Structural Heart 8 (2024) 100328

Articles and Issues Available at ScienceDirect

Structural Heart

journal homepage: www.structuralheartjournal.org

Review Article

Addressing the Occupational Risk of Radiation Exposure in the Evolving Field of Interventional Echocardiography

Philipp Lauten, MD *, Harald Lapp, MD, Björn Goebel, MD

Heart Valve Unit, Department of Cardiology, Heart Center, Zentralklinik Bad Berka, Bad Berka, Germany

ARTICLE INFO

Article history:
Submitted 3 February 2024
Revised 30 April 2024
Accepted 8 May 2024
Available online 21 June 2024

Keywords:
Interventional echocardiography
Radiation exposure
Valve interventions

ABSTRACT

Interventional echocardiography (IE) is a relatively new subspecialty in the field of cardiology that has rapidly evolved to occupy a critical role in the treatment of structural heart disease. Despite this, clear competency guidelines are only now being issued, and, of pressing importance, the health risks associated with the profession, particularly occupational radiation exposure, still need to be recognized and appropriately addressed for both specialists and trainees in IE as well as for supporting sonographers. This review will briefly discuss the extensive training interventional echocardiographers need in advanced imaging modalities and will then present standard measures as well as possible innovative devices that can be implemented to reduce ionizing radiation exposure for those working in the field of IE.

ABBREVIATIONS

ASE, American Society of Echocardiography; CMR, cardiac magnetic resonance; CT, computed tomography; IE, interventional echocardiography; SHD, structural heart disease; TEE, transesophageal echocardiography.

Introduction

Transcatheter procedures have become well established for the treatment of structural heart disease (SHD), and, in parallel, there has been a remarkable evolution in real-time echocardiographic imaging during these procedures. This has given rise to a subset of interventional imaging specialists who are central not only to preprocedural planning and to follow-up monitoring and postprocedural quality measures but also to real-time intraprocedural guidance. Thus, specialty associations are now developing recommendations regarding the training and necessary competencies for those specializing in interventional echocardiography (IE), as well as acknowledging problematic issues such as health risks, funding, and reimbursement.[1–5] Here, we will discuss a particularly serious potential health risk facing this new subspecialty; namely, occupational radiation exposure.

Advanced Imaging Technologies and Methods Used in IE

Interventional cardiology began to use transthoracic echocardiography intraprocedurally 4 decades ago, and the use of transesophageal echocardiography (TEE) for SHD started less than a decade after that.[6,7] More recently, there has been a very rapid development of transcatheter interventional procedures for SHD, and, along with that, the use of pre-interventional, peri-interventional, and postinterventional echocardiographic imaging has also expanded. IE now plays a central role in a wide range of procedures in cardiology, which are summarized in Table 1.

In addition to standard transthoracic echocardiography and TEE, some of the advanced imaging modalities that are now generally understood to fall within the realm of IE are advanced TEE (which includes intraprocedural real-time three-dimensional (3D) imaging, 3D multiplanar imaging, and 3D color Doppler), fusion imaging, photorealistic transillumination imaging, and two-dimensional and 3D intracardiac echocardiography.[2,3,5]

Of these tools used in IE, fusion imaging is particularly worthwhile to note as it preprocedurally aids in understanding complex anatomies and thus helps with intervention planning, and intraprocedurally it helps guide critical steps in transcatheter procedures for SHD. In fusion imaging, data obtained from different imaging modalities is registered and aligned spatially and temporally so as to form a more detailed hybrid image.[8,9] The different imaging modalities that can be combined include

* Address correspondence to: Philipp Lauten, MD, Head Senior Physician, Clinic for Cardiology and Intensive Care Medicine at the Heart Center of the Central Clinic Bad Berka, Structural Heart Disease and Interventional Valve Therapy, R-Koch-Allee 9, 99436 Bad Berka, Germany.
E-mail address: philipp.lauten@zentralklinik.de (P. Lauten).

https://doi.org/10.1016/j.shj.2024.100328

Table 1
Range of interventions with indications for peri-interventional echocardiography

Intervention	Procedures benefiting from echo	Type of echo
Heart valve interventions	• TAVI • Transcatheter "edge-to-edge" repair of the mitral and tricuspid valves • Annuloplasty (cardioband) • AV-replacement/implantation • "Valve-in-valve"-procedures, especially mitral and tricuspid	• 3D-TEE for navigating therapy • Rarely ICE in tricuspid valve interventions • TTE to exclude complications
Transseptal puncture	• Electrophysiological interventions • Valve interventions	• TEE or • ICE
Closure of septal defects	• ASD type II • PFO • VSD	• 3D-TEE or • ICE
Closure of paravavlular leaks	• After mitral or aortic valve replacement	• 3D-TEE
Closure of the left atrial appendage		• 3D-TEE or • ICE
Percutaneous LV-support systems	• For example, microaxial flow pump	• TEE • TTE
Ablation of septal hypertrophy	• TASH for hypertrophic cardiomyopathy	• TTE
Catheter ablation	• Mostly for ventricular arrythmias	• ICE • TEE
Biopsy of intracardiac space occupying lesions	• For precise guidance of the biopsy forceps	• ICE

Abbreviations: 3D, three-dimensional; ASD, atrial septal defect; AV, atrio-venticular; ICE, intracardiac echocardiography; LV, left ventricle; PFO, patent foramen ovale; TASH, transcoronary ablation of septal hypertrophy; TAVI, transcatheter aortic valve implantation; TEE, transesophageal echocardiography; TTE, transthoracic echocardiography; VSD, ventricular septal defect.

real-time two-dimensional and 3D TEE, intracardiac echocardiography, fluoroscopy, computed tomography (CT), and, rarely, cardiac magnetic resonance (CMR) imaging. These modalities all have their strengths and weaknesses and are combined in order to exploit their strengths so as to give the most accurate spatial and structural information possible and, when used intraprocedurally, to give this information in real time. TEE provides information in real time and is good for soft tissue delineation and hemodynamic data, but it is affected by artifacts and has a limited field of view. Fluoroscopy likewise provides real time images and is excellent for viewing catheters and devices, but it can only give limited hemodynamic information and is poor for soft tissue imaging. Extended fluoroscopy times also mean increased radiation exposure. CT and CMR cannot currently be easily used for real-time imaging, but they are critical for preprocedural planning. Although cardiac CT can give very detailed soft tissue images and has a wider field of view than TEE, it does expose the patient to radiation and requires contrast. Both CT and CMR must be electrocardiogram-gated and may require a breathhold to eliminate breathing artifacts. Preprocedurally, one most often sees fusion imaging using CT and echocardiography or CT and fluoroscopy, depending upon the anticipated procedure. Intraprocedurally, the fluoroscopy and TEE imaging are co-registered and overlayed so that the hybrid image is updated in real time.[5,9–12]

Training for Subspecialization in IE

Successful SHD interventions require not only highly trained interventional cardiologists but also equally well-trained specialists in IE. The competencies required in IE are beyond what is currently obtained during a customary echocardiography subspecialty training program. To remedy this, various national and international professional organizations and other leaders in the field have suggested elements necessary for a structured IE training program.[2,3,5,13] The American Society of Echocardiography (ASE) has recently released guidelines that provide uniform training standards for all physicians, be they cardiologists or anesthesiologists, who are interested in subspecializing in IE.[3] For example, the imager must have a thorough knowledge of the procedure taking place during the SHD intervention. Along with this, the IE imager must be an expert in nonstandard and 3D views so that they can obtain and interpret these images in real time. The IE specialist will thus be able to guide the procedure as it is being performed.[3] This essentially means that an IE specialist must be "bilingual" and capable of speaking quickly and clearly in the language of an interventionalist as well as in the language of an imager.

Furthermore, IE specialists, as well as sonographers involved in image acquisition during SHD procedures, need thorough training in radiation safety. The ASE Guidelines address aspects of radiation safety training for trainees as well as their faculty instructors.[3] A prior Expert Consensus Statement suggested that specialists in IE should participate in the same radiation safety courses as their interventional cardiology colleagues.[1] In 2014, the Council on Cardiovascular Sonography of the ASE issued recommendations regarding radiation safety for sonographers. The recommendations broadly addressed concerns about exposure to cardiac patients who had been injected with radioisotopes and about exposure during SHD procedures needing echocardiographic assistance. It was noted within these recommendations that sonographers should be provided with radiation safety training during their education and during the orientation to their workplaces.[14]

Occupational Radiation Exposure

Specialists in IE encounter all of the usual occupational problems associated with standard echocardiography, such as muscle strains and joint discomfort; however, the IE specialist is also chronically exposed to high levels of ionizing radiation. Within the realm of general echocardiography, radiation exposure obviously exists and is unfortunately often overlooked (e.g., close contact with patients who previously received isotopes as part of a myocardial perfusion study). In the new specialty of IE, radiation exposure is closely intertwined with the imager's work environment because, in IE, the imager must often provide real-time guidance for SHD interventions in a cardiac catheterization laboratory.

In 1977, the "ALARA" (As Low As Reasonably Achievable) was developed by the International Commission on Radiologic Protection and has been used ever since to balance the risks and benefits associated with the use of ionizing radiation.[15] In keeping with this, efforts have been made to provide interventional cardiologists with better protection during procedures requiring fluoroscopy. It has only recently been appreciated that the IE specialist is exposed to as much radiation as the operator performing the intervention, or perhaps even more.[16,17] Not unexpectedly, the radiation dose experienced by the imager increases with procedure complexity.[17] Furthermore, procedures that use increasingly steep right anterior oblique projections deliver higher doses of radiation to the imager, which is in contrast to the situation usually seen with the operator.[16] A single-center study comparing radiation doses received by interventional cardiologists, interventional echocardiographers, and sonographers during left atrial appendage closure and transcatheter edge-to-edge mitral valve repair found that the IE specialists received significantly higher doses of radiation than the interventional cardiologists and that the sonographers received less radiation than both of them, presumably secondary to the ability of the sonographer to stay farther away from the radiation source.[18]

It is well established that increasing the distance from a radiation source exponentially decreases exposure such that doubling the distance from the radiation source decreases the radiation exposure by a quarter.[18,19] This is difficult in IE because the TEE operator must be positioned near the patient, and the patient is a source of X-ray scatter. The intensity of this scattered radiation is greatest on the side where the X-ray beam enters the patient.[18] Given this, it is unfortunate that the positioning and shielding of the IE specialist are not universally considered an issue of concern.[19] This point has been well made by a recently published "call to action" for minimizing the radiation exposure of IE specialists and sonographers. Additionally, the authors provide a useful summary and comparison of the fluoroscopy times and angles associated with specific SHD procedures and the current best practices to reduce the amount of radiation to which imagers are exposed during the respective procedures.[20]

Evidence continues to mount that the radiation exposure cardiologists experience during interventional procedures is not without consequences. For example, the ocular lens is known to be exceptionally sensitive to radiation exposure. Consistent with that, it has been found that, in comparison to age-matched controls, interventional cardiologists and others who work in cardiac catheterization laboratories are at increased risk of developing posterior subcapsular cataracts.[21–24] Likewise, cutaneous cancers, such as basal cell carcinomas, are more common among staff working in cardiac catheterization laboratories.[24–26] A possible association of ionizing radiation exposure with left-sided brain tumors in interventional cardiologists has been reported in the literature. This would fit with the left side of the interventionalist's head being more exposed to radiation during interventional procedures.[27,28] Also noteworthy are molecular studies demonstrating that interventionalists have twice as much somatic DNA damage in their circulating lymphocytes as noninterventional cardiologists. This might be viewed as a surrogate marker for the risk of cancer development in interventionalists.[29] Although these concerns are generally directed at interventional cardiologists, they would also apply for interventional echocardiographers. Thus, more effort needs to be made to adapt various forms of radioprotection to the unique requirements of IE.

Radioprotection Considerations for IE

Dosimetry

It is just as critical for people working in IE to monitor their radiation exposure as it is for anyone else working in the cardiac catheterization laboratory. The recent ASE recommendations state that IE specialists should be given by their institutions direct ion storage dosimeters and that these should be regularly monitored.[3] Other thought leaders in the field have more specifically suggested that those working in IE should use operational dosimeters positioned under the lead shields and passive thermoluminescent dosimeters on areas close to the X-ray source, such as the eyes and hands.[19]

Protective Gear

According to the new ASE recommendations, all IE trainees and faculty should use lead aprons that have a minimum lead equivalency of 0.25 mm at the back and 0.5 mm at the front, lead thyroid collars, and lead goggles. Additionally, a lead acrylic shield with 0.5 mm lead equivalency that is either suspended from the ceiling or mobile on the ground should be provided.[3] Other authors have emphasized that the position of the IE specialist can change throughout the procedure relative to both the patient and the X-ray source. Thus, full body lead protection, including on the sides and back are needed. This could be achieved by using a mobile lead panel or a mobile lead cabin.[19]

At least one study has suggested that the IE specialist receives a significantly higher mean dose of radiation than the primary interventionalist, especially at the feet, hands, and arms, which are not protected by lead aprons, skirts, or shields.[17] Lead gloves are available to protect the hands, and in 2013, the Food and Drug Administration approved an X-ray attenuating cream that is applied to the hand before donning gloves and can provide some radiation protection up to 130 kVp (https://www.accessdata.fda.gov/cdrh_docs/reviews/K123422.pdf). An important caveat with respect to the use of lead gloves or X-ray attenuation cream is that it is potentially disadvantageous to use them in the primary X-ray imaging field. This is because the automatic dose rate control of the X-ray imaging system will actually increase the beam intensity in response to the radiopaque object in the field; hence, the radiation dose and X-ray scatter could all be inadvertently increased.[19]

The head of the IE specialist has an equivalent or worse degree of radiation exposure in comparison to the interventionalist.[17] Various styles of lead caps and nonlead caps have been designed with the goal of reducing cranial radiation exposure; however, they are not widely utilized. A small German survey of physicians exposed to ionizing radiation as part of their work found that only 27.9% (29/104) used lead caps or headbands.[30] This is unlikely to be due solely to issues of comfort, as the nonlead caps made of a barium sulfate-bismuth oxide composite are lightweight at 125 g in comparison to the lead caps, which weigh on average 1.14 kg.[31–33] Rather, the larger problem is that the literature is currently not unequivocal. Factors such as gaps between the cap and the skull, the angle of the physician's face relative to the radiation source, and tube angulation itself could all result in exposure to radiation despite the wearing of a protective cap. Also, the lower parts of the physician's face are often, to a greater or lesser degree, depending on the cap style, unprotected, so radiation can enter from below. Still, it can be argued that a cap can protect the physician from scattered radiation, which would be consistent with ALARA. Perhaps lead or lead equivalent caps will be improved in the future, and/or additional studies will more definitively clarify their role. In the interim, the wearing of them has not been enthusiastically adopted, and the topic in general remains one of uncertainty and concern.[28,33–38] The current ASE recommendations do not explicitly refer to the use of lead caps, headbands, or equivalents made of lighter X-ray blocking materials for those training or practicing in IE.[3]

It is also worth noting that some radiation physicists have published results questioning whether lead-free protective clothing is as effective as lead-containing gear. Although from an orthopedic and comfort perspective, the lead-free clothing might be advantageous, there is the possibility that it could be problematic in terms of how its component materials react to ionizing radiation. For example, low energy photons can be created by fluorescence in gear composed of tin or tin-bismuth combinations, and these could penetrate superficial organs such as the breast.[38–40]

From the perspective of the interventionalist, the use of disposable, radioprotective drapes made of nonlead materials such as bismuth and barium is of potential value.[41,42] Although these drapes can reduce scatter radiation, they are of less value to the interventional echocardiographer, who is often positioned near the mouth of the patient while performing a TEE.

Nonshielding Techniques to Decrease Radiation Exposure

In addition to shielding, there are other techniques that can be used to decrease the amount of ionizing radiation to which IE specialists are exposed. For instance, given that increasing the distance from the radiation source can decrease the amount of exposure, a longer TEE probe might be useful in IE. Also, the echocardiographer could step away from the table when active echocardiographic imaging is not required. Furthermore, the duration of fluoroscopy time can be limited by making good use of fusion imaging.[19,43] Anything the interventionalist can do to limit the radiation dose to the patient will, in turn, limit the dose the imager receives. For example, decreasing cine time, decreasing detector magnification, using collimation to reduce field size, and decreasing frame rate and fluoroscopy dose per frame.[43]

New Devices to Limit Scatter Radiation Exposure

There are promising developments that may limit the exposure of the entire cardiac catheterization laboratory, including the interventional echocardiographer, from scatter radiation even when angulated projections are used. The "EggNest" is a carbon fiber platform that replaces the patient mattress and passively moves radiation shielding along with the X-ray system and patient. The developers of this system report that, in comparison to standard shielding, it significantly reduces the scatter radiation dose for all people working in the cardiac catheterization laboratory.[44]

A Role for Professional Societies

A recent global survey by the European Association of Cardiovascular Imaging Scientific Initiatives Committee found that radioprotective gear was frequently underused in IE and advocated for scientific and radioprotection organizations to guide future studies and actions to improve the situation.[45] The European Association of Cardiovascular Imaging also specifically suggested a collaborative approach for radioprotection training in IE, dependable monitoring of radiation dose, and dedicated shielding for the imager.[45] These are all important first steps in providing IE specialists with safer work environments.

Conclusions and Recommendations

IE is a new specialty that not only has unique needs in terms of training but also has occupational risks that may even surpass those of interventional cardiologists in terms of radiation exposure. In light of that, we would recommend the following personal protective gear be worn by the IE specialist during SHD procedures:

- Fitted lead aprons and skirts that provide protection at the front, back, and sides with a minimum lead equivalency of 0.5 mm.
- Tightly fitting, lead thyroid protecting collar with lead equivalency of 0.25 to 0.5 mm.
- Lead googles/glasses of 0.35 to 0.5 mm lead equivalency.
- Lead gloves when performing TEE, but not if the hands are ever in the primary X-ray imaging field.

In addition to these protective personal items, careful consideration needs to be given to the lead shielding of the IE specialist. Good shielding practices are reported to reduce the radiation exposure of the IE specialist by as much as 82%.[1,16] The imager during SHD procedures must have the capability of being very mobile. Thus, we unfortunately do not think that the current models of lead cabins are practical. We recommend the use of a ceiling-suspended lead acrylic shield and/or a mobile lead acrylic floor shield. Given the high level of exposure the feet of the IE specialist receive, we also think the under-the-table shielding is important and recommend a lead shield attached at the side of the table and extending to the floor.

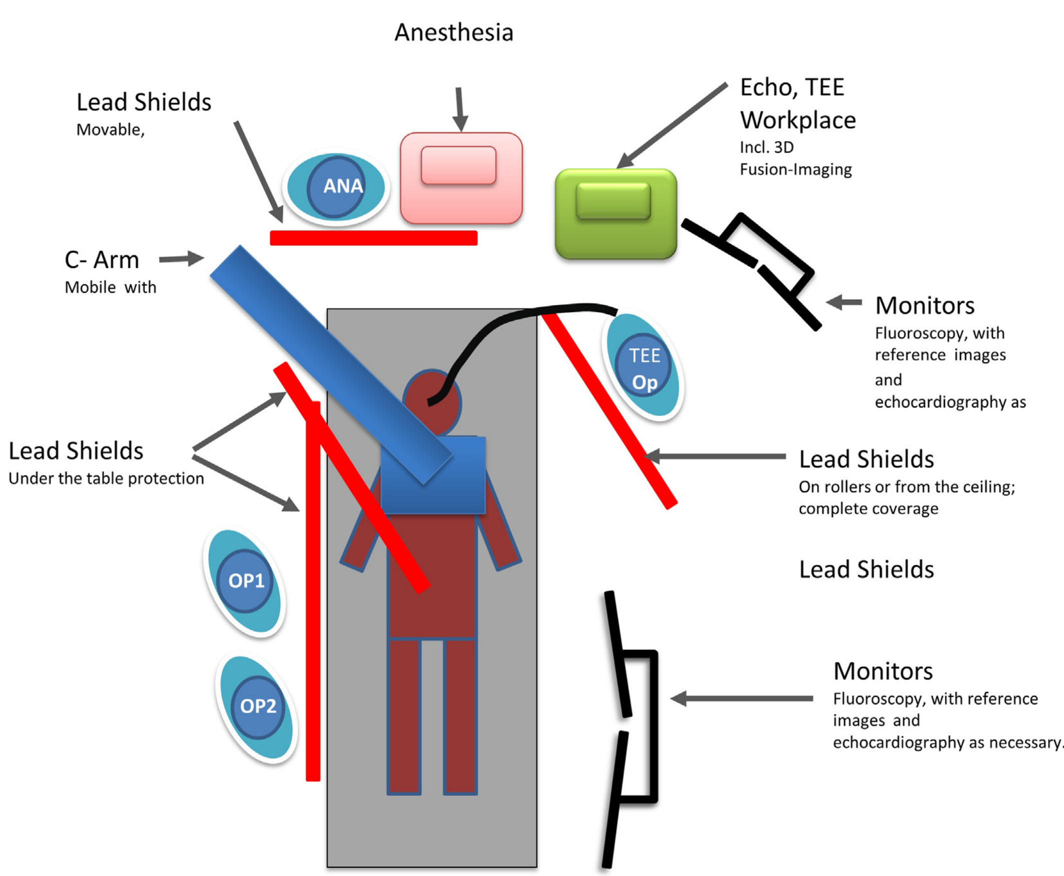

Figure 1. Set-up for cardiac catheterization laboratory that protects the IE specialist and colleague.
Abbreviations: 3D, three-dimensional; ANA, anaesthesia; IE, interventional echocardiography; OP, operator; TEE, transesophageal echocardiography.

Finally, we would also like to suggest a useful set-up for a cardiac catheterization laboratory used for SHD procedures that would adequately protect the interventionalist, the imager, the anesthesiologist, and other staff working in the cardiac catheterization laboratory (see Figure 1). The newly developed EggNest system may also prove promising after more real-world experience is acquired with it.

ORCIDs

Philipp Lauten https://orcid.org/0000-0001-9997-9201
Harald Lapp https://orcid.org/0000-0002-7935-7808

Funding

The authors have no funding to report.

Disclosure Statement

P. Lauten has received speaker and lecture fees from Edwards, Boston Scientific, Medtronic, and Meril. The other authors had no conflicts to declare.

References

1 Hahn RT, Mahmood F, Kodali S, et al. Core Competencies in Echocardiography for Imaging Structural Heart Disease Interventions: An Expert Consensus Statement. *JACC Cardiovasc Imaging*. 2019;12(12):2560-2570. https://doi.org/10.1016/j.jcmg.2019.10.008
2 Agricola E, Ancona F, Brochet E, et al. The structural heart disease interventional imager rationale, skills and training: a position paper of the European Association of Cardiovascular Imaging. *Eur Heart J Cardiovasc Imaging*. 2021;22:471-479. https://doi.org/10.1093/ehjci/jeab005
3 Little SH, Rigolin VH, Garcia-Sayan E, et al. Recommendations for special competency in echocardiographic guidance of structural heart disease interventions: from the American Society of echocardiography. *J Am Soc Echocardiogr*. 2023;36:350-365. https://doi.org/10.1016/j.echo.2023.01.014
4 Little SH, Echocardiography Interventional. The emergence of a new imaging specialty. *J Am Soc Echocardiogr*. 2023;36(4):A13-A14. https://doi.org/10.1016/j.echo.2023.02.003
5 Raja Shariff RE, Soesanto AM, Scalia GM, et al. Echocardiographic imaging in transcatheter structural intervention. *JACC Asia*. 2023;3(4):556-579. https://doi.org/10.1016/j.jacasi.2023.05.012
6 Hellenbrand WE, Fahey JT, McGowan FX, et al. Transesophageal echocardiographic guidance of transcatheter closure of atrial septal defect. *Am J Cardiol*. 1990;66(22):207-213. https://doi.org/10.1016/0002-9149(90)90590-W
7 Agricola E, Meucci F, Ancona F, Pardo Sanz A, Zamorano JL. Echocardiographic guidance in transcatheter structural cardiac interventions. *EuroIntervention*. 2022;17:1205-1226. https://doi.org/10.4244/EIJ-D-21-00582
8 Gao G, Penney G, Ma Y, et al. Registration of 3D trans-esophageal echocardiography to X-ray fluoroscopy using image-based probe tracking. *Med Image Anal*. 2012;16(1):38-49. https://doi.org/10.1016/j.media.2011.05.003
9 Hell MM, Kreidel F, Geyer M, et al. The revolution in heart valve therapy: Focus on Novel Imaging Techniques in Intra-Procedural Guidance. *Structural Heart*. 2021;5(2):140-150. https://doi.org/10.1080/24748706.2020.1853293
10 Ternacle J, Gallet R, Nguyen A, et al. Usefulness of echocardiographic-fluoroscopic fusion imaging in adult structural heart disease. *Arch Cardiovasc Dis*. 2018;111(6-7):441-448. https://doi.org/10.1016/j.acvd.2018.02.001
11 Fresse-Warin K, Plessis J, Benelhadj H, Guérin P. Impact of fused computed tomography and fluoroscopy in the catheterization laboratory. *Arch Cardiovasc Dis*. 2018 Jun-Jul;111(6-7):449-455. https://doi.org/10.1016/j.acvd.2018.03.001
12 DiNardo JA. Commentary: use fusion to avoid confusion. *JTCVS Tech*. 2020;3:152-153. https://doi.org/10.1016/j.xjtc.2020.06.039
13 Rudolph V, von Bardeleben RS, Hagendorff A, et al. Sachkunde Interventionelle Echokardiographie. *Kardiologie*. 2022;16:391-400. https://doi.org/10.1007/s12181-022-00567-z
14 McIlwain EF, Coon PD, Einstein AJ, et al. Radiation safety for the cardiac sonographer: recommendations of the radiation safety writing group for the Council on cardiovascular Sonography of the American society of echocardiography. *J Am Soc Echocardiogr*. 2014;27:811-816. https://doi.org/10.1016/j.echo.2014.05.015
15 ICRP. Recommendations of the ICRP. ICRP Publication 26. *Ann. ICRP*. 1977;1(3).
16 Crowhurst JA, Scalia GM, Whitby M, et al. Radiation exposure of operators performing transesophageal echocardiography during percutaneous structural cardiac interventions. *J Am Coll Cardiol*. 2018;71(11):1246-1254. https://doi.org/10.1016/j.jacc.2018.01.024
17 Salaun E, Carles S, Bigand E, et al. High radiation exposure of the imaging specialist during structural heart interventions with echocardiographic guidance. *J Am Coll Cardiol Intv*. 2017;10(6):626-627. https://doi.org/10.1016/j.jcin.2017.01.016
18 McNamara DA, Chopra R, Decker JM, et al. Comparison of radiation exposure among interventional echocardiographers, interventional cardiologists, and sonographers during percutaneous structural heart interventions. *JAMA Netw Open*. 2022;5(7):e2220597. https://doi.org/10.1001/jamanetworkopen.2022.20597
19 Ternacle J, Salaun E, Ruf T, et al. Radioprotection for the imaging specialist during structural heart interventions: not an option. *Arch Cardiovasc Dis*. 2023;116(6-7):352-356. https://doi.org/10.1016/j.acvd.2023.03.004
20 Garcia-Sayan E, Jain R, Wessly P, Mackensen GB, Johnson B, Quader N. Radiation exposure to the interventional echocardiographers and sonographers: a call to action. *J Am Soc Echocardiogr*. 2024;13:S0894-7317(24)00109-3. https://doi.org/10.1016/j.echo.2024.03.002
21 Ciraj-Bjelac O, Rehani MM, Sim KH, Liew HB, Vano E, Kleiman NJ. Risk for radiation-induced cataract for staff in interventional cardiology: is there reason for concern? *Catheter Cardiovasc Interv*. 2010;76(6):826-834. https://doi.org/10.1002/ccd.22670
22 Ciraj-Bjelac O, Rehani M, Minamoto A, Sim KH, Liew HB, Vano E. Radiation-induced eye lens changes and risk for cataract in interventional cardiology. *Cardiology*. 2012;123(3):168-171. https://doi.org/10.1159/000342458
23 Jacob S, Boveda S, Bar O, et al. Interventional cardiologists and risk of radiation-induced cataract: results of a French multicenter observational study. *Int J Cardiol*. 2013;167(5):1843-1847. https://doi.org/10.1016/j.ijcard.2012.04.124
24 Andreassi MG, Piccaluga E, Guagliumi G, Del Greco M, Gaita F, Picano E. Occupational health risks in cardiac catheterization laboratory workers. *Circ Cardiovasc Interv*. 2016;9(4), e003273. https://doi.org/10.1161/CIRCINTERVENTIONS.115.003273
25 Eagan Jr JT, Jones CT. Cutaneous cancers in an interventional cardiologist: a cautionary tale. *J Intervent Cardiol*. 2011;24:49-55. https://doi.org/10.1111/j.1540-8183.2010.00610.x
26 Eagan JT Jr, Jones CT, Roubin GS. Interventional cardiologists: beware and be aware: an updated report of radiation-induced cutaneous cancers. *Catheter Cardiovasc Interv*. 2018;91(3):475-477. https://doi.org/10.1002/ccd.27258
27 Roguin A, Goldstein J, Bar O, Goldstein JA. Brain and neck tumors among physicians performing interventional procedures. *Am J Cardiol*. 2013;111(9):1368-1372. https://doi.org/10.1016/j.amjcard.2012.12.060
28 Reeves RR, Ang L, Bahadorani J, et al. Invasive cardiologists are exposed to greater left sided cranial radiation. *J Am Coll Cardiol Intv*. 2015;8(9):1197-1206. https://doi.org/10.1016/j.jcin.2015.03.027
29 Andreassi MG, Cioppa A, Botto N, et al. DNA damage in interventional cardiologists: a case-control study. *FASEB J*. 2005;19(8):998-999. https://doi.org/10.1096/fj.04-3287fje
30 Behr-Meenen C, von Boetticher H, Kersten JF, Nienhaus A. Radiation protection in interventional radiology/cardiology-is state-of-the-art equipment used? *Int J Environ Res Public Health*. 2021;18(24), 13131. https://doi.org/10.3390/ijerph182413131
31 Uthoff H, Quesada R, Roberts JS, et al. Radioprotective lightweight caps in the interventional cardiology setting: a randomised controlled trial (PROTECT). *EuroIntervention*. 2015;11(1):53-59. https://doi.org/10.4244/EIJV11I1A9
32 Badawy MK, Deb P, Chan R, Farouque O. A review of radiation protection solutions for the staff in the cardiac catheterisation laboratory. *Heart Lung Circ*. 2016;25(10):961-967. https://doi.org/10.1016/j.hlc.2016.02.021
33 Sattar Y, Sengodan PM, Cheema MS, et al. Lead cap use in interventional cardiology: time to protect our head in the cardiac catheterisation laboratory? *Intervent Cardiol*. 2023;18:e18. https://doi.org/10.15420/icr.2023.10
34 Kuon E, Birkel J, Schmitt M, Dahm JB. Radiation exposure benefit of a lead cap in invasive cardiology. *Heart*. 2003;89(10):1205-1210. https://doi.org/10.1136/heart.89.10.1205
35 Alazzoni A, Gordon CL, Syed J, et al. Randomized controlled trial of radiation protection with a patient lead shield and a novel, nonlead surgical cap for operators performing coronary angiography or intervention. *Circ Cardiovasc Interv*. 2015;8(8), e002384. https://doi.org/10.1161/CIRCINTERVENTIONS.115.002384
36 Fetterly K, Schueler B, Grams M, Sturchio G, Bell M, Gulati R. Head and neck radiation dose and radiation safety for interventional physicians. *JACC Cardiovasc Interv*. 2017;10(5):520-528. https://doi.org/10.1016/j.jcin.2016.11.026
37 Guni E, Hellmann I, Wucherer M, et al. Effectiveness of radiation protection caps for lowering dose to the brain and the eye lenses. *Cardiovasc Intervent Radiol*. 2021;44:1260-1265. https://doi.org/10.1007/s00270-021-02831-3
38 Huet C, Dabin J, Domienik-Andrzejewska J, et al. Effectiveness of staff radiation protection devices for interventional cardiology procedures. *Phys Med*. 2023;107, 102543. https://doi.org/10.1016/j.ejmp.2023.102543
39 Schlattl H, Zankl M, Eder H, Hoeschen C. Shielding properties of lead-free protective clothing and their impact on radiation doses. *Med Phys*. 2007;34(11):4270-4280. https://doi.org/10.1118/1.2786861
40 Schmid E, Panzer W, Schlattl H, Eder H. Emission of fluorescent x-radiation from non-lead based shielding materials of protective clothing: a radiobiological problem? *J Radiol Prot*. 2012;32(3):N129-N139. https://doi.org/10.1088/0952-4746/32/3/N129
41 Murphy JC, Darragh K, Walsh SJ, Hanratty CG. Efficacy of the RADPAD protective drape during real world complex percutaneous coronary intervention procedures. *Am J Cardiol*. 2011;108:1408-1410. https://doi.org/10.1016/j.amjcard.2011.06.061
42 King JN, Champlin AM, Kelsey CA, Tripp DA. Using a sterile disposable protective surgical drape for reduction of radiation exposure to interventionalists. *AJR Am J Roentgenol*. 2002;178:153-157. https://doi.org/10.2214/ajr.178.1.1780153
43 Hirshfeld JW Jr, Fiorilli PN, Silvestry FE. Important strategies to reduce occupational radiation exposure in the cardiac catheterization laboratory: No lower limit. *J Am Coll Cardiol*. 2018;71(11):1255-1258. https://doi.org/10.1016/j.jacc.2018.01.025
44 Wilson R, Gainor J, Valeti U, et al. TCT-248 A new device to markedly reduce cardiac cath lab radiation levels. *J Am Coll Cardiol*. 2018;72(13_Supplement):B103. https://doi.org/10.1016/j.jacc.2018.08.1376
45 Galli E, Soliman-Aboumarie H, Gargani L, et al. EACVI survey on radiation exposure in interventional echocardiography. *Eur Heart J Cardiovasc Imaging*. 2024;18: jeae086. https://doi.org/10.1093/ehjci/jeae086