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REVIEW

Radiation Management in Coronary Angiography: Percutaneous Coronary Intervention for Chronic Total Occlusion at the Frontier

Glenn R. Ison, Dip Med Rad [a], Usaid Allahwala, FRACP [b], James C. Weaver, FRACP, PhD, FCSANZ [c*]

[a]Department of Cardiology, St George Hospital, Sydney, NSW, Australia
[b]University of Sydney, Sydney, NSW, Australia
[c]Department of Cardiology, Royal Prince Alfred Hospital, Sydney, NSW, Australia

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The usage of ionising radiation in medical investigations and procedures continues to increase. Cardiologists are responsible for a disproportionately high amount of this radiation, and the performance of percutaneous coronary intervention for chronic total occlusions (CTO PCI) often requires particularly high radiation doses. Consequently, both patients and proceduralists are potentially being exposed to harmful doses of radiation. This review discusses the potential dangers of radiation exposure during CTO PCI, as well as techniques to minimise radiation dose to the patient and proceduralist. Specific attention is paid to recent innovations in real-time dose monitoring and X-ray system developments that afford considerable dose savings during routine PCI as well as CTO PCI.

Keywords Radiation dose • Radiation minimisation • Chronic total occlusion • Noise reduction technology

Introduction

> ''X-rays . . . I am afraid of them. I stopped experimenting with them two years ago, when I came near to losing my eyesight ...''.
> Thomas Edison (August 1903).

In 1895, the discovery of X-rays by Wilhelm Conrad Roentgen provided the scientific basis for medical imaging using ionising radiation and was, therefore, an essential precursor to modern day imaging in the cardiac catheter laboratory. The significance of this discovery was acknowledged by the awarding of the first Nobel Prize in 1901. Over the last 100 years there have been dramatic advances in X-ray technology and the current cardiac catheter laboratory, with flat panel detectors and large digital displays, bears little resemblance to the original systems of Image Intensifiers and Cine film. Despite these advances, radiation exposure during medical procedures is as important as ever. Furthermore, the true lifetime risk of adverse effects, to either the proceduralist or patient, from high radiation doses remains incompletely understood.

The evolution and dissemination of contemporary percutaneous coronary intervention for chronic total occlusions (CTO PCI) provides renewed emphasis on radiation dose, management and monitoring for both patients and cardiologists. In addition, radiation management technology and techniques refined during CTO PCI are well placed to re-focus attention on this often neglected issue during routine PCI.

The increasing availability and utilisation of medical imaging using ionising radiation has resulted in patient exposure

*Corresponding author at: Cardiology Department, Royal Prince Alfred Hospital, Missenden Rd, Camperdown, NSW, 2050, Australia., Email: james.weaver@health.nsw.gov.au

to higher cumulative radiation doses. Between 1980 and 2006 there has been a 700% increase in radiation dose from medical procedures and investigations [1]. Cardiologists are disproportionately responsible for this increase with cardiac investigations comprising 40% of the annual medical radiation dose to the US population [2]. In an adult cardiac patient, coronary angiography accounts for 12% of investigations but 48% of radiation dose [3]. These temporal changes in radiation usage may have adverse effects on the individual patient. Potential damage from ionising radiation includes either deterministic or stochastic injuries. The linear dose-response relationship of deterministic radiation injury makes them predictable when above a minimum threshold. These include skin changes, cataracts, decreased white cell count, fibrosis and sterility [4]. The stochastic injury of major concern is the long-term genotoxic effects which include genetic mutations, genomic instability and malignant transformation [5]. The probability of their occurrence is related to dose but clinical manifestations are dose independent [4].

The dose to the procedural cardiologist may also be of increasing importance. An interventional cardiologist is exposed to two to three times more doses than a radiologist [6]. Over a career this equates to 50–200 mSv, corresponding to a whole body dose equivalent of 2,500–10,000 chest X-rays [7]. It is now widely agreed that occupational exposure to the lens of the eye increases the risk of cataract formation. In a systematic review and meta-analysis the prevalence of cataracts in interventional cardiologists was 36% [8]. The increased risk was confined to posterior subcapsular cataract with a relative risk of 3.21 compared to unexposed controls ($p < 0.0001$). The risk of malignancy at levels of exposure >100 mSv is well documented [9,10] yet the consequences of chronic ''low dose'' exposure below these levels are less clear. Anecdotal evidence suggests there is sufficient concern to warrant further research and greater diligence in monitoring outcomes of health care workers in the cardiac catheter laboratory. The ''Healthy Cath Lab Study Group'' recently reported results of a questionnaire completed by 466 radiation workers with median 10 years radiation exposure [7]. Prevalence of a range of health related endpoints, including cataract and malignancy, were compared with 280 controls that did not have occupational radiation exposure. Radiation workers (including nursing staff and technicians) were more likely to have cataracts (odds ratio 6.3, $p = 0.01$) and a trend towards higher rates of malignancy ($p = 0.09$). Physicians highly exposed to radiation, compared to those with lower exposure or controls, had borderline higher rates of malignancy (odds ratio 4.5, $p = 0.06$) and higher rates of cataract (odds ratio 9, $p = 0.004$) [7]. There has been renewed focus on the risk of brain tumours in those performing coronary angiography, due to the proximity and relative lack of shielding protection to the left side of the proceduralist's brain. Early reports suggested increased rates of brain tumours in physicians performing fluoroscopy [11,12]. However, these observations gathered support when Roguin et al. reported a cohort of nine cases of brain tumours in physicians performing fluoroscopy procedures [13]. A follow-up was published a year later reporting 31 cases of which 85% were left sided; increasing the likelihood of the relationship with radiation exposure [14]. The absence of data on what proportion of the total exposed population (interventional cardiologists or radiologists) these cases represent, prevents interpretation of a causal link. Based upon the available data it has been proposed that the attributable lifetime risk of a malignancy is in the order of 1 case per 100 exposed proceduralists [15,16]. Whilst the additional risk of malignancy in interventional cardiologists remains contentious, there is direct evidence that scatter radiation is having an effect. Interventional cardiologists have altered levels of oxidative stress and consequently enhanced antioxidant defence and increased susceptibility to apoptotic induction compared with age matched controls [17].

It is important to acknowledge that the validity of a causal relationship between malignancy and chronic occupational radiation dose of less than 100 mSv has been questioned. Not only is there a lack of biological evidence supporting the relationship, there is no robust confirmatory epidemiological data in humans [5]. In contrast, a hormesis model has been proposed where a radiation dose at these occupational levels may be protective from the development of malignancy [4]. It is likely that, at low dose chronic exposure, there is DNA damage produced by irradiation, yet the endogenous protective repair and cell death mechanisms have the capacity to maintain DNA integrity [5,18]. These same protective mechanisms are inadequate at higher radiation doses and it is likely that this dose threshold has inter-subject variability. Large-scale observational prospective studies are ongoing in this area.

It is crucial to balance the potential risk of radiation exposure during medical procedures with the clinical benefit of the test. When an investigation or intervention is appropriately indicated it is of paramount importance that the correct radiation dose be applied in order to obtain an optimal outcome for the patient. For a diagnostic procedure the dose required is that needed to provide an accurate result that can be fully interpreted. An interventional procedure needs the minimum dose needed to complete the procedure successfully. Low dose investigations that do not attain the desired outcome are inappropriate and may result in additional procedures (conceivably with higher dose), complications, or adverse clinical outcomes. Therefore, the focus within the cardiac catheter laboratory must be the *balance* between image quality and radiation dose; the aim being to perform a diagnostic and successful procedure, whilst minimising the dose to the patient and proceduralist. This is the premise for the As Low As Reasonably Achievable (ALARA) principle.

Measurement of Radiation Dose

For physicians working with ionising radiation there are a number of clinically important definitions required. Modern cardiac catheterisation imaging systems display a variable number of parameters. Both the parameters displayed and

units used vary between vendors, which is a significant issue for physicians who may alternate between different laboratories. The most widespread parameters (Figure 1) are Reference Point Air Kerma (AK) and Dose Area Product (also known as Air Kerma Area Product). AK is the energy extracted from the X-ray beam per unit mass of air at the predefined interventional reference point, which is usually 15 cm below the isocentre [19]. AK is measured in Gray and, in the absence of skin dose measurement, provides the closest indication of deterministic skin injury risk. Skin dose is a more accurate measure of skin injury risk, however, accurate measurement in the clinical setting has been challenging. Integrated real-time skin dose maps are now commercially available and include the Dose Tracking System (Canon Medical Systems, Otawara-shi, Tochigi-ken, Japan) [20]. This system incorporates a calculation of dose emitted from the tube, patient characteristics such as body mass index and body shape, C-arm angulation as well as acquisition characteristics such as collimation and filtration to approximate cumulative and peak skin dose.

Dose Area Product (DAP) is the dose emitted from the entire X-ray tube and is measured in Gray.cm^2 [20]. It is suggested that DAP may be a better reflection of random stochastic radiation effects [19]. Other parameters often displayed are fluoroscopy time (expressed in minutes), cathode current (expressed in milliAmps) and tube voltage (expressed in kiloVolts). Increases in cathode current or tube voltage, increase or decrease patient dose respectively and are predominantly established during system setup. Based upon these pre-set protocols, the system will automatically adjust either variable in an attempt to optimise image quality when, among other variables, patient thickness changes.

Effective dose is not displayed on cardiac catheter imaging systems but is used in the literature to estimate the stochastic risk to an individual [21] from an investigation requiring ionising radiation. The effective dose takes into account the dose received by an organ (or sum of organs) and the radio sensitivity of that tissue [21]. It is measured in Sieverts and is estimated by statistical modelling. Effective dose provides the best quantitation of the whole body radiation exposure and therefore can be used to compare the dose received during different investigations.

There are a number of situations where patient dose, patient skin dose and operator scatter dose may vary substantially. Dose emitted from the tube may vary from skin dose when there are multiple changes to a non-overlapping acquisition angle. Extreme angulation of the C-arm during acquisition in certain projections will disproportionately increase scatter dose to the operator. This is particularly the case in the left anterior oblique projection with either cranial or caudal offset.

Radiation Dose During CTO PCI

Average radiation dose during coronary angiography and routine PCI varies between studies and is influenced by many variables. Representative values for both the patient and proceduralist during common procedures are outline in Table 1. Expression of Effective Dose values in relation to numbers of chest X-rays (CXR's) or years of background radiation provides a perspective that the patient could comprehend; a concept that may be relevant for informed consent. Independent predictors of high dose during coronary angiography are patient body mass index (BMI) [20,22], PCI compared with diagnostic angiography [20,22–24], previous coronary artery bypass graft (CABG) [20], lesion complexity [25] and CTO PCI [25,26]. In challenging CTO cases the cumulative radiation dose may reach up to 10 Gray [27]. Dose threshold levels requiring patient follow-up due to potential risk of deterministic skin injury are outlined in Table 2 [21]. Incorporating a representative subset of recently published studies with procedures performed by expert operators indicates that a substantial proportion of patients

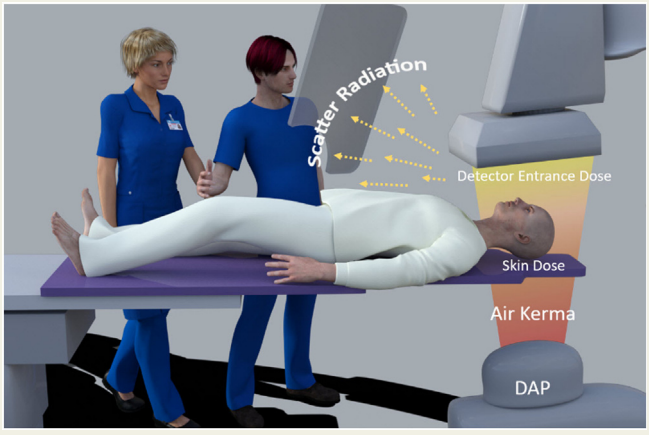

Figure 1 Schematic representation of parameters used to measure dose. Site of parameter measurement/calculation is indicated by position of parameter display on figure.
Abbreviations: DAP, dose area product.

Table 1 **Representative Effective Dose for the spectrum of cardiac investigations.**

Procedure	Patient			Proceduralist
	Effective Dose (mSv)	Equivalent CXR's	Equivalent background radiation	Dose (μSv)
CXR	0.02	1	2–3 days	N/A
Diagnostic Angiography	7 (2–16)[a]	350	2.9 years	0.02–38[c]
PCI	15 (7–57)[a]	750	6.3 years	0.17–31[c]
CTO PCI	41 (27–52)[b]	2045	17 years	0.3–170[c]
99mTc-Sestamibi scan	9.4[a]	470	3.9 years	N/A

Table adapted from Picano et al. [15].

Background radiation due to environmental sources is assumed to be 2.4 mSv per year.

Abbreviations: Sv, Sieverts; CXR, chest X-ray; CTO, chronic total occlusions; PCI, percutaneous coronary intervention.

[a]Values are expressed as mean (range in the literature) as outlined by Mettler et al. [63].

[b]Mean Effective Dose derived from average dose area product (DAP) reported by Wilson et al. [29], Christopoulos et al. [28] and Werner et al. [30]. Effective dose calculated by DAP ($Gy.cm^2$) x 0.2 [15].

[c]Proceduralist Effective Scatter Dose is expressed as a range as outlined by Picano et al. [64].

receive a dose that puts them at risk of skin injury (Figure 2A and B) [28–34]. Predictors of prolonged fluoroscopy time during CTO PCI are previous CABG, right coronary artery chronic total occlusion (RCA CTO), use of the retrograde approach and operator inexperience [35].

Systematic follow-up to evaluate radiation skin damage is rarely performed after CTO PCI and, therefore, not commonly reported in the published literature. Evidence supporting under-reporting is demonstrated in a meta-analysis of 65 studies incorporating 18,061 patients. Only 11 studies reported skin injury with an incidence of less than 0.01% [36]. It is likely that rates are significantly higher if a dedicated routine assessment of skin injury was performed and less severe transient skin changes included. Wei et al. performed a retrospective analysis of 2,454 PCI procedures, of which 238 underwent CTO PCI, and found nine that required surgery for a non healing radiation ulcer [37]. The rate in CTO PCI was 2.1% and in non-CTO lesions 0.18% with a manifestation time delay after the procedure between 3 weeks and 3 months.

The effective dose received by the patient during CTO PCI is not inconsequential and may potentially increase the lifetime risk of malignancy. Godino et al. [38] estimated the lifetime risk of malignancy in 543 patients having CTO PCI and compared them with 555 patients having primary PCI for ST elevation myocardial infarction. The projected lifetime risks of malignancy increased as the patients got younger and in the 45–49 year-old age group the risk of both lung and bone marrow malignancy were double in the CTO patients compared to those presenting with myocardial infarction.

There is a trend towards transradial access for CTO PCI and the effect this may have on radiation dose to either the patient or proceduralist has not been fully clarified. In coronary angiography and routine PCI a meta-analysis demonstrated a small but significant increase in radiation dose with transradial access [39]. Recently published studies have suggested no difference in fluoroscopy time and/or radiation dose with transradial access for CTO PCI compared with transfemoral access [40–42].

Table 2 **Threshold levels placing the patient at high risk for deterministic injury and therefore requiring follow-up.**

Measurement	Dose
Fluoroscopy	60 min
Dose Area Product	50000 $cGy.cm^2$
Reference Point Air Kerma	5 Gy
Skin Dose	3 Gy

Values are derived from Stecker et al. [21]. Due to an individual's biological variation they are only indicative, with patients possibly at risk below these levels and injury not universal above the thresholds.

Abbreviations: Gy, Gray.

Radiation Dose Minimisation Strategies

The development of new techniques for CTO PCI and the subsequent expansion of this procedure warrants a re-appraisal of radiation protection and minimisation techniques. There are many dose minimisation strategies that are well documented to reduce procedural radiation dose (Table 3). The fundamental concepts of maximising the distance between staff and the X-ray source as well as shielding to reduce scatter radiation are at least as important in CTO PCI as routine PCI. Many of the dose minimisation strategies reduce dose to both the patient and proceduralist. Some, such as personal protective equipment reduce dose exclusively to the proceduralist and others such as radioprotective drapes reduce proceduralist dose but may, paradoxically, increase scatter dose to the patient [43]. Use of a sterile

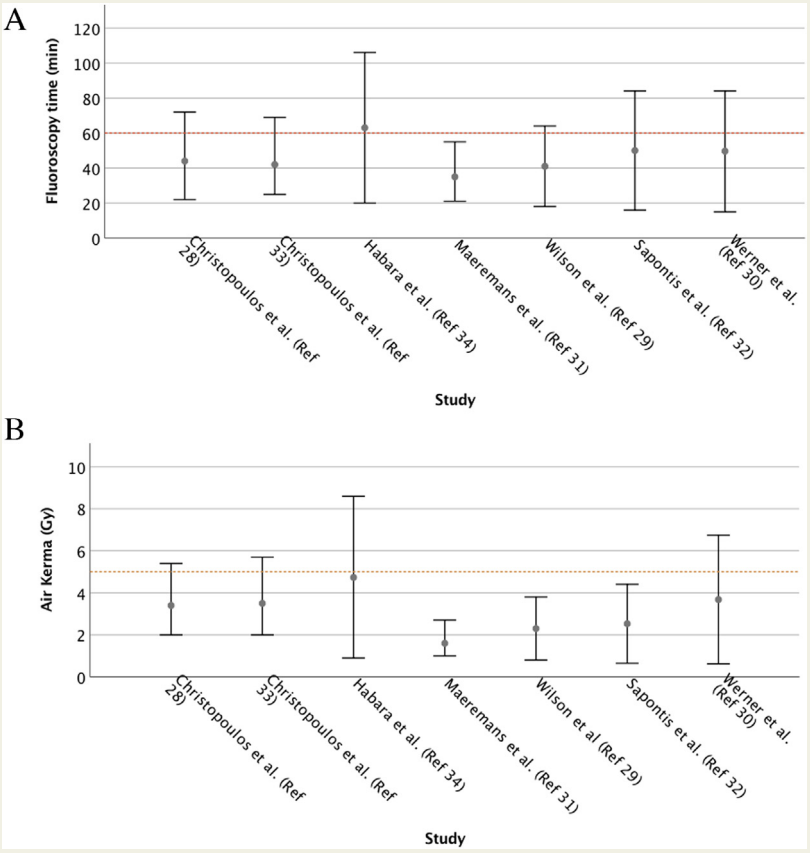

Figure 2 (A) Fluoroscopy Dose During CTO PCI. Representative studies were selected from expert operator registries published between 2015 and 2018. Lines represent median and interquartile range or mean and standard deviation as published in the original paper. Reference line represents high dose as defined by fluoroscopy time greater than 60 minutes. (B) Air Kerma Dose during CTO PCI. Reference line represents high dose as defined by Air Kerma greater than 5 Gray. Abbreviations: CTO, chronic total occlusions; PCI, percutaneous coronary intervention.

disposable bismuth containing radioprotective drape (Radpad, Worldwide Innovations & Technologies Inc. Overland Park, KS, USA) reduces dose to the eyes 12-fold [44]. When used in CTO PCI it can reduce proceduralist dose to levels seen in non-CTO PCI despite a greater than three-fold increase in total dose emitted from the tube [45]. Custom made reusable lead pelvic drapes also provide effective scatter dose reductions [46] with improved cost effectiveness.

For protection of the proceduralist's cranium and eyes the most effective equipment is a correctly positioned ceiling-suspended shield [47]. Lead glasses provide additional protection, especially if the ceiling-suspended shield is not constantly repositioned for optimal protection [47]. Radiation-absorbing surgical caps are unlikely to provide any additional benefit, which is thought to reflect the inferior deflection of scatter radiation from the patient towards the proceduralist's head [48].

Whilst many of these dose minimisation strategies are well recognised by cardiologists, they are often neglected which highlights the need for real-time radiation dose feedback. Currently available systems include the integrated real-time Dose Tracking System (Canon Medical Systems, Japan), which provides a visual avatar depicting a derived peak and total skin dose. In a consecutive real-world cohort of patients the Dose Tracking System, compared with control, reduced peak skin dose by 46% in those having PCI [20]. Audible warning devices indicating proceduralist dose are also available and result in significant reductions in radiation dose during PCI which included CTO PCI in 7% of cases [49]. Similarly, systems such as the Raysafe personal dosimeter (Unfors Raysafe, Cleveland, OH, USA), provide real-time visual feedback of proceduralist's dose. Taken as a whole, this range of tools providing real-time feedback is effective at prompting improvements in proceduralist-dependent radiation minimisation strategies.

Recent developments have seen improvements in catheter laboratory imaging system technology with specific refinements focussed on radiation safety. Simply having a more modern (younger) imaging system provides radiation dose savings during CTO PCI [50,51]. However, there may be vendor specific benefits due to a focus on dose reduction technology. The Allura ClarityIQ system (Philips Healthcare, Best, The Netherlands) includes an algorithm-based low dose protocol that incorporates ''noise reduction technology''

Table 3 Radiation minimisation strategies during coronary angiography.

Intervention	Notes
Pre-procedure	
Physician radiation education	Ideally recurring
Procedural planning	CTO PCI algorithm may shorten procedure
Remove anti-scatter grid	In low BMI patients
Catheter laboratory updates	Multidisciplinary team approach
Peri-procedure	
Limit fluoroscopy and cine acquisition	Low frame rate fluoroscopy and fluoroscopy store
Avoid magnification	Less important with digital imaging
Avoid steep C-arm angulation	Certain views specifically increase scatter to operator
Use collimation and filters	
Table height high and image detector as close to patient as possible	High table height positions patient at maximal distance from X-ray source. Image detector close to patient optimises number of photons reaching detector and therefore reduces tube output
Maximise protective shielding[a]	Continually re-adjust
Personal protective equipment Eg. Lead glasses[a]	
Radioprotective drapes[a]	Significant dose reduction to proceduralist
Real-time dose monitoring[a]	Either patient skin dose maps, proceduralist visual monitor or audible beepers
Post-procedure	
Routine surveillance for high dose exposures	Patient safety
Quality assurance monitoring and feedback	Reinforces radiation message to proceduralists continuously

Abbreviations: CTO, chronic total occlusion; PCI, percutaneous coronary intervention; BMI, body mass index.
[a]Refers to interventions that predominantly reduce proceduralist dose.

(NRT). The software based noise reduction algorithms and hardware upgrades potentially reduce dose through two mechanisms:

1 Enhancements in spatial and temporal filtering that decrease X-ray dose whilst maintaining image quality [52]. ''Noise'' is a fundamental but unwanted and random phenomenon of X-ray systems. The random nature of background noise is in contrast to the more consistent signal seen from X-ray absorption of anatomical structures within the field of interest [52]. Therefore, NRT exploits these different characteristics to remove a large part of the image noise (i.e. that which does not correspond to known coronary anatomy via pixel matrix interrogation). This is performed by spatial averaging (multiple pixels within one image) and temporal averaging (one pixel over multiple images) whereby inconsistent readings are filtered out during image post processing. The recent advance, compared with previous iterations of the same system, is the ability to rapidly process large amounts of data [52] that provides the capacity to perform spatial averaging over larger areas and temporal averaging over longer periods. Essentially, by variable filtering of each frame, the system enhances structures of interest (such as coronary arteries and guide wires) whilst subtracting noise and unwanted background structures. Better image post processing allows a dose reduction for similar image quality.
2 The system provides the capacity, with various pre-sets, to modify tube parameters such as levels of copper inherent filtration, frame rate and pulse width [52,53].

NRT therefore provides radiation dose savings through proceduralist independent algorithms and other strategies that require active interaction between the proceduralist and machine.

Compared with other systems the radiation dose saving seen with the NRT system has been confirmed with an anthropomorphic phantom [53] and extended to patients having PCI [22,24,54]. There have been two studies specifically assessing the role of NRT in CTO PCI. The implementation of the Allura ClarityIQ system reduced AK by 36% in 187 patients with CTO PCI [52]. A similar impressive dose reduction was seen in 276 patients having CTO PCI where the Allura Clarity delivered a 48% reduction in AK despite higher procedural complexity [51]. The later study also introduced the concept of an Efficiency Index (EI) that represents the number of fluoroscopy minutes to reach a total AK of 1 Gray. Therefore, EI is proportional to X-ray system efficiency [52], which is particularly important in CTO PCI where fluoroscopy constitutes a relatively high proportion of total dose. Both studies demonstrated improved EI with the Allura Clarity NRT system compared with the older systems.

The impact of NRT on image quality has been quantitated in a phantom study [55]. During both cine and fluoroscopy modes there was a mild deterioration in image quality,

measured as signal-to-noise ratio, with the newer Allura Clarity system compared with a similar system without NRT. To balance the beneficial effects of dose saving with deterioration in image quality, the authors expressed this as a ratio and calculated the ''Figure of Merit''. This favoured the low fluoroscopy setting of the newer Allura Clarity system suggesting the dose saving is of greater magnitude than the loss of image quality [55]. The objective drop in image quality seen in this phantom study was not replicated by proceduralists reporting on a semi-quantitative Likert-like scale during CTO PCI [52]. Furthermore, CTO PCI success rates remained unchanged [52] or improved [51] after implementation of the NRT system that suggests any potential fall in image quality is not of clinical relevance.

An improvement in imaging post processing with other vendor systems has allowed alternative methods of radiation dose reduction to be evaluated. This includes removal of the anti-scatter grid which resulted in considerable dose savings with similar image quality in normal or low BMI patients having PCI [56]. The anti-scatter grid is located within the image detector and filters non-aligned scattered photons prior to image post processing to decrease noise and improve image quality. Unfortunately, the grid itself increases tube output [57] and the advent of better noise reduction post processing compensates for a fall in image quality when it is removed.

Improvements in image quality have allowed the use of lower fluoroscopy pulse rates and acquisition frame rates. CTO PCI, when compared to routine PCI, has a disproportionately high proportion of fluoroscopy time. Lower fluoroscopy pulse rates can result in large radiation dose savings and therefore permit longer procedures. Reducing fluoroscopy pulse rate from 15 pulses-per-second (pps) to 7.5 pps, resulted in a 30% reduction in proceduralist dose and 19% reduction in DAP during diagnostic angiography and PCI [58]. During routine PCI the fluoroscopy pps has been successfully reduced to as low as 3 pps [59]. From a practical perspective, the lowest fluoroscopy pulse rate should be used that allows successful completion of that part of the procedure. It, therefore, is reasonable to place guide catheters when initiating the procedure using a low pulse rate (3–7.5 pps depending upon system capacity). Wiring of the CTO segment will require higher pulse rates and better image quality (often 10–15 pps) as too will crossing of collaterals during retrograde procedures. After wiring of the CTO the pulse rate can again be reduced for the less complex aspects such as passing balloons and stents. Using fluoroscopy store will record important aspects of the procedure without the extra radiation associated with cine acquisition.

Another important influence on radiation dose is beam angulation. Fluoroscopy dose is particularly sensitive to even small movements to more extreme angulation [60]. Those performing CTO PCI need to be aware of the appropriate non-overlapping angle that produces the lowest possible tube output and scatter. In general, left anterior oblique (LAO) and caudal projections have higher radiation dose (to patient and proceduralist) than right anterior oblique (RAO) and cranial projections [60]. For example, passing and engaging guide catheters in the anteroposterior (AP) rather than LAO 30° results in a three-fold reduction in dose [60]. Favouring an AP/Cranial 0°/30° instead of LAO/Cranial 60°/20° provides a 2.6-fold reduction in patient dose and five-fold reduction in proceduralist dose [61]. At certain times during the procedure, imaging can be performed using less cranial or caudal angulation without compromising success. Simply moving from RAO/caudal 20°/30° to RAO/caudal 15°/20° provides a fluoroscopy dose saving of 29% [60]. This is significant during a single CTO PCI but even more important for a proceduralist's lifetime dose.

Guide for Dose Management

In recent times there have been recommendations for a threshold at which radiation dose should prompt the proceduralist to abandon a CTO PCI case. A procedure time of greater than 3 hours or AK greater than 5 Gray, unless the procedure is well advanced and making satisfactory progress, have been proposed as thresholds [62]. Clinical follow-up should be arranged when above these thresholds and is usually recommended at 2–4 weeks after exposure [47].

Future Directions

Radiation management and dose minimisation is not limited to CTO PCI but, rather, is an important aspect of all procedures performed in the cardiac catheter laboratory. The performance of CTO PCI is associated with higher radiation doses where ''high dose'' thresholds are not infrequently attained and this means additional attention needs to be afforded to radiation management. Often the longest and most complex PCI cases are the ones where the greatest dose savings can be attained. Consideration should be given to radiation management when planning a case and during informed consent of the patient.

In this era of personalised medicine, there are opportunities to tailor cardiac catheter laboratory setup to both the patient and proceduralist. Opportunities exist to alter X-ray system setup to image with a different emphasis during certain aspects of the case. For example, fluoroscopy with a low dose (cathode current or mA) and low pulse rate with normal pulse width and extra inherent filtration may be appropriate during guide engagement and simple wiring. Conversely, whilst wiring the CTO segment or collateral channels, a higher fluoroscopy dose and pulse rate with a narrower pulse width and less inherent filtration will improve image quality. Centres that perform CTO PCI would benefit from a cardiac catheter laboratory team that includes a radiographer and radiation scientist with a special interest in this area. Engagement with vendors producing cardiac catheter laboratory imaging systems will also allow further development and refinement of tailored protocols.

The establishment and maintenance of a local quality assurance program to monitor radiation dose, training and outcomes is an important responsibility of the cardiologist [47]. Currently, in Australia, there is no established national system of radiation dose reporting, dose thresholds where mandatory follow-up is required and no standardisation of vendor dose reporting. Opportunity exists, particularly in centres performing CTO PCI, to show leadership in developing a local and national framework in these areas.

Finally, the adoption of technology and techniques that minimise radiation is an important aspect of optimal CTO PCI. Investment in real time radiation monitors, up to date imaging systems and ongoing staff education are crucial aspects of radiation dose management. Complex CTO cases in patients with a high body mass index may benefit from referral to a centre where this holistic approach to radiation minimisation is feasible.

Conclusion

Ionising radiation is playing a greater role in medical imaging and this is no more evident than in cardiac catheterisation. CTO PCI is at the forefront of high radiation dose thresholds and needs to be at the frontier of radiation dose minimisation. For the safe and effective performance of CTO PCI it is prudent to incorporate radiation management as a priority. Therefore, technology for radiation minimisation should be included in the CTO PCI ''toolbox''.

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