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Occupational Radiation Exposure Health Risks And Radiation Safety Practices Relative to Interventional Cardiology Providers

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Relative to Interventional Cardiology Providers

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Abstract

Background: Occupational radiation exposure is a health risk for many healthcare professionals working in interventional cardiology. As technology has progressed, interventional procedures have become more complex and subsequently longer in radiation exposure duration, resulting in a need for radiation safety practices to meet the ever growing demands of the interventional team and ideally outpace these demands.

Methods: A comprehensive systematic literature review was conducted using PubMed. Articles on the health risks of occupational radiation exposure were selected to demonstrate the breadth of potential adverse effects of radiation exposure with less focus on the depth of these effects. Articles covering occupational radiation safety practices were selected with a focus on radiation safety practices relative to body region and procedural aspects.

Results: Brain cancer, cataracts, cardiovascular disease, thyroid disease, mental health conditions, skin lesions, and orthopedic problems are some of the most prevalent occupational radiation exposure health risks. Fortunately, these risks have largely been reduced through utilization of personal and ancillary radiation shielding and improved procedural aspects.

Conclusion: Radiation is invisible and adverse effects may not present until years later, which may result in interventional cardiology providers becoming complacent and less vigilant with radiation safety practices. Furthermore, some interventional cardiology providers utilize suboptimal radiation safety practices due to perceived inconveniences and discomfort as well as the belief that optimal radiation safety practices may risk image quality and procedural efficiency. Ultimately, the greatest occupational radiation exposure reductions result from the reduction of radiation exposure to the patient due to reduced radiation scatter.

Occupational Radiation Exposure Health Risks and Radiation Safety Practices Relative to Interventional Cardiology Providers

Introduction

Occupational radiation exposure is a health risk for many healthcare professionals working with radiographic imaging. This risk is of particular concern in the practices of interventional medical specialties, such as interventional radiology, interventional neuroradiology, and interventional cardiology.[1] Healthcare workers in interventional specialties, including physicians, advanced practice providers, and other interventional suite staff, are at a heightened radiation exposure risk, especially during radiographically guided procedures, such as fluoroscopy.[1] Interventional medical providers have been trained to perform minimally invasive procedures, usually involving blood vessels, instead of the typically more invasive surgical alternatives.[1-2] When applied to cardiology, these techniques allow interventional cardiology providers to treat conditions such as coronary artery disease with minimal invasion via procedures such as balloon angioplasty and stent placement in coronary arteries.[1] This particular procedure restores blood flow through stenotic coronary arteries, which provides symptomatic relief and reduces patient pain as well as recovery time.[1]

Although interventional medicine is becoming increasingly beneficial to patients, the potential adverse effects of occupational radiation exposure to interventional medical providers should not be neglected. As with the majority of medical specialties, the advances in interventional cardiology have focused on improving procedural safety, comfort, and efficacy for patients.[3] This pursuit has often overlooked those same goals for providers, resulting in a culture of thought that glorifies sacrificial providers in the interest of patients, but at the cost of compliance with radiation safety practices.[3-4] Advances in interventional medical technology, such as X-ray beam spectral shaping filters, automatic exposure control with multiple low dose algorithms, electronic image magnification, anatomic programming, and image quality enhancement logic have progressively lowered levels of occupational radiation exposure, but as technology has progressed, interventional procedures have become more complex and subsequently longer in radiation exposure duration, resulting in a need for radiation safety practices to meet the ever growing demands of the interventional team and ideally outpace these demands.[2,5] Some of the factors influencing the varying levels of radiation exposure include the X-ray equipment used, fluoroscopy frame rate, procedure complexity, the distance between the provider and the X-ray tube, magnification, collimation, digital acquisition, beam angulation, patient body habitus, and radiation shielding use.[6]

In order to monitor radiation exposure levels, dosimeters with varying units of measurement are utilized. The amount of radiation exposure transmitted to the whole body is termed as the effective dose and is expressed in units of Sieverts (Sv).[7] Similarly, the absorbed dose or tissue dose represents the amount of radiation exposure transmitted to an organ or living tissue and is expressed in units of Grays (Gy).[7] The International Commission of Radiological Protection and the National Commission of Radiation Protection guidelines recommend all occupational radiation exposures be as low as reasonably achievable.[6] The ultimate goal of this philosophy is to reduce cancer and genetic risks associated with occupational radiation exposure via the highest attainable reduction of the maximum permissible radiation exposure dose of 10 mSv per year.[6] This value is based on the effective dose of thyroid and waist personal dosimetry readings.[6] Unfortunately, the effective dose does not address other potential adverse effects, such as epilation, delayed wound healing, skin changes, fracture rate, and vision changes.[6] The 2 primary sources of occupational radiation exposure to interventional suite staff are scattered X-ray photons from a patient's body and X-ray tube leakage.[8] Lifetime occupational radiation exposure to cardiology providers is estimated to be equivalent to 2500 to 10000 chest X-rays.[9]

Some studies have proposed that the occupational radiation exposure per head per year of interventional cardiologists is 2 to 3 times higher than that of radiologists and cardiologists.[10-12] Considering hundreds to thousands of procedures can be performed each year, experienced interventional cardiologists in high volume medical centers have been documented to have an annual occupational radiation exposure below the apron equivalent to 5 mSv, lifetime occupational radiation exposure equivalent up to 200 mSv, and a lifetime fatal or nonfatal cancer risk of approximately 1 in 100.[10-11]

The subsequent adverse effects of radiation exposure are generally categorized into theoretical routes of tissue reactions, stochastic effects, and cellular damage.[7] Tissue reactions, which used to be known as deterministic effects, are believed to happen in a dose response relationship when damage to a number of cells exceeds a certain limit potentially resulting in skin injuries, such as burns and hair loss.[2,7,13] Stochastic or probabilistic effects are believed to be damage to single cells that result in all or none occurrences, which happen more frequently with higher radiation exposure rates potentially resulting in cataracts, pregnancy complications, neurovascular and neurodegenerative effects, and malignancies, such as leukemia, brain, thyroid, and breast cancers.[2,7,11,13] Although the single radiation exposure dose per procedure to providers may be as low as one thousandth of the exposure to the patient, the associations of occupational radiation exposure, specifically low dose chronic radiation exposure, and health risks are currently inconclusive.[11-12]

Background

Occupational Radiation Exposure Health Risks

The adverse effects of radiation exposure typically occur in DNA and can result in cellular death, cells successfully repairing any injury or damage, or cells being unable to properly repair themselves, resulting in alterations that can lead to cancer or genetic defects.[7] Biomarker tests of chromosomal abnormalities in peripheral blood lymphocytes suggest that high chromosomal breakage frequency is a strong predictor of cancer risk.[7] Studies have demonstrated that interventional cardiologists have a 2-fold increase of chromosomal damage in circulating lymphocytes, which act as biomarkers of cancer risk, compared to clinical cardiologists.[9] The head in particular receives radiation exposure 10 to 20-fold higher than the rest of the body.[12] Furthermore, the brain is typically the primary target of radiation exposure in the interventional suite, and it can have direct effects on the thyroid and pituitary glands.[11] Annual occupational radiation exposure to a cardiologist's head can be up to 100 microSv per ablation procedure and 20 to 30 microSv per year.[11] After a 25-year career as an interventional cardiologist, occupational radiation exposure to the unshielded head may be equivalent to 1 to 3 Sv, which corresponds to a brain equivalence of approximately 500 mSv.[11] According to the law of Bergonie and Triboneau, which states that radiosensitivity is directly proportional to the mitotic activity of tissues and inversely proportional to the degree of differentiation of their cells, the brain may be perceived to be radioresistant due to its low mitotic activity and highly differentiated cells.[11] This assumption can lead to inadequate radiation safety practices relative to the head.[11] Even with proper radiation safety practice, the bystander radiation effect, which states that unirradiated cells experience irradiated effects as a result of signals from nearby irradiated cells, has been suggested to increase brain cancer in experimental models of mice with medulloblastoma despite their heads being shielded from radiation exposure.[11] Similarly, data on international nuclear workers suggests a positive association between low dose radiation exposure and leukemia.[9] Additionally, considering the left side of an interventional cardiology provider is typically more exposed to radiation than the right side, tumors on the left side of the brain have been more prevalent.[9] While occupational radiation exposure induced brain cancer is suggestive, it is unfortunately still inconclusive.[11]

In addition to brain tumors, cataracts can also be found in up to 50% of interventional cardiologists.[11] Cataracts were initially thought to be tissue reactions but are now recognized as stochastic effects.[11] The formation of cataracts is suggested to be developing at radiation exposure levels lower than what were previously considered negligible.[14] Studies among Chernobyl clean-up workers, atomic bomb survivors, astronauts, and interventional suite staff suggest that there is an increased incidence of cataracts at radiation exposure doses below 0.5 Gy.[11] According to the Retrospective Evaluation of Lens Injuries and Dose study, interventional cardiologists were 3 times more likely to have cataract type eye opacities than the age matched control group.[15] In a study by Jacob et al[16] comparing posterior subscapular lens opacities prevalence in 106 interventional cardiologists and 99 participants without radiation exposure, posterior subscapular lens opacities were more common among the former at a percentage of 17% compared to 5% in the latter ($p = 0.006$). The pathogenesis of cataracts due to radiation exposure is believed to be caused by oxidation processes or protein damage.[2] The crystalline lens is the most radiosensitive tissue of the eye, which correlates with cataracts being the most common ocular complication associated with radiation exposure.[2,9]

Chronic low dose radiation has also been demonstrated to cause changes in lipid metabolism and endothelial cells that result in premature senescence, which may offer an explanation for data suggesting an associated increased prevalence of cardiovascular disease with radiation exposure.[9] More specifically, chronic low dose radiation exposure has been correlated with early signs of subclinical atherosclerosis.[12] In a study by Andreassi et al[12] of 223 cardiac catheterization laboratory personnel exposed to occupational radiation and 222 unexposed staff members, leukocyte telomere length and left and right carotid intima media thickness were assessed for accelerated vascular aging and early atherosclerosis, respectively. Left and right carotid artery intima media thickness were significantly increased in the radiation exposed personnel in comparison to the unexposed personnel ($p < 0.04$).[12] Additionally, leukocyte telomere length was significantly decreased in the radiation exposed personnel in comparison to the unexposed personnel ($p = 0.008$).[12] Telomere shortening is suggested to be a marker for biological aging and chromosomal instability.[12] The data from this study suggests that chronic low dose occupational radiation exposure may lead to accelerated vascular aging and early atherosclerosis.[12]

In a subsequent study by Andreassi et al[9] comprised of 746 questionnaires surveying the prevalence of health problems in cardiac catheterization laboratory personnel, 446 occupational radiation exposed staff members and 280 unexposed staff members responded. Interventional cardiologists, electrophysiologists, nurses, and technicians were represented in the study.[9] The data demonstrated that interventional cardiologists and electrophysiologists had a 69% higher prevalence of health problems potentially associated with occupational radiation exposure than other staff members ($p = 0.03$).[9] In general, providers had triple the prevalence of health problems compared to nurses, and nurses had double the prevalence of health problems compared to technicians.[9] Overall, occupational radiation exposed staff members in comparison to unexposed staff members had significantly higher rates of skin lesions ($p = 0.002$), orthopedic problems ($p < 0.001$), cataracts ($p = 0.003$), anxiety and depression ($p < 0.001$), hypertension ($p = 0.02$), hypercholesterolemia ($p < 0.001$), and thyroid disease ($p = 0.03$).[9] It should also be noted that in comparison to unexposed staff members, exposed staff members had a higher proportion of smokers, which is a risk factor for many health conditions ($p = 0.001$).[9] Radiation exposure doses of less than 50 mSv have also been associated with hypertension and hypercholesterolemia in atomic bomb survivors.[9] While the stress of a career in interventional cardiology may explain the higher prevalence of anxiety and depression in occupational radiation exposed staff members, chronic low dose radiation exposure may also directly influence adverse changes to hippocampal neurogenesis and neuronal plasticity, resulting in mood instability and psychiatric morbidity.[9]

Aside from direct effects of occupational radiation exposure, indirect effects due to heavy lead aprons have been linked with increased neck and back pain, lost work hours, and cervical disc herniation ($p < 0.01$).[14] Although the lumbosacral and cervical regions are the most prevalent, other joints such as hips, knees, and ankles are also reported.[17] Unsurprisingly, as the careers of interventional cardiology providers progresses, so does their risk of spine problems ($p < 0.05$).[17] In a study by Goldstein et al[17] of 423 respondents, 60% of interventional cardiologists with 21 or more years of experience reported spine problems in comparison to 26% of interventional cardiologists with 5 years of experience. Ross et al[18] investigated the prevalence of spinal disc disease associated with lead apron use in 385 interventional cardiologists with averages of 16.1 years of experience, 8.4 hours of apron usage per day, and 21.1 procedures per week. The average weights of 1-piece lead aprons were 17.9 lb and 2-piece lead aprons were 6.1 to 8 lb for the top half and 6.2 to 13 lb for the bottom half.[18] The intervertebral disc spaces can reach pressures of 300 lb per square inch with the use of 15 lb lead aprons.[18] Compared to orthopedic surgeons and rheumatologists, interventional cardiologists expressed significantly more axial skeletal complaints, and they were the only group to experience multiple level disc herniations ($p < 0.002$).[18] Interventional cardiologists also missed, on average, more days of work due to back or leg pain in comparison to the other provider groups ($p = 0.04$).[18] This particular group also experienced more cervical rather than lumbar complications.[18] Some of the skeletal problems were so debilitating that the providers had to change their practice by eliminating certain procedures from their repertoire.[18]

Occupational Radiation Exposure Health Risks Relative to Pregnancy

Occupational radiation exposure and the associated health risks are of particular concern to interventional cardiology providers who are pregnant or in the process of planning a family. Potential health risks associated with occupational radiation exposure are often cited as reasoning for why women only comprise 8.7% of interventional cardiology fellows and only 5.9% of board-certified interventional cardiologists.[7] Inadequate guidelines for radiation safety practices during pregnancy and inconclusive data regarding the true risk of occupational radiation exposure perpetuate this concern.[7] Fetal and embryonic tissue reactions from radiation exposure may present as intrauterine growth retardation, pregnancy loss, mental retardation, small head size, reduced intelligence quotient, and congenital malformations.[7] Fetal and embryonic tissue stochastic effects from radiation exposure may present as childhood risk of cancer and hereditary diseases in descendants.[7] Fetal radiation exposure greater than 100 mSv is suggested to increase the risk of malformation and childhood cancer, though low dose radiation exposure is also associated with childhood cancer.[7] Radiation exposure during the first trimester presents the highest risk.[7] Not much is known about the radiation exposure risks during the first 10 days following conception.[7] Radiation exposure during days 18 through 20 following conception could cause death and expulsion of the ovum.[7] Fetal radiation exposures of 1 to 2 Gy during days 20 through 50 following conception could cause developmental abnormalities of the nervous system, eyes, and skeletal system.[7] Intrauterine growth retardation of the entire body or the skull and brain individually could present in a fetus exposed to radiation after day 50 following conception.[7] Considering the necessary radiation exposure threshold for tissue effects to potentially occur is much higher than what an interventional cardiology provider would receive with proper radiation safety practices, the likelihood of adverse effects occurring is likely negligible.[7]

When compared to spontaneous risk in pregnant persons without radiation exposure, the risk of miscarriages, malignancies, or major congenital malformation in embryos or fetuses with radiation exposures of 50 mGy is negligible.[7] The American College of Obstetricians and Gynecologists and the National Council on Radiation Protection and Measurements support the assessment that radiation exposures of 50 mGy are not associated with increases in fetal anomalies or pregnancy losses.[7] As a measure to assure radiation exposure to a fetus is kept to a minimum, the International Commission on Radiological Protection recommends the limitation of radiation exposure to a fetus to less than 1 mSv.[7] Similarly, the National Council for Radiation Protection recommends monitoring fetal radiation exposure to ensure a monthly threshold of less than 0.5 mSv and a total pregnancy threshold of less than 5 mSv.[7] Although the most concerning risk for a pregnant interventional cardiology provider's child is cancer, the available data does not suggest that a fetus is at any significant risk due to occupational radiation exposure, as the probability that the child would become afflicted with cancer is 0.07% and radiation exposures above 10 mSv only increase the risk by 0.1%.[7]

Radiation Safety Practices Relative to Body Region

The incessant search for optimal occupational radiation exposure reduction is necessary as radiation exposure varies incredibly across different procedures and up to 10-fold within the same procedure due to the variability of dose delivered per minute and the number of minutes elapsed.[19] Occupational radiation exposure doses per interventional procedures can range from

0.2 to 9.6 microSv for ablation, 0.3 to 17.4 microSv for pacemaker or intracardiac defibrillation implants, 0.2 to 31.2 microSv for percutaneous coronary intervention, 0.02 to 38 microSv for diagnostic catheterization, up to 50 microSv for chronic total occlusion dilation, up to 100 microSv for transcutaneous aortic valve implantation, and up to 200 microSv for endovascular thoracoabdominal aneurysm repair.[11] Fortunately, the combined use of personal and ancillary radiation shielding may reduce the theoretical risk of fatal or nonfatal cancer by 22-fold and severe genetic defects by 25-fold for the average provider.[6] Awareness of occupational radiation exposure risks and proper utilization of radiation safety practices can reduce radiation exposure by 90%.[11] Conventional radiation shielding, such as lead aprons, have long been a mainstay of first line radiation safety practice, but the modern use of fluoroscopic procedures have demonstrated increasing needs for better radiation safety practices as highlighted by a provider who accumulated the equivalent of 60 skull X-rays during 1 month of performing interventional procedures while using their available radiation safety practices.[14]

Lead aprons and thyroid collars, which are typically worn under aprons, are some the most ubiquitous forms of radiation safety practice and are used up to 96% of the time.[2,8] Lead aprons benefits from high absorption and attenuation of X-ray photons as well as cost effective manufacturing.[20] Conversely, a drawback of lead aprons is their heavy weight, which can weigh up to 7 kg and lead to musculoskeletal problems, resulting in a reduction of quality of life.[8,20] Two-piece lead aprons can help to shift some of the shoulder loading to the hips potentially reducing lead apron induced back problems.[8] In a study by Challa et al[6] of 50 coronary procedures, radiation shielding aprons with lead equivalents of 0.5 mm and 1 mm, achieved by overlapping aprons, resulted in a radiation exposure reduction of 72% to 95% and 96%, respectively. In another effort to minimize occupational radiation exposure and musculoskeletal risk, lighter weight radiation shielding aprons of around 4 kg containing lead free composites made of metals, such as antimony, bismuth, tin, aluminum, tungsten, titanium, and barium, are being investigated.[20] Unfortunately, radiation shielding aprons do not always provide the level of lead equivalence claimed by manufacturers.[6,20] In a study by Lu et al[20] of 15 lead containing and led free composite aprons produced by 5 different manufacturers using 8 different composites, 47% of front panels and 90% of back panels provided lower lead equivalent radiation shielding than claimed by the manufacturers. According to the International Electrotechnical Commission minimum requirements for angiographic use, 20% of front panels and 62% of back panels did not meet the minimum threshold hold for procedural practice.[20] With this lack of quality control, it would seem to be in the best interest of interventional teams to annually test equipment for quality control and periodically test the lead equivalence accuracy of new radiation shielding before practical use.[8]

Although current radiation safety practices at the thorax level are mostly effective, radiation shielding above and below the thorax level is often suboptimal.[7,14,21] Radiation exposure below the table is at least 3 times higher than above the table, due to 90% of radiation exposure being absorbed by patients or scattered from patient's backs below the table.[6] To dismay, dedicated radiation shielding for legs are only used approximately 20% of the time.[7,21] This is a particularly important concern to women of reproductive age, as radiation exposure increases risk for future pregnancy complications.[21] In a study by Sciahbasi et al[21] of 205 percutaneous coronary procedures with under table radiation shielding in comparison to no under table radiation shielding, pelvic region radiation exposure was reduced by 71% ($p < 0.0001$). The under table radiation shield is a relatively uncomplicated radiation safety practice that can reduce occupational radiation exposure without procedural compromise. Above the thorax level, lead glasses typically only attenuate radiation exposure by a factor of 2 to 3 times due to the coverage angle relative to the radiation path and scatter.[14] Research conducted by Challa et al[6] resulted in a radiation exposure reduction of 67% to the left eye and 45% to the right eye with the use of 0.75 mm lead glasses. Although the left eye received greater radiation shielding, the right eye still received 14% less radiation exposure due to being slightly further from the X-ray tube.[6] The results of this study also conflicted with the manufacture claim of 85% radiation exposure reduction, though the authors state the discrepancy may be justified by factors such as radiation wavelength angles and provider height.[6] It's been suggested that occupational radiation exposure doses to the head may be lower in providers over 180 cm.[8] In a study by Rose and Rae[2] of 54 interventional medical providers, lead glasses were only used consistently 10.2% of the time, while 61.1% of the time they were never used. Unfortunately, lead glasses are often condemned for being heavy, fog prone, and difficult to use with corrective eyewear.[14]

Radiation safety practices often fail to provide a continuous barrier in the path of radiation scatter leaving the head and neck particularly exposed.[14] Ancillary radiation shielding, such as table shields, hanging lead acrylic shields, and attenuating drapes, can be difficult to position due to space constraints.[14] Ceiling mounted radiation shields can reduce radiation exposure to the head and neck by 50% to 90%, but availability is often scarce, use is irregular when available, and procedural dexterity may be hindered.[2] Lead caps have demonstrated an ability to reduce radiation exposure up to 30 times more than ceiling mounted radiation shields, but an average weight of 1.14 kg is often cited as a reason for discomfort and noncompliance.[8] In order to combat these drawbacks and some of the indirect health detriments of performing interventional procedures such as orthopedic problems due to heavy and cumbersome lead usage, radiation safety practices are being reimagined.[14] A study by Alazzoni et al[22] of 230 coronary angiography or percutaneous coronary interventions demonstrated a significant radiation exposure reduction from a bismuth and barium containing lead free cap ($p < 0.001$). The radiation exposure dose data was obtained from the difference of the external and internal measurements of the lead-free cap.[22] The lead-free cap has a lead equivalency of 0.125 mm and weighs only 53 g, which provides adequate radiation shielding and increased comfort that would theoretically result in increased compliance.[22] In a study by Savage et al[14] of 126 fluoroscopic procedures, the use of a suspended personal radiation protection system in comparison to a conventional lead skirt, vest, thyroid shield, under table shield, side shield, and mobile suspended lead acrylic shield resulted in a 94% reduction to the provider's head and neck. In addition to greater head and neck radiation protection, the suspended personal radiation protection system was also less cumbersome and relieved previously noted back pain.[14] Some drawbacks to the suspended personal radiation protection system include a prohibitive cost, limitation in provider mobility, and a lack of radiation shielding for other interventional suite staff.[14]

Similar to other lead radiation shielding, lead gloves can be cumbersome and restrict tactile sensitivity.[23] These drawbacks, coupled with the fact that unshielded hands can receive 45 to 1500 microSv of radiation exposure per procedure, indicate a need for lead gloves to be reimagined.[8] In a study by Challa et al[6], lead gloves, specifically on the left hand, only provided a radiation exposure reduction of 20%. In a study by Kamusella et al[23] of 24 interventional angiography procedures, gloves made of a radiation shielding metal oxide in comparison to conventional sterile gloves reduced radiation exposure by 42.6% ($p < 0.001$). The metal oxide gloves also maintained provider tactile sensitivity.[23] The implementation of similar radiation shielding gloves appear to be a beneficial addition to radiation safety practices that are not currently standard practice.[23]

Radiation Safety Practices Relative to Procedural Aspects

According to the inverse square law, doubling the distance from the radiation source should reduce radiation exposure by a factor of 4.[6] Panetta et al[24] observed a reduction in radiation exposure dose by 30% ($p < 0.005$) and 47% ($p < 0.005$) upon increasing provider distance from 40 cm to 120 cm away from access site, respectively. In a similar study, increasing the distance from 40 cm to 80 cm resulted in approximately a 25% reduction in radiation exposure.[7] Also, retreating from the X-ray tube during higher radiation exposure steps of procedures, such as during cine acquisition, can reduce radiation exposure dose by 9-fold.[8] Furthermore, posteroanterior and right anterior oblique working views relative to the patient compared to left anterior oblique views tend to reduce radiation exposure, as the provider is typically working on the right side of the table.[7] Another method proposed to achieve greater distance from the X-ray tube is the use of a passive robotic device for arterial puncturing.[25] In a study by Khan et al[25] of 30 fluoroscopy guided femoral artery punctures using a passive robotic device with manually actuated joints in comparison to hand puncture, fluoroscopy time was significantly reduced from 4.5 minutes to 4.3 minutes ($p = 0.002$). The average radiation exposure dose to the head of the provider was significantly reduced by 50% ($p < 0.001$).[25] The average radiation exposure dose to the hand of the provider was subsequently significantly reduced by 85% ($p < 0.001$).[25] The average radiation exposure dose to the dominant arm of the provider was significantly reduced by 42% ($p < 0.001$).[25] In addition to passive robotics, active robotics have also been studied in an effort to reduce occupational radiation exposure by increasing provider distance from the X-ray tube.[15]

In an effort to not only reduce occupational radiation exposure, but also eliminate the long hours and associated orthopedic health problems of wearing a lead apron while standing, Granada et al[15] investigated the use of a robotic assisted coronary angioplasty system. This robotic system has the capabilities to manipulate guidewires, balloons, and stents.[15] The robotic system is comprised of a remote radiation shielded interventional cockpit and a multicomponent bedside unit that allows the interventional cardiology provider to manipulate guidewires and rapidly exchange catheters.[15] The robotic system was used during 8 percutaneous coronary interventions and resulted in a radiation exposure reduction of 97.1% ($p < 0.012$).[15] Telerobotics could also be utilized to allow for single interventional cardiology providers to remotely pilot at multiple long-distance sites from a single location.[26] In a study by Patel et al[26] of 5 patients undergoing percutaneous coronary intervention 20 miles away from a robotic assisted coronary angioplasty system, procedures were completed successfully without complication. Robotic systems have also been studied for use during the severe acute respiratory syndrome coronavirus-2 pandemic, which would provide increased provider protection from coronavirus disease-19 in addition to radiation.[27] Further studies involving procedures with multiple wires and balloons and more intricate anatomy, such as tortuous blood vessels and severe calcification, are necessary to ascertain the full capabilities of robotic assisted angioplasty systems.[15]

Choice of procedural access site is also important when attempting to reduce occupational radiation exposure. In a study by Sciahbasi et al[28] of 777 cardiac catheterization procedures, radial artery access in comparison to femoral artery access resulted in a significant 2-fold increase in radiation exposure at the thorax level ($p = 0.02$). Radial artery access of 300 catheterization procedures is similar to the cumulative radiation exposure of 17 chest X-rays.[28] Provider position relative to the X-ray tube can influence radiation exposure by a factor of 40 during catheterization procedures.[28] The authors state that the provider's position relative to the X-ray tube and the complexity of the radial artery access may factor into the increased radiation exposure.[28] Technical skill in catherization is more demanding in radial artery access due to the tortuosity of the subclavian aortic axis, which can be present in up to 30% of patients.[28] This is unfortunate because coronary angiography and percutaneous coronary interventions with radial artery access, in contrast to femoral artery access, have been associated with decreased vascular complication and increased survival in patients with acute coronary syndrome.[28] Radial artery access in contrast to femoral artery access prevents 6 deaths for every 1000 patients treated.[28]

Fluoroscopy frame rate can also be adjusted throughout procedures and manipulation can significantly reduce radiation exposure by 40 to 60%.[7] Conversely, fluoroscopy frame rate reduction must be balanced by the need to obtain adequate, high quality images and should not be sacrificed in the pursuit of occupational radiation exposure reduction.[7] In a study by Abdelaal et al[10] of 363 cardiac catheterization procedures, lowering the fluoroscopy frames rate from 15 frames per second to 7.5 frames per second resulted in a significant 30% relative reduction of radiation exposure ($p < 0.0001$). These results were achieved without adversely effecting fluoroscopy time, procedural duration, or contrast volume.[10] This reduction can potentially avoid 6 years of occupational radiation exposure over a 30-year career in interventional cardiology.[10] Similarly, choices of interventional suite equipment, such as digital flat panel systems, are also associated with reduced radiation exposure to interventional cardiology providers as well as patients when compared to conventional equipment.[7]

In addition to reimaging radiation shielding, real time radiation exposure monitoring can also assist in reducing excessive occupational radiation exposure as it occurs.[13] Standard thermoluminescent personal dosimetry can take months for radiation values to become available and electronic personal dosimetry are typically only accounted for at the end of a procedure.[28] Both of these resources result in a delay of the necessary data required to make adjustments to radiation exposure in real time.[28] In a study by Best et al[7] of 380 cardiologists and Society for Cardiovascular Angiography and Interventions members, 76% reported wearing personal dosimetry always or most of the time, 8% never wear a personal dosimetry, and 16% reported occasionally wearing personal dosimetry. Furthermore, 18% reported not wearing personal dosimetry at some point in their career due concerns that they would exceed the radiation limit and 6% reported being forced to stop working at some point in their career because of exceeding the occupational radiation exposure limit.[7] As a potential solution, the Bleeper Sv device records radiation exposure and emits a real time warning sound in response to excessive radiation exposure.[13] In a study by Christopoulos et al[13] of 505 cardiac catheterization cases, use of the Bleeper Sv in comparison to the absence of it resulted in a 36% reduction in radiation exposure ($p < 0.001$). The real time signaling of radiation exposure excess allows providers to implement radiation exposure reduction modifications, such as reducing fluoroscopy frame rate, decreasing fluoroscopy time, maximizing provider distance from the X-ray tube and patient, and adjusting radiation shielding.[13]

Fluoroscopic X-ray imaging has been used to guide cardiac catheterization for the last 60 years, but the drawbacks of radiation and poor soft tissue contrast become increasingly apparent as procedures become more complex, resulting in increased radiation exposure due to longer procedure times and a need for greater anatomical visualization.[29] Imaging modalities without the exposure risk of ionizing radiation, such as magnetic resonance imaging (MRI) and ultrasound, are currently being investigated.[29] MRI has demonstrated the most promise recently due to the fact that ultrasound guidance has limited soft tissue contrast, acoustic shadowing effects, and a limited field of view.[29] In contrast, MRI improves soft tissue contrast and allows dimensional visualization and localization of infarction, ischemia, arrhythmogenic tissue, ablation lesions, and hemorrhages.[29] Although interventional MRI has been studied over the past 2 decades, the current MRI environment lacks many devices, such as MRI safe guidewires, delivery systems, and additional catheters necessary for proper clinical application.[29]

Novel forms of training have also been implemented in an attempt to reduce occupational radiation exposure, such as the provision of real time training without the associated radiation exposure. Interventional cardiology training front loads high rates of radiation exposure to providers with 60% more radiation exposure in the first year of fellowship in comparison to the second year, likely due to inexperience leading to longer fluoroscopy times.[10] A particular study by Popovic et al[30] employed coronary angiography simulation training to assess the transferability of experience from virtual reality to clinical practice. After 10 simulated cases, the average procedure time of 4 actual cases in comparison to cases without simulation training was significantly shorter ($p = 0.002$) and the average radiation exposure was significantly lower ($p = 0.001$).[30] Unfortunately, this method of simulation training is currently prohibitive due to the high cost of simulators and the lack of standardized curricula in interventional cardiology training.[30]

Radiation Safety Practices Relative to Pregnancy

Occupational radiation exposure in pregnancy can be minimized by taking similar approaches to radiation safety practices as before pregnancy. Pregnant interventional cardiology providers can utilize standard radiation shielding aprons and upgrade to larger sizes or layer aprons as their pregnancy progresses, though layering lead aprons may increase musculoskeletal risks already associated with pregnancy.[7] Some manufacturers also make radiation shielding aprons designed specifically for pregnancy that can accommodate the growing body habitus during pregnancy, but these aprons are not sufficiently marketed to buyers.[2,7] Additionally, it may be in a pregnant interventional cardiology provider's best interest to alter which procedures they perform in order to minimize radiation exposure risk. In comparison to coronary interventions, peripheral vascular interventions have a higher risk for radiation exposure due to longer procedure time, radiation shielding challenges, and shorter provider distance to the X-ray tube.[7] Minimizing cases that require peripheral vascular interventions is a potential option to reduce occupational radiation exposure risk during pregnancy. It would also be beneficial to alter procedural approaches, such as refraining from using radial artery access in favor of femoral artery access due to higher radiation exposures risks in the former.[7] Moreover, if a provider is planning to become pregnant and is concerned about their current occupational radiation exposure, they can preemptively wear personal dosimetry under radiation shielding to mimic fetal radiation exposure monitoring and make adjustments in order to further reduce occupational radiation exposure during pregnancy.[7] Pregnant interventional cardiology providers should also make sure to inform the proper institutional radiation safety personnel to make certain that they are supported and monitored throughout their pregnancy.[7]

Methods

A comprehensive systematic literature review was conducted using PubMed in order to gather the collection of literature referenced throughout this document. The search terms used in PubMed were ((("radiation scatter") OR (“scatter radiation”) OR ("occupational radiation") OR ("operator radiation")) AND ((“interventional”) OR (“interventionalist”))), (“occupational radiation”), (“operator radiation”), and (“interventionalist”), resulting in 245, 514, 125, and 549 results, respectively. The full text filter was also enabled. The literature search with these parameters resulted in a total of 1433 articles, albeit with redundancy in the articles displayed. After examining all of the results, a total of 84 articles were selected, which were eventually pared down to 15 articles. The references of collected articles and similar articles suggested in PubMed and were also explored and used to expand upon topics. In total, this document references 30 articles.

An effort to minimize content redundancy in regard to the similarity of information was taken in order to highlight novel and imaginative innovations and inventions rather than reviewing the multitude of various similar radiation safety practices that are already standard in most healthcare systems. This was achieved by selecting articles covering various methods of occupational radiation safety practices with a focus on radiation safety practices relative to body region and procedural aspects. Radiation safety practices relative to body region included personal and ancillary radiation shielding of the head, eyes, neck, thorax, hands, and pelvic area. Radiation safety practices relative to procedural aspects included body position relative to the X-ray tube, passive robotics, active robotics, adjusting fluoroscopy frames per second, real time radiation monitoring, MRI guided procedures, simulation training, and mini courses on occupational radiation safety practices. A similar method was employed in selecting articles regarding the health risks of occupational radiation exposure, though to a lesser extent. These articles were selected to demonstrate the breadth of potential adverse effects of occupational radiation exposure with less focus on the depth of these effects.

Discussion

Unfortunately, some interventional cardiology providers utilize suboptimal radiation safety practices due to perceived inconveniences and discomfort as well as the belief that optimal radiation safety practices may risk image quality and procedural efficiency as a tradeoff, which can lead to longer radiation exposure times during procedures.[6] Furthermore, some interventional cardiology providers are purposefully noncompliant with wearing required personal dosimeters in order to avoid problems with regulatory authorities if they are at risk of accruing too much occupational radiation exposure.[6] In a study by Rose and Rae[2] of 54 interventional medical providers, all forms of radiation shielding were demonstrated to be used inconsistently by 92.6% of the participants. Lack of appropriate sizing, availability, and procedural dexterity were high on the list of reasons for inconsistency.[2] In addition, providers of smaller stature or varying body habitus have particular difficulty with appropriate sizing.[2] A similar study of urology residents corroborated the lack of availability as a reason for inconsistent use.[14]

Although radiation safety is increasingly included in interventional cardiology fellowship training, relative objectives are often considered satisfied by no more than an hour lecture or web-based training module.[3] Cardiologists do not always receive the same residency training in radiobiology, radiophysics, and radiation protection as interventional radiologists, though they are exposed to similar levels of radiation.[4,6] As a result, fellows may devolve into inconsistent and inadequate radiation safety practices, which are seldomly corrected by their colleauges or attending physicians.[3] This gap in knowledge makes it difficult to uphold guidelines that require providers to be able to recognize patients and circumstances with increased risk of radiation induced injuries.[19] It is also recommended that providers not only be able to audit their own occupational radiation exposure, but also the occupational radiation exposure of the other interventional suite staff.[19] The continual increase in procedural fluoroscopy time requires radiation safety practices to keep pace, and the implementation of a culture of radiation protection can provide the management and organizational structures, policies, and operating procedures in order to sustain a safe interventional suite environment.[2]

Traditionally, healthcare managers and interventional suite staff often have competing priorities, which can result in a challenging relationship.[4] Healthcare managers may prioritize budgets, profit margins, and cost saving measures, rather than safety measures that may include new equipment and equipment maintenance, resulting in a barrier against the development of a culture of radiation protection.[4] When management and staff can agree on the importance of radiation safety practice, designated healthcare managers can help to establish a culture of radiation protection by ensuring radiation shielding is available for providers of every stature and body habitus and that providers are competently trained and compliant with proper utilization.[2] Organizational structures would support radiation shielding provision and maintenance as well as personal dosimeter monitoring and evaluation, training, and education.[2] Additionally, gender disparity and hierarchal power imbalances may hinder interventional suite staff, such as nurses and radiographers who are predominantly female, from addressing inadequate radiation safety practices of providers, resulting in another barrier.[4] The United Kingdom mandates all interventional cardiology providers attain a certificate from the Radiation Medical Exposure Regulations signifying sufficient training to properly protect employees from occupational radiation exposure before using radiation equipment in the interventional suite.[7] Hospitals in other countries, including the United States, have implemented similar policies.[7] A combination of similar certificates, continuing medical education activities, robust formal training curricula, and establishing a culture of radiation protection can help to ensure consistency in radiation safety practices.[4]

Conclusion

Further studies are necessary to validate much of the data presented in this document. It is possible that some providers made an effort to employ more optimized radiation safety practices than they normally would in their usual practice. Subsequent research could investigate ergonomics and cost analyses of new equipment, which might address some of the issues with discomfort and consequent failure of systems wide adoption of novel occupational radiation reducing measures.[14] It would also be beneficial to implement an international standard for measuring the lead equivalence and transmission values with a range of photon energies for radiation shielding, which would encourage confidence in providers that the radiation shielding they are expecting is indeed what they are receiving.[20] A focus on longitudinal studies would be valuable considering the longest follow up study for providers with occupational radiation exposure was 24 years, resulting in sparse inconclusive data relative to the long-term effects of chronic low dose occupational radiation exposure.[6] Considering radiation exposure during interventional cardiology procedures are largely asymmetrical and often leave the left side the most vulnerable, future research should also investigate asymmetrical effects of occupational radiation exposure.[11] In addition to recruiting participants for these studies, the United States and some European countries compile large scale up to date registries that can link occupational radiation exposure with death and other hospitalization records.[11]

Although occupational radiation exposure risks have largely been reduced through utilization of personal and ancillary radiation shielding and improved procedural aspects, radiation is invisible and adverse effects may not present until years later, which may result in interventional cardiology providers becoming complacent and less vigilant with radiation safety practices.[6] Furthermore, the perception of occupational radiation exposure risks may still be insufficient in many interventional cardiology practices, resulting in inadequate application of radiation safety practices.[11] Unfortunately, first generation interventional cardiology providers 30 to 40 years ago were often under the impression that occupational radiation was not a warranted concern, and the field has been diligently reversing that ideology as every new data set presents with the safety of everyone in the interventional suite in mind.[11] Ultimately, the greatest occupational radiation exposure reductions result from the reduction of radiation exposure to the patient, as majority of the radiation exposure is due to the radiation scatter from the patient.[6] This document was designed to highlight the potential health risks of occupational radiation exposure on interventional cardiology providers and the various radiation safety practices implemented to reduce those risks.

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