, a relative disadvantage when scanning in sequential mode is the inability to generate high-quality multi-plane reformatted (MPR) images; this refers to producing images in the sagittal, coronal, and oblique planes. Therefore, when compared to sequential scanning, MDCT volume helical scanning, which does allow MPR image production, has the *potential* for dose reduction, but this is dependent on how the system is used (Bushong, 2017; Valentin, 2007).

Although AEC has become the most important tool to help technologists effectively manage CT dose (Kalender et al., 2008; Valentin, 2007; Yu et al., 2009), manufacturers and users need more information on defining quality reference levels for various diagnostic tasks (Dixon, 2007). To effectively use AEC in CT, technologists need to be familiar with the concepts of noise, reference mAs, and reference images. CT manufacturers have designed various AEC systems that have unique features, and operator knowledge of the system being used is important in ensuring the effective use of AEC (Valentin, 2007). Raman et al. (2013) concluded that many imaging centers fail to take advantage of CT dose reduction capabilities because of a lack of understanding about how exposure reduction tools work.

To better enable CT imaging facilities to reduce unnecessary dose to patients, the ACR established dose reference levels for various body regions (McCollough et al., 2004). As of January 1, 2012, as part of the Medicare Improvement for Patients and Providers Act of 2008 (MIPPA), facilities that bill the Centers for Medicare and Medicaid Services for the technical component of CT scans must be accredited by the ACR. The ACR reference level for an adult CT head is CTDI vol 75 mGy, and the accreditation pass/fail criterion is CTDI vol 80 mGy (American College of Radiology, 2017).

Introduction of Helical CT

Although CT scanning equipment and methods have evolved since Hounsfield's first-generation CT scanner, most CT scanners in use today are MDCT variations of the third generation scanner and use a cone-shaped beam and curved detector arrays that rotate around the patient who moves longitudinally through the gantry. Depending on the number of detector-array rows, a MDCT scanner may have up to tens of thousands of individual detectors. MDCT helical volume scanning enables operators to obtain images during one breath hold, allowing high-quality reformatting in multiple planes (Bushong, 2017).

> When the examination begins, the x-ray tube rotates continuously. While the x-ray tube [and curved detector array] rotates, the couch moves the patient through the plane of the rotating x-ray beam. The x-ray tube is energized continuously, data are collected continuously, and an image then can be reconstructed at any desired *z*-axis position along the patient. (Bushong, 2017, p. 446)

In CT, noise and contrast resolution are two of the five principal characteristics of image quality. Noise is described as a variation in CT numbers above and below the average actual attenuation value; it is the standard deviation of at least 100 pixels. The emitted dose or the number of x-rays used (mAs) to produce images is the controlling factor for noise (Bushong, 2017). There is a negative relationship between exposure and noise. For example, Valentin (2007) stated that a decrease in detector exposure by a factor of five will result in a noise increase proportional to the square root of five, or about 124 %.

In addition to mAs, other factors that affect noise also include kVp, filtration, pixel size, slice thickness, and detector efficiency. Noise primarily affects contrast resolution and appears as graininess on CT images. High-noise images appear grainy with relatively less contrast resolution, while low-noise images appear smooth with relatively higher contrast resolution (Bushong, 2017; Long et al., 2016). Using an image on a system’s display monitor, noise measurements can be obtained using a circular region-of-interest (ROI) cursor. Generally, quality control (QC) standards in CT indicate that 20-cm water-bath phantoms should have a CT attenuation value of zero, with a standard deviation (noise) of 10 HU (Bushong, 2017).

Noise can be quantified in HU, and low noise is conducive to detecting low-contrast lesions. On the other hand, higher noise values are acceptable on some contrast-enhanced scans and when scanning inherently high contrast regions of the body. CT colonography; chest, sinus, and vertebral CTs; and CT kidney stone protocol are examples of scans where lower doses that result in higher noise are acceptable (Mullins et al., 2003; Valentin, 2007). Conversely, scans of the liver, pancreas, and brain are examples of low-contrast regions that warrant relatively higher doses with lesser noise (Valentin, 2007). As of 2008, there was little consensus on recommended noise levels for most diagnostic tasks (Kalender et al., 2008).

While noise is primarily related to dose and has a significant effect on contrast resolution, contrast is also related to kVp. There is a negative relationship between kVp and contrast. While a decrease in kVp can decrease the dose, it also increases contrast. On the other hand, an increase in kVp decreases contrast (Valentin, 2007).

There is a direct relationship between patient makeup (size and density) and the x-ray beam intensity needed to produce diagnostic CT images. Therefore, in the absence of AEC capabilities, CT technologists should use size-based technique charts for most body regions. However, since the skull is the primary attenuation material in the cranium, with little variation in size, some recommend that manual CT head charts should be age-based rather than size-based. Nevertheless, it is impossible to ensure optimal exposure parameters simply by viewing CT images. Therefore, in contrast to scans in which AEC was used, scans performed using manual CT techniques often result in overexposure of small patients (Valentin, 2007).

Aldrich, Chang, et al. (2006) studied the relationships between body weight, radiation dose, and image quality in 37 patients who underwent abdominal CT scans. The researchers measured noise levels at nine relatively homogenous points in their patients' abdomens. Using linear regression, they calculated that an optimal target noise level of 16 HU was ideal for high quality images of the abdomen. The researchers also determined that, based on a patient's weight, they could calculate the tube current required to generate high-quality images. Similarly, they learned that they could use a patient's size or weight and tube current to predict the amount of noise in their abdominal images. They did not use AEC to modulate their doses, but rather, a constant 120 kVp was used, and the technologists intuitively adjusted the mA based on each patient's size. However, they stated that their data could be helpful in determining target noise limits in AEC systems.

CT Scan of the Head

Although a CT scan of the head may be called by other names such as CT brain, CT skull, and CT cranium, these are all defined as a diagnostic imaging method that use x-rays to produce cross-sectional images of the head. A CT scan of the head may be performed for various indications including mental status and/or behavioral changes; fainting or multiple convulsion; trauma; headache, when combined with other signs and symptoms; and symptoms of damage to part of the brain, such as vision problems, muscle weakness, numbness and tingling, hearing loss, difficulty speaking, and difficulty swallowing. Some of the conditions that may be diagnosed and monitored with CT head scans include abnormal development of the neck or head, brain hemorrhage and/or infarct, brain tumor, pre-mature skull suture fusion, and hydrocephalus (Jibiri & Adewale, 2014). According to Valentin (2007), exposure parameters for a given CT procedure could be based on the clinical indication for the procedure.

Skin, Organ, and Eye Doses

In contrast to radiography and fluoroscopy, where the entrance skin exposure (ESE) is relatively high at the entrance surface (the side of the patient where the x-ray beam enters the patient), ESEs and organ doses from CT are of greater concern; this is mainly due to the x-ray beam rotating *around* the patient, emitting relatively large amounts of radiation. For example, a typical CT head will yield an ESE of 40 mGy, with a mean marrow dose of .20 mGy, and a gonadal dose of .50 mGy; despite these apparent variations, dose distribution for a head CT is fairly uniform in that the midline dose is approximately the same as the 40 mGy ESE. In contrast, the midline dose for a body scan is approximately 50% of the ESE (Bushong, 2017).

When compared to most other tissue, the lens of the eye is relatively radiosensitive, particularly in children, and should be selectively avoided during CT. Although the precise level of cataract threshold dose is difficult to assess, most researchers would suggest a threshold dose of approximately 2 Gy (Bushong, 2017). However, Jibiri and Adewale (2014) stated that the eyes are frequently exposed to x-rays during CT scans of the head. The researchers stated that the absorbed-dose threshold for damage to the lens of the eye is 500 mGy, with 6-14 Gy required for cataract formation. Jibiri and Adewale concluded that their patients' eyes received an average absorbed dose of 35.6 mGy during CTs of the head. Therefore, the authors determined that it would take approximately 120 CT scans of the head for a patient to develop CT-related cataracts.

Automatic Exposure Control in CT

Increased CT use and the potential harmful effects of radiation have led manufacturers to develop dose reduction techniques such as iterative reconstruction, automated tube potential (kVp) selection, and AEC (Soderberg as cited in Raman et al., 2013). Although AEC has been used in radiography for decades, it was developed for use in CT during the 1980s and early 1990s. The first AEC system for CT became commercially available in 1994 with initial mA reductions averaging 8 to 13%. By 2001, other mA modulated AEC systems became available with dose reductions ranging up to 40% in elliptical-shaped body regions (Valentin, 2007).

Modern AEC systems have the potential to reduce dose 40-60% by modulating the mAs relative to patient size and attenuation. Multiple manufacturers refer to AEC by different names, and there are slight variations among various systems. Siemens CARE Dose 4D system combines two dose-modulating methods. It provides longitudinal dose modulation in the scanning direction (*z*-axis) by using a localizer image to provide the AEC system with information regarding the size, shape, and density of the patient. Using a mathematical algorithm, the system estimates an attenuation profile based on the information obtained from a localizer image. In addition to *z*-axis modulation, which is based on the localizer image, CARE

Dose 4-D also provides angular modulation of the mAs in the *x*- and *y*-axes. In other words, the system's angular modulation system uses real-time noise monitoring to adjust the mA higher for high attenuation areas and vice-versa (Rizzo et al., 2006). According to Greess et al. (2000), attenuation for elliptical-shaped anatomy can change by several orders of magnitude.

Although other manufactures' AEC systems use noise indices and reference images to provide a quality reference during angular modulation, CARE Dose 4D relies on stored quality reference mAs (QRM) values for three different strengths of angular modulation: normal, weak, and strong. The QRM values are determined by the manufacturer but can be adjusted according to the task for each scan (Valentin, 2007). The QRM values are set to the mAs needed to achieve optimum noise for average patients (normal), obese patients (strong), and small patients (weak). Strength settings are selected by the technologist and saved into each protocol based on the body region to be scanned. The technologist can change the modulation strength based on patient size and the desired amount of noise by selecting a different modulation strength (Rizzo et al., 2006). Together, angular and longitudinal modulations create a comprehensive, modulated dose profile for acquiring images with relatively uniform noise regardless of varying attenuation factors. Generally, the modulated x-ray beam reduces patient dose. However, doses may increase when using AEC with obese patients (Valentin, 2007).

Using the correct tube orientation for the localizer image(s) is vital when using AEC and can affect dose. Soderberg (2016) used a Siemens CARE Dose 4D AEC system and an adult anthropomorphic phantom to determine that a 13% increase in dose was observed when the localizer orientation for a scan of the thorax was changed from anterior-posterior (AP) to posterior-anterior (PA). Soderberg stated that the difference in dose may have been due to a consequence of the table and the high-attenuation spine being relatively closer to the x-ray tube, which caused more magnification of the spine.

In 2018, Siemens mailed certified letters regarding an Urgent Device Correction Notice to inform their customers to use a lateral localizer image when utilizing CARE Dose 4-D on their head scans. According to the notice, the system's algorithm may perform incorrect calculations when referencing an AP or PA head localizer image, which may result in unnecessary increased exposure. Siemens stated that their experts were working to resolve the problem and would inform their customers once the problem was resolved (Siemens, 2018).

Adequate and ongoing CT training is important for workers related to CT. It is especially important for CT technologists who control the scan parameters and for radiologists who are responsible for designing institution-specific protocols to ensure the production of diagnostic CT images at reasonable radiation costs (Valentin, 2007). Dixon (2007) stated that some CT scans contribute a disproportionate radiation burden to the community. For example, Rizzo et al. (2006) studied the use of AEC on 152 abdomen and pelvic scans and determined that using AEC resulted in dose reductions up to 44%, while maintaining adequate image noise and quality.

Aldrich, Bilawich, et al. (2006) studied radiation doses from 1,070 CT scans, which included *axial* CTs of the head (also known as sequential scanning). The researchers demonstrated that abdominal CT scan doses from 18 different hospitals varied by a factor of around seven, and CT head scan doses varied by a factor of nearly three. One hospital included in the study consistently ranked higher in CT doses than the others; after the imaging team at this hospital was informed of the results of this study, they were able to alter some protocols and reduce their overall CT doses by 30%. Aldrich, Bilawich, et al. concluded that the DLPs from

CT head scans performed in their region ranged from about 750 to 2,200 mGy cm, with an average DLP of 1,300 mGy cm.

Similarly, Sadri et al. (2013) also demonstrated that wide dose variations exist among hospitals and scanners; more specifically, the authors determined that head scans performed on a 16-slice Siemens Somatom Emotion were among those that resulted in the highest head-scan doses. Their rationale was that the scanner did not have the option of using 120 kVp. However, despite the authors' acknowledgment of the scanner's AEC system, their reported technique parameters did not include whether or not AEC was used. The authors concluded that head scan doses among nine scanners varied by a factor of about 2.5.

Greess et al. (2000) studied the use of AEC using phantoms, cadavers, and patient scans of six body regions, which included the base of the skull. Overall, the researchers observed a typical dose reduction of 15-50 % in their patient scans, with an 18 % dose reduction in their base-of-the-skull samples.

In a prospective study, Mullins et al. (2004) performed limited, noncontrast CT head scans on 20 elderly patients using two protocols. The researchers compared dose and image quality between the two protocols, a standard manual head protocol and a manual low-dose protocol. Although their low-dose protocol resulted in slightly less subjective diagnostic quality and slightly greater noise (22%), the researchers demonstrated that lowering the mAs approximately 50%, from 170 to 90 (65 to 35 CTDI vol mGy), did not significantly reduce image quality. However, while the researchers stated that they obtained 5 mm sections thickness, they did not state what collimation thickness was used.

Wallace et al. (2015) concluded that AEC was an effective means to reduce pediatric patient doses on their CT cerebrospinal fluid shunt protocol. Intraventricular shunts are frequently implanted surgically to treat patients with hydrocephalus, and these patients are prone to repeat scanning to assess shunt efficacy. Therefore, the authors decided to assess the use of AEC to reduce these patients' radiation dose received from repeated follow-up scanning. They concluded that using AEC resulted in a dose savings of approximately 40 % on this particular pediatric CT head protocol.

Summary

Optimizing dose in CT is a complex task, and excessive dose reduction can decrease lesion detectability. Therefore, the risk to the patient of a misdiagnosis from a low-dose CT scan can be greater than the statistical risk of a radiation-induced malignancy (Valentin, 2007). Researchers have reported effective CT dose reduction using phantoms and cadavers (Naseri et al., 2014; Kalender et al., 1999; Soderberg, 2016), but studies involving actual patients are scarce and limited. For example, Wallace et al. (2015) reported on the effective use of AEC for a certain pediatric head protocol, but they did not state why AEC was not used on all of their CT head protocols. Greess et al.'s (2000) study, which examined the use of a mA-modulated AEC prototype for patient scans in six anatomical regions, used only 10 patient scans in each of their head-scan samples. Of their two head-scan samples, 111 mA was used for both samples. Their reported 18% dose reduction resulted from comparing their head-scan samples to cadaver samples.

AEC has become an important tool to moderate dose and image quality in CT, and studies that compare retrospective, diagnostic CT scans in which different scan parameter were used are needed to help establish optimal CT protocols and diagnostic reference levels (Kalender, 2008). However, there remains a paucity of literature regarding the use of AEC during routine adult CT head scans, and its effectiveness when CT scanning this particular region remains unclear.

CHAPTER 3

METHODS

Overview

According to Valentin (2007), technologists should use AEC for CT scans whenever possible. However, the effective use of AEC for CT scans of the head has not been thoroughly established. Dixon (2007) stated that the medical imaging community needs more information to define quality reference levels for various diagnostic tasks. Therefore, in the absence of proper benchmarks and to build on others' research, the purpose of this study was to determine if using AEC on routine adult CT scans of the head was an effective way to manage patient dose in one particular CT setting. During this study, objective and subjective image data were used for causal-comparative and correlation coefficients analyses to investigate whether or not AEC was effective at balancing radiation dose and image quality during routine, adult CT head scans.

Research Questions

The following questions guided this project:

1. Is there a significant difference in radiation dose between adult CT head scans performed without and with AEC?
2. Is there a significant difference in objective image quality between adult CT head scans performed without and with AEC?
3. Is there a significant difference in subjective image quality between adult CT head scans performed without and with AEC?
4. Is there a relationship between head size and radiation dose when AEC is used in adult CT head scans?

5. Is there a relationship between head size and image noise when AEC is used in adult CT head scans?

Research Design

Using adult CT head scans, causal-comparative and correlational research methods were used to study the effect of using AEC. I used existing CT scans that were performed with two different techniques (without and with AEC) and used causal-comparative methods to determine the effect AEC had on dose, objective image quality (noise), and subjective image quality. In addition, using head diameter measurements from existing scans performed with AEC, I calculated correlation coefficients to study the relationships between head size, dose, and noise.

Objective data that included dose and noise were used to answer research questions 1 and 2. Subjective data that consisted of radiologists' image quality scores were used to answer research question 3, which addressed three aspects of image quality, (a) noise, (b) resolution, and (c) streak artifact. Objective data that included dose, noise, and head diameter measurements were used to answer research questions 4 and 5.

Strengths and Limitations

As was briefly described above, causal-comparative and correlational research methods were used. According to Cottrell and McKenzie (2011), both of these methods follow the scientific method. Causal-comparison studies use non-experimental research methods that attempt to determine cause and effect relationships between two or more groups and one independent variable; this method is used when the research occurs ex-post-facto and variables are not manipulated. Similarly, correlational research is also non-experimental but involves only one group and attempts to determine relationships between two or more variables (Cottrell & McKenzie, 2011).

Although the methods that were used followed the scientific method, Cottrell and McKenzie (2011) stated that non-experimental research methods are not as reliable as experimental methods in determining cause and effect and do not maintain as much control over the experimental conditions (Cottrell & McKenzie, 2011).

Population

The study population was comprised of existing CT head scans that were performed from January 1, 2017 to September 30, 2018 at Johnson County Community Hospital in Mountain City, Tennessee.

Samples Selection

Stratified random sampling was used to ensure that each group was equally represented. Existing adult CT head scans were used to form two sampling frames. The sample that did not include the use of AEC was collected from routine adult CT head scans performed prior to the facility's protocol change, from January 1, 2017 to October 30, 2017. The sample that included the use of AEC was collected from scans performed after the facility began using AEC on routine adult CT heads, from December 1, 2017 to September 30, 2018. As a result, two samples were formed from two groups: one without AEC and one with AEC. An interim period (November, 2017) in which either protocol could have been used was excluded.

The stratified samples were formed by systematically sampling existing adult CT head scans from the facility's picture archiving and communication system (PACS) system. The sampling frame was determined by using the search filters "All Exams", "MCT HEAD WO CONT", and designated time periods. Based on the number of routine CT head scans that were performed in a 3-month-period, each sampling frame was estimated to contain 320 CT head scans.

According to Cottrell and McKenzie (2011), reliable correlational research samples require at least 30 sampling units (participants). Therefore, the sample size (*n*)30 was self-selected. Pediatric scans and scans that were degraded by motion, metal artifact, or other artifact were excluded from the study.

Using the numbers 1- 30, the fishbowl sampling method was used to select the first participant (scan) for each sample. Then, the selection interval (11) was determined by dividing the estimated number of exams in each sampling frame *(N)*320 by the sample size (*n)*30. After the participant for each sample was selected, the determined selection interval (11) was used to select the remaining 29 participants. The exam accession numbers of the selected participants were recorded onto a file in the secure drive (s-drive) of the hospital's computer network, and to protect patients' confidentiality, a key code was created by assigning a study participant number to each accession number; the file was titled AEC Data Collection Form. Along with the exam accession numbers and participant numbers, a column for each variable and a "Comments" column was included in the form (see Appendix A).

Instrumentation

CT Scanner

The CT unit used to produce the scans was a 2010 Siemens SOMOTOM Emotion™ 16-slice CT scanner. With the exception of using the scanner's AEC system (CARE Dose 4-D™) on the with-AEC sample, scan technique parameters for both samples were identical. The dose reports for the helical portion of each scan were reported in mGy and mAs; they included total mAs, DLP, and CTDI vol relative to a 16 cm phantom. These measurements were automatically calculated by the CT scanner software and stored in the facility's PACS system.

Scan Parameters

Localizer images were obtained using 25 mA, 110 kV, with a lateral tube position and a collimation thickness of 0.6 mm. Manual-technique (without AEC) helical adult head scans were obtained using the following parameters: effective mAs- 270, kV- 130, collimation configuration- 16 x 1.2 mm, total collimation width- 19.2 mm, pixel spacing- .2967 and .2969 mm, display slice thickness- 5.0 mm, recon increment- 5.0 mm, tilt- 0°, rotation time- 1.0 s, pitch- .55, filtered backprojection reconstruction algorithm- H41s medium +, window width (80), window level (35), FOV- 152 mm x 205 mm, imaging matrix- 512 x 512. With the exception of effective mAs, which varies when AEC is used, the with-AEC scans used the same scan parameters with organ characteristic set to "brain", and a normal strength setting, and a quality reference mAs of 230.

PACS

The PACS system, which was used to retrieve the CT head images and data, was a GE Healthcare Radiology Centricity™ PACS RA1000. Distance, attenuation region-of-interest (ROI), and noise measurements were calculated using the PACS system and a NEC Multisync LCD 1990SXi monitor. The CT head images were viewed and image quality was subjectively scored by the radiologists using a dedicated, multi-monitor Barco viewing station, equipped with two, high resolution 3MP LCD monitors.

PACS was also used to measure the lateral localizer images to determine head diameter measurements in the following manner: While keeping the distance measurement tool parallel with the orbitomeatal plane and including the outer-most soft tissues of the scalp, I began each measurement at a point anterior to the frontal sinuses and extended the measurement posteriorly to the most posterior outer edge of the scalp.

I also used PACS to perform attenuation ROI and noise measurements of the cerebrospinal fluid (CSF) within the fourth ventricle. First, I reviewed the axial images to locate the fourth ventricle. Then- I magnified the size of the image by 2.5 to record mean CSF attenuation and noise measurements in Hounsfield units (HU); I measured these by placing an oval ROI cursor, which covered a ventricle-dependent area of about 3-6 mm^2, within a relatively homogenous area of the CSF in the fourth ventricle, just posterior to the pons. Mean average and standard deviation (noise) data were measured and collected.

Data Collection

The technique that was used to perform the scans in each sample was the independent variable used for analyses to answer research questions 1-3. Head diameter was the independent variable that was used for analyses to answer research questions 4 and 5. Dose- and quality-related data were dependent variables for all research questions.

The variables for both samples, which I characterized as scale variables, were noise, mean ROI, CTDI vol, DLP cm, total mAs, head diameter, and table height. Subjective image quality scores, described later, were also characterized as scale variables. Technique (AEC vs. manual) was characterized as a string variable.

Data Analyses

Objective Data Analyses

Objective data analyses were used to answer research questions 1 and 2. Causal-comparative methods were used to determine the effect AEC had on dose and objective image quality (noise). I performed *t*-tests for independent samples to determine if there were differences in dose and noise, research questions 1 and 2 respectively. The technique used to perform the scan was the independent variable for these analyses; dose and noise were dependent variables.

Objective data analyses were also used to answer research questions 4 and 5. Using head-size measurements exclusively from the sample performed with AEC, I calculated correlation coefficients to determine the effect AEC had on dose and noise, questions 4 and 5 respectively. Head size was the independent variable for these analyses; dose and noise were dependent variables.

Subjective Data Analyses

The samples were also used to collect subjective data. I combined both samples to form a second sampling frame (*N*)60. Next- fishbowl sampling was used to assign a random order to the sampling units. I wrote each participant number onto small pieces of paper and placed them together in a container. I removed each piece of paper until the container was empty, and the participant numbers were recorded onto a Subjective Image Quality Evaluation form in the order that they were drawn (see Appendices B, C, and D); the form with the recorded exam accession numbers remained protected by storing it on the shared drive of a password-protected computer.

To score the subjective image noise (Q3a), subjective image resolution (Q3b), and streak artifact (Q3c) of the samples, I adopted the evaluation scales that Wallace et al. (2015) used to evaluate a pediatric CT head protocol:

> Subjective image noise was evaluated on a 4-point scale: 1, unacceptable; 2, noisy but permits evaluation; 3, average noise; and 4, below average noise. Subjective image resolution was evaluated on a 5-point scale: 1, structures cannot be identified; 2, though structures can be visualized, resolution is diagnostically unacceptable; 3, resolution is below average but diagnostically acceptable; 4, structures are defined but contours are not sharp; 5, structures are well defined with sharp contours. The resolutions of the gray-white matter differential, subarachnoid space margins, basal ganglia, and posterior fossa

structures were evaluated. Streak artifact was evaluated on a 4-point scale: 1, artifact renders image uninterpretable; 2, major artifact but images are interpretable; 3, minor artifacts; and 4, no artifacts. (pp. 640-641)

Subjective Image Quality Evaluation forms, which included the randomized accession numbers of the 60 sampling units, were printed on-site at the facility where each radiologist was working. Each of the forms was placed into a sealed envelope marked “Confidential”, and hand-delivered to three board-certified radiologists. Using the evaluation scales described above, each radiologist visually evaluated and scored the images and recorded his/her scores onto the Subjective Image Quality Evaluation form. After the form was completed, each radiologist contacted me and, at the soonest reasonable time, I returned to the site to receive the completed form directly from the radiologist. I immediately redacted the accession numbers from the form, and used a key code to link the data to the correct CT scan.

I studied the relationships of the subjective image quality scores using *t*-tests for independent samples. The technique used was the independent variable, and image quality scores, a- noise, b- resolution, c- streak artifact, were the dependent variables. IBM SPSS Statistics 25 was used for all statistical analyses.

Institutional Review Board (IRB)

IRB approvals were obtained from East Tennessee State University and Ballad Health. Based on criteria published by the Office for Human Research Protection (2016), this study was categorized by the IRBs as an expedited review because it involves minimal risk.

CHAPTER 4

RESULTS

Introduction

There is a direct linear relationship between exposure to ionizing radiation and the stochastic effects, such as cancer, that can develop as a result of such exposure (Bushong, 2017). Any reduction in patient exposure to ionizing radiation resulting from medical imaging procedures reduces the chances of developing radiation-induced malignancies. However, in medical imaging, a change in exposure may affect image quality. Generally, higher exposures are associated with better image quality (Valentin, 2007). As a result, CT image quality is often greater than what is needed for accurate diagnoses (Naseri et al., 2014). AEC has been proven effective at balancing dose and image quality for many types of CT scans, but AEC's effectiveness for CTs of the head remains unclear. The purpose of this research was to study AEC's effects on dose and image quality when it is used for adult CT scans of the head.

Population

A retrospective study, the study population was comprised of existing CT head scans that were performed from January 1, 2017 to September 30, 2018 at Johnson County Community Hospital in Mountain City, Tennessee.

Participants

Stratified random sampling was used to ensure that each group was equally represented in number, and existing adult CT head scans were used to form two samples (n = 30). The sample that did not include the use of AEC was collected from routine adult CT head scans performed from January 1, 2017 to October 30, 2017; this sample has been designated as the *standard (STD)* sample. The sample that included the use of AEC was collected from scans performed from December 1, 2017 to September 30, 2018; this sample has been designated as the *AEC* sample. As a result, two stratified samples of participants were formed, one without AEC and one with AEC.

Using the data collection procedures detailed in Chapter 3, retrospective data were collected during a 10-week period of July, August, and September, 2019; these data were used to answer five research questions. Causal comparative analyses were used to answer research questions 1-3. Correlational analyses were used to answer research questions 4 and 5. In all analyses, a 95% confidence limit (alpha .05) was used to test for significance.

Analyses of the Data

Research Question 1- Is there a significant difference in radiation dose between adult CT head scans performed without and with AEC?

A *t*-test for independent samples was conducted on the radiation dose data of the STD and AEC samples. There was a significant difference in radiation dose between the two samples ($p < .001$, alpha = .05). The mean dose of the STD sample was 1205 mGy ($s = 48$ mGy). The mean dose of the AEC sample was 747 mGy ($s = 98$ mGy). When compared to the STD protocol, a 38% dose reduction was observed in the AEC sample.

Research Question 2- Is there a significant difference in objective image quality between adult CT head scans performed without and with AEC?

A *t*-test for independent samples was conducted on the objective noise data (mean CSF attenuation values) of the STD and AEC samples. There was a significant difference in objective image quality between the two samples ($p = .034$, alpha = .05). The mean noise of the STD sample was 2.62 HU. The mean noise of the AEC sample was 3.08 HU.

Research Question 3- Is there a significant difference in subjective image quality between adult CT head scans performed without and with AEC?

Both samples were randomized and submitted to three radiologists for image quality scoring which was detailed in Chapter 3. The radiologists' scores were averaged, and a *t*-test for independent samples was conducted. Overall, there was no significant difference in subjective image quality between the two samples.

Question 3a- Is there a significant difference in subjective image noise between the two samples?

There was no significant difference in subjective image noise between the two samples ($p = .055$, alpha = .05).

Question 3b- Is there a significant difference in subjective image resolution between the two samples?

There was no significant difference in subjective image resolution between the two samples ($p = .344$, alpha = .05).

Question 3c- Is there a significant difference in streak artifact between the two samples?

There was no significant difference in streak artifact between the two samples ($p = .174$, alpha = .05).

Research Question 4- Is there a relationship between head size and radiation dose when AEC is used in adult CT head scans?

A Pearson product correlation was calculated for the two variables of head size and radiation dose. The resulting r value was .646 ($p < .001$, alpha = .05). The null hypothesis, which stated there would be no relationship between head size and radiation dose, was rejected. These results indicated that there was a moderately strong positive correlation between head size and radiation dose when AEC was used. In summary, as either head size or radiation dose increased, the other variable tended to increase as well.

Research Question 5- Is there a relationship between head size and image noise when AEC is used in adult CT head scans?

A Pearson product correlation was calculated for the two variables of head size and image noise. The resulting *r* value was .127, ($p = .504$). The null hypothesis, which stated that there would be no relationship between head size and image noise, was not rejected. These results indicated that there was no relationship between head size and image noise when AEC was used.

CHAPTER 5

SUMMARY, CONCLUSIONS, DISCUSSION, AND RECCOMENDATIONS

Summary

The effects of using AEC during adult CT heads in one particular setting were assessed in this study. The radiation dose and image quality between two samples, a standard protocol and a protocol that used AEC, were compared. In addition, two correlational analyses were conducted on the sample in which AEC was used; these were conducted to study the relationships between head size and dose, and head size and noise.

Systematic random sampling was used to select (*n*)60 preexisting adult CT head scans out of a population of about 640 scans to form two stratified samples (*n*)30. Exposure parameters for the samples were identical with the exception that AEC was used to modulate the mA during acquisition of one the samples. The samples have been designated as *STD* and *AEC* samples.

Five research questions were used to guide this study, and statistical tests were conducted to evaluate seven hypotheses. The research questions were introduced in Chapter 1, and Chapter 2 contained the literature review. The research methods were described in Chapter 3, and the results of the statistical analyses used to answer the research questions were described in Chapter 4. Causal comparative analyses were conducted to answer research questions 1-3. Correlational analyses were conducted to answer research questions 4 and 5. SPSS was used for all analyses with a 95% (alpha .05) significance level.

Conclusions

When compared to the STD sample, a substantial radiation dose reduction (38 %) was observed in the AEC sample, but no statistical difference in subjective image quality between the samples was observed. However, a statistically significant .46 HU (18%) objective noise increase was observed in the AEC sample.

Despite the 38% decrease in dose and 18% increase in objective noise, a reduction in image quality was not visually appreciated in the AEC sample. Therefore, the principle investigator of this study, in collaboration with the three radiologists that scored the images, determined that AEC was effective at optimizing dose for routine adult CT heads in this setting.

Causal Comparative Analyses

Research Question 1- When compared to the STD protocol, a 38% DLP reduction was observed in the AEC sample; this resulted in a mean DLP difference of 458 mGy.

Research Question 2- The objective noise (mean CSF attenuation value) between the STD and AEC samples was statistically significant; the observed objective noise was 2.62 HU and 3.08 HU respectively, for a difference of 0.46 HU (18%).

Research Question 3- The subjective image quality of both samples was scored by three radiologists who were blinded to the techniques that were used to perform the CT scans; they visually evaluated and scored the images on three aspects of quality: resolution, noise, and streak artifact. The results were unanimous: For all three aspects of quality, no statistical differences were observed.

Correlational Analyses

Research Questions 4 and 5- There was a moderately strong positive correlation between head size and radiation dose when AEC was used (r = .646). In contrast, there was no relationship between head size and image noise when AEC was used (r = .127).

Discussion

While the DLP is one standard for dose reporting, CTDI vol and mAs are also relevant. Therefore, to add breadth to the study, CTDI vol and mAs values were also collected. The mean average CTDIs vol for the STD and AEC samples were about 65 mGy and 40 mGy respectively. When compared to the STD sample, the AEC sample resulted in a 38% CTDI vol reduction. The ACR's accreditation pass/fail threshold for adult CT head is CTDI vol 80 mGy. The evidence from this study showed that both protocols met the ACR's CTDI vol accreditation threshold.

The mean total mAs used for the STD and AEC samples was about 2688 and about 1715 respectively. When compared to the STD sample, the AEC sample was lower by an average of 973 mAs (36%). Regardless of the radiation unit used, according to the linear non-threshold theory, any reduction in radiation dose reduces the chances of developing associated stochastic effects such as cancer. Theoretically, when compared to the STD sample, the chances of developing cancer are lower for patients that comprised the AEC sample.

According to Valentin (2007), there is a negative relationship between exposure and noise; when the exposure decreases, noise increases. The observed objective noise difference between the samples was 0.46 HU (18%). However, the objective noise difference between the samples was not appreciated visually in a blind subjective image quality comparison by three radiologists.

The moderately strong correlation (r = .646) between head size and radiation dose that was observed in the AEC sample showed that AEC was effective at moderating dose relative to head size. In contrast, there was no relationship (r = .127) between head size and image noise in the AEC sample; this showed that, regardless of head size, AEC was effective at maintaining a fairly constant level of noise.

The findings from this study are consistent with other AEC research. For example, Rizzo et al. (2006) reported a 42-44 % dose reduction in CT scans of the abdomen and pelvis without sacrificing image quality. While Rizzo et al.'s observed dose reduction was slightly greater than the 38 % reduction reported here, the difference could be related to the different anatomical regions which were studied.

Recommendations

The evidence from this limited study showed that AEC was effective at optimizing the radiation dose for adult CT head scans in one particular setting. However, additional research on this topic to confirm or refute these results is needed.

Additionally, even though the radiologists' image quality scores in this study did not detect a difference in noise between the samples, the objective noise increase observed in the AEC sample should not be considered meaningless. Valentin (2007) stated that some CT scans can tolerate higher noise levels and some cannot. Therefore, CT protocols should be designed for specific diagnostic tasks. Valentin also stated that some imaging professionals advocate the practice of obtaining the maximum amount of information on any *initial* CT scan. As a result of the current study and this learning experience, the principle investigator has plans to collaborate with his supervising radiologists and other team members to investigate the possibility of developing a system of tiered adult CT head protocols which would be designed and used based on the indication for the exam and/or the patient's previous scan history.

In conclusion, it should be emphasized that the benefits of having a medically-necessary CT scan outweigh the associated risks. However, to ensure the safest possible exam for various diagnostic tasks, medical imaging professionals should be thoroughly familiar with their equipment and must be diligent in ensuring that radiation exposures remain ALARA. From previous research and this study, there is evidence that AEC is an effective tool to optimize radiation dose for various anatomical regions. However, more research about the use of AEC during adult CT head scans would benefit the imaging community, and more importantly, the patients who are in our care.

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APPENDICES

Appendix A

AEC Data Collection Form

AEC Data Collection Form (Technologist)

Exam Accession #	Partici-pant Study #	Tech-nique	Noise (HU)	CSF Mean (HU)	CTDI vol (mGy)	DLP (mGy cm)	Total mAs	Head Diam -eter (mm)	Table Height (mm)	Comments

Appendix B

Subjective Image Quality Evaluation

Automatic Exposure Control During Computed Tomography Scans of the Head: Effects on Dose and Image Quality

Noise- Evaluation is on a 4-point scale: 1, unacceptable; 2, noisy but permits evaluation; 3, average noise; and 4, below average noise.

Resolution- Evaluation is on a 5-point scale: 1, structures cannot be identified; 2, though structures can be visualized, resolution is diagnostically unacceptable; 3, resolution is below average but diagnostically acceptable; 4, structures are defined but contours are not sharp; 5, structures are well defined with sharp contours. The resolutions of the gray-white matter differential, subarachnoid space margins, basal ganglia, and posterior fossa structures were evaluated.

Streak artifact- Evaluation is on a 4-point scale: 1, artifact renders image uninterpretable; 2, major artifact but images are interpretable; 3, minor artifacts; and 4, no artifacts (Wallace et al., 2015).

Accession #	Participant #	Noise	Resolu-tion	Streak Artifact	Comments
	1				
	2				
	3				

(Continued 57 spaces for a total of 60 scores)

Appendix C

Request Permission to use Grading Scale

On February 23, 2019, the following letter was submitted in the "Contact Us" section on the webpage https://www.consultingradiologists.com/; this is the webpage for Consulting Radiologists Ltd, Edina, Minnesota.

My name is Stephen Osborne, RT(R)(CT)(QM). I am working on my Master's thesis at East Tennessee State University and will be conducting research similar to Wallace et al.'s study titled *Evaluation of the use of Automatic Exposure Control and Automatic Tube Potential Selection in Low-Dose Cerebrospinal Fluid Shunt Head CT* (2015). I am writing to request the e-mail address of Dr. Adam N. Wallace so that I may correspond with him. My goal is to receive permission to use the 4- and 5-point scales and criteria that he used for subjective image quality evaluation in his 2015 study. I will be comparing dose and quality between two CT protocols in adults (*N*)60; therefore, I will not be using the hydrocephalus-specific aspect of the evaluation instrument.

Thank you for considering this request.

Reference: Wallace, A. N., Vyhmeister, R., Bagade, S., Chatterjee, A., Hicks, B., Ramirez-giraldo, J., & Mckinstry, R. C. (2015). Evaluation of the use of automatic exposure control and automatic tube potential selection in low-dose cerebrospinal fluid shunt head CT. *Neuroradiology*, *57*(6), 639-644. doi:http://dx.doi.org/10.1007/s00234-015-1508-6

Appendix D

Permission to use Grading Scale Granted

The following e-mail was received from Dr. Adam Wallace:

Adam Wallace <adam.n.wallace@gmail.com>
Mon 2/25, 10:55 AM
Hi Stephen,

I received your email regarding the scales used in our 2015 paper on CT image quality of two shunt protocols. Please feel free to use those scales in your work.

Best of luck,
Adam

VITA

STEPHEN OSBORNE

Education:	Public Schools, Mountain City, Tennessee
	A.A.S. in Radiography, East Tennessee State University, Johnson City, Tennessee 1989
	B.S. in Radiography, East Tennessee State University, Johnson City, Tennessee 2015
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Professional Experience:	Radiographer/CT Technologist, Johnson County Community Hospital, 1992 – Present
	Adjunct Faculty, East Tennessee State University, College of Clinical and Rehabilitative Health Sciences, 2017
	Mobile CT/MRI Technologist, RIA Management Services, Brentwood, Tennessee, 1990-1992
	Radiographer, Johnson City Medical Center Hospital, Johnson City, Tennessee, 1988-1990
Honors and Awards:	Shining Star Award, Mountain States Health Alliance
	Tri-Cities Health Care Hero, Tri-Cities Business Journal
	Servant’s Heart Award, Mountain States Health Alliance