Reduction of Radiation Risk to Interventional Cardiologists and Patients during Angiography and Coronary Angioplasty

Mohsen Mohammadi, MD\textsuperscript{1}, Leili Danaee, MD\textsuperscript{2}, Effat Alizadeh, MD\textsuperscript{3}\textsuperscript{*}

\textsuperscript{1}Department of Medical Radiation Science, School of Paramedicine, Shahid Beheshti University of Medical Sciences, Tehran, Iran.
\textsuperscript{2}Department of Medical Physics, Faculty of Medicine, Tabriz University of Medical Sciences, Tabriz, Iran.
\textsuperscript{3}Department of Medical Biotechnology, Faculty of Advanced Medical Sciences, Tabriz University of Medical Sciences, Tabriz, Iran.

Abstract

Radiation risk allied to invasive cardiology is relatively high, and protecting both patients and cardiologists is necessary. The aim of this review is to discuss how to better protect patients and cardiologists against radiation exposure. We performed a global search on PubMed, Science Direct, and Scopus databases via keywords of “interventional cardiologist”, “patient”, “radiation”, and “exposure” and then performed an overview of the main strategies for risk reduction among interventional cardiologists and exposed patients. The 1st line for protection is awareness of both radiation risk factors and exposure doses and how to manage and minimize exposure levels. In conclusion, radiation-attenuating techniques can effectively reduce occupational/treatment radiation exposure to both operators and patients in cardiology interventions.

This paper should be cited as: Mohammadi M, Danaee L, Alizadeh E. Reduction of Radiation Risk to Interventional Cardiologists and Patients during Angiography and Coronary Angioplasty. J Teh Univ Heart Ctr 2017;12(3):101-106.

Keywords: Radiation exposure • Cardiologists • Patients

Introduction

Ionizing radiation is necessary for invasive cardiology procedures such as coronary angiography, percutaneous coronary intervention (PCI), and electrophysiological diagnostics or therapeutics.\textsuperscript{1} Radiological examinations are necessary for therapeutic processes.\textsuperscript{2, 3} About 12% of all radiological examinations are interventional cardiac procedures, leading to exposure to the highest radiation dose (up to 50% of the total collective effective dose). Therefore, such examinations are a serious cause for concern for interventional cardiologists and patients given the high exposure.\textsuperscript{4}

According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report in 2008, fluoroscopic procedures are considered the largest source of medical occupational exposure. The American Heart Association (AHA) Science Advisory specified the reference doses of cardiology examinations in 2009, and in 2010 the American College of Cardiology (ACC) committee also highlighted the need for the development of safer radiation techniques in cardiology.\textsuperscript{5}
The mean radiation exposure for left ventriculography and coronary angiography is equivalent to about 300 chest X-rays, a peripheral artery intervention to 1500 to 2500, a coronary stent to 1000, and finally in a cardiac radiofrequency ablation from 9000 to several thousands. The cardiologist is the only person involved in most of the procedures, without any training regarding radiation protection. Furthermore, interventional cardiologists are usually exposed to the highest dose of ionizing radiation among the medical staff. It is estimated that the exposure per head per year of this group is 2 to 3 times higher than that of radiologists. Recent reports have documented that an experienced interventional cardiologist in high-volume centers has an exposure near to 5 mSv per year, which is not negligible from the carcinogenic point of view.7

The risk model for low-level exposures is based on a linear relationship between the dose of radiation and the long-term risk of carcinogenesis. The assessment of health risk in low doses has been controversial and is estimated from the extrapolation of the high-dose-derived dose-effect curve.8

In particular, in spite of the deepening scientific knowledge about the adverse health effects of radiation, there is a particular need to introduce new epidemiological approaches in radioprotection programs aiming at the health surveillance of the hospital staff exposed to ionizing radiations chronically.9

The cardiac catheterization laboratory is deemed a source of radiation. Radiation risks are divided into 2 types: the deterministic type, which causes effects after passing from a certain threshold (e.g., skin burns), and the stochastic type, which is a risk proportional to the dose of radiation received by the patient (e.g., malignancy and teratogenicity). Since procedures are becoming more complex, radiation exposure attenuation in the cardiac catheterization laboratory is vital. However, utilizing decreased doses results in lower image quality because of a diminished signal-to-noise ratio.1

Recently, Engin et al.10 (2005) studied the genomic instability of γ- and X-ray-exposed hospital personnel and showed that chronic exposure to ionizing radiation, even in lower levels than the accepted limit, could induce oxidative stress and increased apoptosis in comparison with nonexposed personnel.11

Scientific evidence gathered from both human and animal experiments has revealed that the risk associated with lower radiation doses is due to the stochastic effect. Thus, other factors such as low-dose hypersensitivity can intensify the consequences of the radiation, but adaptive responses against targeted and non-targeted damage may relieve the chronic damage.12,13

According to previous studies, there are 2 ranges of the radiation dose for the staff in the coronary angiography department: 0.5 to 6 mSv (median effective dose = 1.3 mSv) and 1 to 11 mSv (median effective dose = 5 mSv). The International Commission for Radiation Protection proposed a radiation dose that is “As Low As Reasonably Achievable” (ALARA) to keep radiation safe.14 The aim of this paper is to discuss strategies vis-à-vis radiation attenuation for patients and interventional cardiologists.

Methods

We performed a literature review in PubMed, ScienceDirect, and Scopus databases using the terms “radiation”, “exposure”, “interventional cardiologist”, and “patient” as keywords. Additionally, we drew upon Boolean operators to connect and define the relationship between our selected search terms. We excluded studies before 1990 and reviewed strategies aimed at reducing radiation risks to interventional cardiologists and patients.

Measuring occupational exposure at the cardiac laboratory

Several quantities are used for characterizing the amount of radiation. The 1st quantity is called “air kerma”, defined as kinetic energy per mass unit. Its quantification is based on the energy that is transferred from non-directly ionizing particles for instance photons to charged particles. Gray (Gy) is the unit used for expressing air kerma: 1 Gy is equal to the energy transfer of 1 J/kg of the air.15 The other common quantities are fluoroscopy time, dose-area product (DAP), number of cine frames, effective dose, cine time, skin dose, and coronary dose. The coronary dose is defined as the dose to a coronary artery, and it can be measured using a dosimeter (catheter-based) during irradiation. The non-dosimetric quantity fluoroscopy time (expressed in min) is common for the evaluation of the patient’s dosimetry because it is the only readily available routine dose metric quantity in many interventional laboratories.16 However, the fluoroscopy time does not show any information on the skin entrance ports as well as the dose rate. The DAP, which is measured in Gy·cm², is based on the dose in air for a certain plane by the area of the irradiating beam. It is not dependent on the distance from the X-ray source because the reduction of the dose with distance is equivalent to the increase in the area. It is the initial quantity for estimating the patient’s skin dose as well as establishing the stochastic risk to the patient by the effective dose.17,18

International organizations have recommended the quantities and units that should be considered for occupational dosimetry. Also, national regulations have recommended specific requirements for staff dosimetry in interventional practices.19

Limitation of the dose for workers is the equivalent dose in a tissue (or organ) for an exposed part of the body and for whole-body exposure is the effective dose. The SI unit for the equivalent dose and the effective dose is the sievert.
It is recommended that the physician avoid

The previously reported conversion factors are

operators is affected by tube angulation. Fluoroscopy shows

exposure reduction

than the acquisition air kerma rate. The fluoroscopic air

movement of the beam.

The most important procedure-related factors for governing

dose reduction is to lessen the beam-on time for both

radiation risk to the patient. Accordingly, minimization of the dose to balance the radiation risk by the

Gy·cm

0.185 mSv/ Gy·cm

true.

factor for effective dose estimation from DAP values is

found, providing evidence that using a simple conversion
correlation between the DAP and the effective dose has been

measurements and Monte Carlo simulations, a powerful

personnel in the interventional space. Based on phantom

reduction in the scatter dose to both the operator and other

risk for high-volume operators (occupational exposure of 5

mSv for 1 year) for either fatal or nonfatal cancers is near
to 1%. 6 A 28% to 40% decrease in the operator radiation
exposure could significantly reduce the risk. For trainees, the
estimated radiation in the 1st year of training is 60% higher
than that in the 2nd year. The reason for that higher exposure
is the longer fluoroscopy time to position the catheter.7, 21, 22

Reducing patient exposure to radiation

Using decreased patient doses could result in a proportional
reduction in the scatter dose to both the operator and other
personnel in the interventional space. Based on phantom
measurements and Monte Carlo simulations, a powerful
correlation between the DAP and the effective dose has been
found, providing evidence that using a simple conversion
factor for effective dose estimation from DAP values is
true.15, 22 The previously reported conversion factors are
0.185 mSv/ Gy·cm², 0.183 mSv/ Gy·cm², and 0.221 mSv/
Gy·cm².22, 23

The ALARA optimization principles necessitate the
minimization of the dose to balance the radiation risk by the
interventional procedure benefit to the patient. Accordingly,
it is essential that efforts be made to properly manage the
radiation risk to the patient.24 The best approach for patient
dose reduction is to lessen the beam-on time for both
fluoroscopy and acquisition to the smallest possible amount.
The most important procedure-related factors for governing
the amount of scattered radiation are the orientation and
movement of the beam.25-27

Fluoroscopy has a significantly higher proportion of whole
air kerma during PCI than acquisition. The fluoroscopic air
kerma rate shows more sensitivity to changes in angulation
than the acquisition air kerma rate.24

Modifying fluoroscopic views for operator radiation
exposure reduction

The amount of the radiation dose to both patients and
operators is affected by tube angulation. Fluoroscopy shows

more sensitivity to changes in angulation than acquisition. A reduction in patient and staff exposure to radiation requires
the minimization of extreme angulations, whenever possible.
In addition to beam angulation, another strong predictor of
the total air kerma rate on the complex spatial map is the
body surface area, which is developed by modeling based on
multivariable regression.15, 20, 28, 29

Angulations of steep left anterior oblique (LAO) tubes are
the most radiation intensive for both the operator and the
patient. When the former LAO 60°/0° view was replaced
with the caudal right anterior oblique (RAO) 10°/30°, the
fluoroscopic operator dose was reduced by around 75% .20
LAO 060° having cranial or caudal angulation 020° is not
recommended, and suggestions regarding how to replace
common tube angulations by alternative safer angulations
without significant loss of capture information are important.
For any target structure, RAO or posterior anterior (PA)
angulation with the appropriate amount can be used as an
alternative to the standard LAO angulation.15 The LAO
cranial projection, when used by a physician in the femoral
approach for a patient, will result in the highest operator dose
rate for the radiation scatter.30, 31 When cardiologists became
aware of the relatively high scatter dose to operators after
the LAO projection, the researchers observed a significant
decrease in the use of the LAO projection. As a result, the
average physician dose was decreased by about twofold.32
Raising awareness as regards radiation dose levels and
radiation protection through educational programs is
necessary.26, 33 It is recommended that the physician avoid
being on the side of the tube during oblique and lateral
projections because just by standing on the side of the image
intensifier, the dose rate can be reduced by up to fivefold.34
A large reduction in the radiation exposure of the patient
and, to a lesser degree, of the invasive cardiologist, along
with an improvement in image quality, can be achieved by
holding the image intensifier closer to the patient and the
tube further away.35

Pulsed fluoroscopy

The reduction of the dose by factors 2 and 4 can be
attained through maximum dose reduction, which utilizes
X-ray techniques for 15 fps and 7.5 fps when it is in the case
of 30 fps. The application of this strategy directs a reduction
of the quality of the perceived image in lower frame rates
in mode than the 30 fps mode due to the characteristics of
human vision.36

A longer fluoroscopy period with high performance of the
tube in the same irradiation geometry for cardiac procedures
leads to high-dose skin spots and an increase in the possibility
of transient erythema and even organ failure. Awareness of
interventional cardiologists as regards the physical and
anatomical conditions can help minimize the risk of skin
spots by utilizing the best rotation in the tube so that there is
more distribution in the patient’s body.\textsuperscript{37,38}

**Removal of the anti-scatter grid**

The role of the anti-scatter grid is to attenuate the scattered radiation and prevent it from entering the image receptor. For patients with a higher mass, an obligation is present for the removal of the scatter and preserving subject contrast in the image for enough image quality. Since scatter contributes to the brightness of the monitor image, primary radiation must be used instead of scatter. Primary radiation will increase the patient radiation dose 2 or more times.\textsuperscript{39}

In pediatric cases, the removal of the grid could result in a dose decrease of up to 1/3 to 1/2, without showing any degradation in the quality and contrast of the image. Therefore, for children, grids should be used with caution in fluoroscopic examinations and the systems should have easy removal/introduction of the grid facility.\textsuperscript{24,40}

**Image magnification**

Fluoroscopes have 3 or more field of views (FOVs) on the display monitor, allowing the operator to select 1 of them. The biggest FOV is provided by the “normal” mode in that it irradiates in all the surface area of the image receptor. Other modes (e.g., mag 1, mag 2, etc.) utilize shorter X-ray beam areas at the receptor. Because smaller areas are expanded to fill the entire display monitor, the image of the anatomy is magnified for smaller FOVs.\textsuperscript{41} The sharpness of the image is also higher in magnified FOVs. The operator should be aware that when the FOV decreases, the radiation dose rate in fluoroscopy increases. It is dependent on the design of the machine. A bisecting dose 1/FOV or dose 1/FOV2 would increase the radiation dose rate by factors of 2 and 4, respectively.\textsuperscript{24,27,39}

For the magnification of the image in fluoroscopy, 2 basic ways are employed: geometric and electric magnifications. In geometric magnification, the diverging X-ray is used to project a smaller area from the patient’s body to a larger region on the image intensifier.\textsuperscript{42,43} When the distance from the source to the image receptor is constant, as the patient moves closer to the source, image magnification as well as skin dose will increase. Modern fluoroscopes have an option for image magnification within the image intensifier, electronically. Systems typically have electronic magnification modes, with each one having a unique dose level, and the dose increases with larger electronic magnifications.\textsuperscript{41} A rule of thumb is that the radiation dose to the patient increases by the square of the ratio of the image intensifier diameters. For example, if the entrance skin exposure is 100 units for a 23-cm FOV, the radiation entrance dose is augmented to 235 units, once the FOV is decreased to 15 cm (23/15) 2 and to 440 units for an FOV of 11 cm (23/11) 2.\textsuperscript{27,39} Recently developed flat panel angiography, which has the advantage of pixel size enhancement, could perform large gain, flexible optical output with different types of optical cameras.\textsuperscript{44}

**Digital subtraction angiography**

State-of-the-art interventional fluoroscopy sets have 2 properties: unlimited fluoroscopy time and the potential for performing digital subtraction angiography (DSA). DSA is used for diagnosis and documentation; it produces about twofold the radiation dose of the fluoroscopy-guided portion of the process. In these procedures, the total radiation dose can be substantially decreased either by storing fluoroscopy loops or extracting representative images from fluoroscopy loops instead of storing higher-quality DSA images in the recent generations of angiography systems.\textsuperscript{26,45,46}

**Improving lead shielding**

Two effective strategies for the reduction of operator radiation exposure (down to 0.8% of the typical levels in catheterization laboratories) are radiation-attenuating interventional techniques and improved lead protection. For scatter radiation leakage, fitting a 1.0-mm lead top along the under-couch lead shield, and introducing a 1.0-mm lead flap below the lead glass sheet adjacent to the table could be effective. For cranial LAO angulation (LAO 60°/20°), inducing intensive scatter entrance surface air kerma (ESAK) to the operator, the lead flap is very effective in comparison with the under-couch top. With the co-installation of the aforementioned shields, we can reduce the mean scatter entrance skin air kerma to the operator position (S-ESAK-O) in this projection to a level of 0.7% of the primary scatter radiation. The angulation results in the mean S-ESAK-O reaching 2.6 to 15.8 Sv/h at the former leakage height.\textsuperscript{47} Three main types of shielding are equipment-mounted shields, personal protective devices, and architectural shielding. The last one is employed in the walls of the room. Moreover, additional shielding for operators, nurses, and anesthesia personnel is provided by other shields such as stationary and rolling ones.\textsuperscript{20}

Previous reports have documented an average annual effective dose of 46.2 mSv for interventional cardiologists not wearing protective devices. By using a lead pinafore alone, the dose will reduce to 3.5 mSv annually, and by both a lead pinafore and a thyroid shield to 1.7 mSv.\textsuperscript{5}

The most radiosensitive tissue in the body is the lens. A deterministic effect of radiation exposure (a threshold of 2 Gy) is cataract. The threshold for cataract development is reported by some investigations to be 0.5 Gy, which is less than the previous estimations. According to the International Commission on Radiological Protection reports, threshold values for detectable opacities of acute exposure and chronic exposure are 0.5 to 2.0 and 5 Sv, respectively.\textsuperscript{48}

Ceiling-suspended lead shields could be replaced with
leaded eye-protective glasses, which have protective side shields and show acceptable safety compared to other glasses. There are 4 personal protective shields: gloves, glasses, aprons, and thyroid shields. A 0.5-mm lead thickness apron or thyroid shield can reduce more than 95% of X-rays used during fluoroscopy. Leaded glasses can reduce from 35% to 95% of X-rays of typical X-ray energies. Ceiling-suspended shields can attenuate the operator dose by a factor of 3 to 20.

Conclusion

Interventional cardiology is associated with some of the highest radiation doses in diagnostic radiology. We must assume that the practice of radiation protection with respect to both patients and operators needs improvement. The risk to patients and staff associated with these procedures can be kept to a minimum if operators maintain a diligent approach to radiation protection. If interventionists adopt the dose reduction techniques already available, particularly with reference to fluoroscopy, significant dose reduction can be achieved. Awareness of one’s own radiation dose is essential inasmuch as it provides enough motivation for incorporating changes in personal practice that result in reducing the radiation dose. The changes in the operator’s practice can be implemented very fast by a motivated operator at minimal or no cost and can have a substantial effect on the operator dose.

References

1. Wassef AW, Hiebert B, Ravandi A, Ducas J, Minhas K, Vo M, Kass M, Parmar G, Hussain F. Radiation dose reduction in the cardiac catheterization laboratory utilizing a novel protocol. JACC Cardiovasc Inter 2014;7:550-557.
2. Rad MH, Alizadeh E, Ilkhanizadeh B. Recurrent laryngeal papillomatosis with bronchopulmonary spread in a 70-year-old man. Tuberk Toraks 2007;55:299-302.
3. Rahimi-Rad MH, Alizadeh E, Samarcì R. Aquatic leech as a rare cause of respiratory distress and hemoptyosis. Pneumonologia 2011;60:85-86.
4. Vano E, Gonzalez L, Canis M, Hernandez-Lezana A. Training in radiological protection for interventionalists. Initial Spanish experience. Br J Radiol 2003;76:217-219.
5. Sun Z, AbAziz A, Yusof AK. Radiation-induced noncancer risks in interventional cardiology: optimisation of procedures and staff and patient dose reduction. Biomed Res Int 2013;2013:976962.
6. Venneri L, Rossi F, Botti N, Andreassi MG, Salcone N, Emad A, Lazzeri M, Gori C, Vano E, Picano E. Aquatic leech as a rare cause of respiratory distress and hemoptyosis. Pneumonologia 2011;60:85-86.
7. Abdelalad E, Plourde G, MacHaally J, Arsenault J, Rimac G, Déry JP, Barbeau G, Larose E, De Larochellière R, Nguyen CM, Allende R, Ribeiro H, Costerousse O, Mongrain R, Bertrand OF; Interventional Cardiologists at Quebec Heart-Lung Institute. Effectiveness of low rate fluoroscopy at reducing operator and patient radiation dose during transradial coronary angiography and interventions. JACC Cardiovasc Interv 2014;7:567-574.
8. Andreassi MG, Cioppa A, Manfredi S, Palmieri C, Botto N, Picano E. Acute chromosomal DNA damage in human lymphocytes after radiation exposure in invasive cardiovascular procedures. Eur Heart J 2007;28:2195-2199.
9. Angeliini S, Kumar R, Carbone F, Maffei E, Forti GC, Violante FS, Lodi V, Curti S, Hemminki K, Hrelia P. Micronuclei in humans induced by exposure to low level of ionizing radiation: influence of polymorphisms in DNA repair genes. Mutat Res 2005;570:105-117.
10. Engin AB, Ergun MA, Yurtcu E, Kan D, Sahin G. Effect of ionizing radiation on the pteridine metabolic pathway and evaluation of its cytotoxicity in exposed hospital staff. Mutat Res 2005;585:184-192.
11. Dias FL, Antunes LM, Rezende PA, Carvalho FE, Silva CM, Matheus JM, Oliveira JV, Jr, Lopes GP, Pereira GA, Balarin MA. Cytogenetic analysis in lymphocytes from workers occupationally exposed to low levels of ionizing radiation. Environ Toxicol Pharmacol 2007;23:228-233.
12. Feinendegen LE, Brooks AL, Morgan WF. Biological consequences and health risks of low-level exposure to ionizing radiation: commentary on the workshop. Health Phys 2011;100:247-259.
13. Ropolo M, Balia C, Reggeri P, Lodi V, Nucci MC, Violante FS, Silingardi P, Colacci A, Bolognesi C. The micronucleus assay as a biological dosimeter in hospital workers exposed to low doses of ionizing radiation. Mutat Res 2012;747:7-13.
14. Agarwal S, Parasarah A, Bajaj NS, Khan I, Ahmad I, Heupler FA, Jr, Bunte M, Modi DK, Tuzcu EM, Kapadia SR. Relationship of beam angulation and radiation exposure in the cardiac catheterization laboratory. JACC Cardiovasc Inter 2014;7:558-566.
15. Einstein AJ, Moser KW, Thompson RC, Cerqueira MD, Henzlou MJ. Radiation dose to patients from cardiac diagnostic imaging. Circulation 2007;116:1290-1305.
16. Bogaert E, Bacher K, Thiérens H. A large-scale multicentre study in Belgium of dose area product values and effective doses in interventional cardiology using contemporary X-ray equipment. Radiat Prot Dosimetry 2008;128:312-323.
17. Pantos I, Patatoukas G, Katrisitis DG, Esfathopoulos E. Patient radiation doses in interventional cardiology procedures.Curr Cardiol Rev 2009;5:1-11.
18. Esfathopoulos EP, Makrygiannis SS, Kotou S, Kavouri E, Giaziitgoglou E, Korovessis S, Tzanalaridou E, Rapoù PD, Katrisitis DG. Medical personnel and patient dosimetry during coronary angiography and intervention. Phys Med Biol 2003;48:3059-3068.
19. Schauer DA, Linton OW. National Council on Radiation Protection and Measurements report shows substantial medical exposure increase. Radiology 2009;253:293-296.
20. Miller DL, Vahl E, Barta G, Balzer D, Papadoni R, Schueler B, Cardella JF, de Baère T; Cardiovascular and Interventional Radiology Society of Europe; Society of Interventional Radiology. Occupational radiation protection in interventional radiology: a joint guideline of the Cardiovascular and Interventional Radiology Society of Europe and the Society of Interventional Radiology. Cardiovasc Intervent Radiol 2010;33:230-239.
21. Morris OW, Goldstone KE. An investigation into patient and staff doses from X-ray angiography during coronary interventional procedures. Br J Radiol 2008;81:35-45.
22. Neofotistou V. Review of patient dosimetry in cardiology. Radiat Prot Dosimetry 2001;94:177-182.
23. Karamatsakidou A, Tomvall P, Saleh N, Chouliaras T, Löfberg P, Fransson A. Skin dose alarm levels in cardiac angiography and measurements reporting: a national survey of present practice in Sweden. J Radiol Prot 1998;18:143-151.
American Heart Association; American College of Physicians. ACCF/AHA/HRS/SCAI clinical competence statement on physician knowledge to optimize patient safety and image quality in fluoroscopically guided invasive cardiovascular procedures. A report of the American College of Cardiology Foundation/American Heart Association/American College of Physicians Task Force on Clinical Competence and Training. J Am Coll Cardiol 2004;44:2259-2282.

26. Padovani R, Le Heron J, Cruz-Suarez R, Duran A, Lefaure C, Miller DL, Sim HK, Vano E, Rehani M, Czarwinski R. International project on individual monitoring and radiation exposure levels in interventional cardiology. Radiat Prot Dosimetry 2011;144:437-441.

27. Miller DL, Balter S, Noonan PT, Georgia JD. Minimizing radiation-induced skin injury in interventional radiology procedures. Radiology 2002;225:329-336.

28. Picano E, Vahé E, Rehani MM, Cuocolo A, Mont L, Bodi V, Bar O, Maccia C, Pierard L, Sicari R, Plein S, Mahrholt H, Lancellotti P, Knaut J, Heidbuchel H, Di Mario C, Badano LP. The appropriate and justified use of medical radiation in cardiovascular imaging: a position document of the ESC Associations of Cardiovascular Imaging, Percutaneous Cardiovascular Interventions and Electrophysiology. Eur Heart J 2014;35:665-672.

29. Kuon E, Dahn JB, Empen K, Robinson DM, Reuter G, Wucherer M. Identification of less-irradiating tube angulations in invasive cardiology. J Am Coll Cardiol 2004;44:1420-1428.

30. Pratt TA, Shaw AJ. Factors affecting the radiation dose to the lens of the eye during cardiac catheterization procedures. Br J Radiol 1993;66:346-350.

31. No authors listed. Radiation hazards to the cardiologist. A report of a subcommittee of the British Cardiac Society. Br Heart J 1993;70:489-496.

32. Pitney MR, Allan RM, Giles RW, McLean D, McCredie M, Randell T, Walsh WF. Modifying fluoroscopic views reduces operator radiation exposure during coronary angiography. J Am Coll Cardiol 1994;24:1660-1663.

33. Kim KP, Miller DL. Minimising radiation exposure to physicians performing fluoroscopically guided cardiac catheterisation procedures: a review. Radiat Prot Dosimetry 2009;133:227-233.

34. Fazel R, Krumholz HM, Wang Y, Ross JS, Chen J, Ting HH, Shah ND, Nasir K, Einstein AJ, Lammoth BK. Exposure to low-dose ionizing radiation from medical imaging procedures. N Engl J Med 2009;361:849-857.

35. Gerber TC, Carr JJ, Arai AE, Dixon RL, Ferrari VA, Gomes AS, Heller GV, McCollough CH, McNitt-Gray MF, Mettler FA, Mieres JH, Morin RL, Yester MV. Ionizing radiation in cardiac imaging: a science advisory from the American Heart Association Committee on Cardiac Imaging of the Council on Clinical Cardiology and Committee on Cardiovascular Imaging and Intervention of the Council on Cardiovascular Radiology and Intervention. Circulation 2009;119:1056-1065.

36. Vano E, Goicolea J, Galvan C, Gonzalez L, Meiggs L, Ten JJ, Macaya C. Skin radiation injuries in patients following repeated coronary angioplasty procedures. Br J Radiol 2001;74:1023-1031.

37. Giordano C, D’Ercole L, Gobbi R, Bocchiola M, Passerini F. Coronary angiography and percutaneous transluminal coronary angioplasty procedures: Evaluation of patients’ maximum skin dose using GaFčromic films and a comparison of local levels with reference levels proposed in the literature. Phys Med 2010;26:224-232.

38. Koenig TR, Mettler FA, Wagner LK. Skin injuries from fluoroscopically guided procedures: part 2, review of 73 cases and recommendations for minimizing dose delivered to patient. AJR Am J Roentgenol 2001;177:13-20.

39. Rana R, Singh V, Jain A, Bednarek DR, Rudin S. Anti-scatter grid artifact elimination for high resolution x-ray imaging CMOS detectors. Proc SPIE Int Soc Opt Eng 2015;9412:941243.

40. Ul Haque M, Shufflerbarger HL, O’Brien M, Macagno A. Radiation exposure during pedicle screw placement in adolescent idiopathic scoliosis: is fluoroscopy safe? Spine (Phila Pa 1976) 2006;31:2516-2520.

41. Schneider K, Krüger-Stollfuss I, Ernst G, Kohn MM. Paediatric fluoroscopy--a survey of children’s hospitals in Europe. 1. Staffing, frequency of fluoroscopic procedures and investigation technique. Pediatr Radiol 2001;31:238-246.

42. Bolch WE, Ponjiie BD, Sessions JB, Arreola MM, Williams JL, Pazik FD. A video analysis technique for organ dose assessment in pediatric fluoroscopy: applications to voiding cystourethroms (VCUG). Med Phys 2003;30:667-680.

43. Steffenino G, Rossetti V, Ribichi F, Dellavalle A, Garbarino M, Cerati R, Norbiato A, Usłenghi E. Short communication: staff dose reduction during coronary angiography using low framing speed. Br J Radiol 1996;69:860-864.

44. Rudin S, Bednarek DR, Hoffmann KR. Endovascular image-guided interventions (EIGIs). Med Phys 2008;35:301-309.

45. Durán A, Hian SK, Miller DL, Le Heron J, Padovani R, Vano E. A summary of recommendations for occupational radiation protection in interventional cardiology. Catheter Cardiovasc Interv 2013;81:562-567.

46. Miller DL. Efforts to optimize radiation protection in interventional fluoroscopy. Health Phys 2013;105:435-444.

47. Kuon E, Schmitt M, Dahn JB. Significant reduction of radiation exposure to operator and staff during cardiac interventions by analysis of radiation leakage and improved lead shielding. Am J Cardiol 2002;89:44-49.

48. Vano E, Kleiman NJ, Duran A, Rehani MM, Echeverri D, Cabrera M. Radiation cataract risk in interventional cardiology personnel. Radiat Res 2010;174:490-495.

49. Ainsbury EA, Bouffler SD, Dörr W, Graw J, Muirhead CR, Edwards AA, Cooper J. Radiation cataractogenesis: a review of recent studies. Radiat Res 2009;172:1-9.

50. Mohammadpour M, Ebadi Movahedan Z, Jabbarvand M, Hashemi H. Radiation cataract: clinicopathologic report. J Cataract Refract Surg 2013;39:285-288.

51. Maeder M, Brunner-La Rocca HP, Wolter T, Ammann P, Roelli H, Rohnert F, Rickli H. Impact of a lead glass screen on scatter radiation to eyes and hands in interventional cardiologists. Catheter Cardiovasc Interv 2006;67:18-23.

52. Blakely EA, Kleiman NJ, Nerishi K, Chodick G, Chylack LT, Cucinotta FA, Minamoto A, Nakashima E, Kumagami T, Kataoka T, Kanamoto T, Kiuchi Y, Chang P, Fujiy RE. Radiation cataractogenesis: epidemiology and biology. Radiat Res 2010;173:709-717.