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# Optimization of Radiation Dose and Image Quality in Cardiac Catheterization Laboratories

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## 1. Introduction

Radiation exposure is a concern for those who participate in the practice of interventional cardiology. However, many cardiologists are unaware that they may be exposing patients to relatively high levels of radiation during cardiac catheterization procedures. Interventional cardiology techniques are highly appreciated for its less invasive character than surgery. A wide range of interventions, from diagnosis to treatment of heart and coronary specific disorders are performed in both adults and children. Interventional cardiology procedures can involve significant radiation exposure. Therefore, it is essential to reduce the radiation dose as far as possible, by keeping an adequate image quality for diagnostic and therapeutic purposes. Over the last years, introduction of new technologies like flat-panel detectors have revolutionized fluoroscopy imaging. Most of the digital detectors can potentially be used at lower doses. In practice, technical optimization studies are rarely reported (especially for cardiac catheterization laboratories), notwithstanding the fact that optimal settings could be very different from the optimal settings with the traditional image intensifier systems.
This chapter is structured in three parts. The first part focuses on background notions concerning X-ray production, radiation quantities and units, personal health risks and concepts of radiation protection. The second part reviews the radiation exposure in cardiovascular practice. The last part presents optimization strategies of image quality and radiation dose and recommendations for limiting radiation exposures.

## 2. Radiation dose related to interventional cardiology

X-rays are special types of electromagnetic radiation which can ionize matter. The interaction of radiation with tissue is dependent on the spectral distribution of the radiation as well as on the thickness, density, and atomic composition of the matter. Cardiac imaging systems use two forms of dynamic X-ray imaging: fluoroscopy and cineangiography. Fluoroscopy mode uses relatively low radiation dose levels and aids in the guidance and

positioning of medical devices within the patient. Cineangiography mode (shortly cine mode) is the acquisition of a series of high definition dynamic images. It is mainly used to image vessels injected with contrast media. The necessity of obtaining high contrast and sharp edge definition with low noise images requires higher radiation dose rates. The basic components of a fluoroscopic imaging chain are shown in Figure 1. The chain is composed by an X-ray tube and generator, which are capable to produce a stable X-ray output over long exposure times, a detector mounted opposite the X-ray tube, capable of dynamic imaging, digital image processing and storage facilities, and a display system capable for viewing real-time or recorded digital image series.

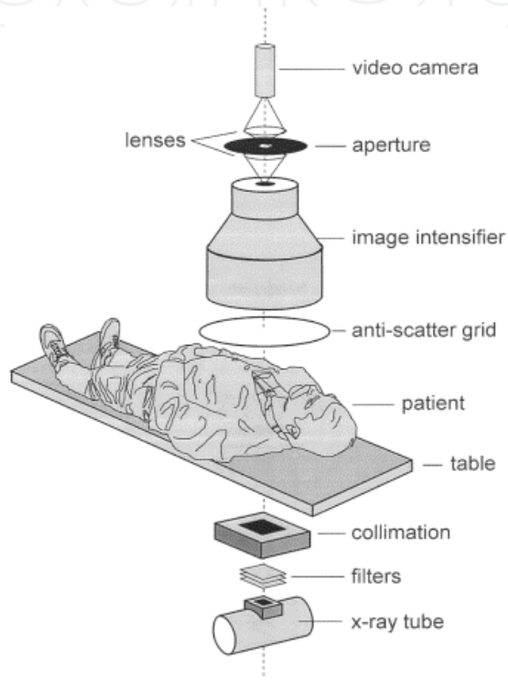


Fig. 1. Example of a fluoroscopic imaging chain equipped with image intensifier

X-ray detector is a significant component of the overall imaging chain. Two generations of detector technology are present in the catheterization laboratories: image intensifier (II) connected to a charged coupled device camera and flat-panel detectors (FD), also known as active-matrix flat-panel imagers. Briefly, for II-based fluoroscopy systems, X-ray photons exiting the patient are incident on the II's input surface. The photons strike the CsI input phosphor, absorbed and produce a large number of light photons. Then electrons are produced from visible light photons and accelerated until they hit the output screen. From the collision with output screen results light photons that are recorded by a video or cine camera. Charges coupled device camera is used for direct digitalization of the image. The process is illustrated in Figure 2, left. The FD detectors are classified into indirect and direct detectors. Indirect detectors use a phosphor (scintillator) material that absorbs X-rays and produces a proportionate number of light photons that subsequently interact with a photodiode electrode on the TFT array (thin film transistor). A typical indirect FD detector is shown in Figure 2, right. Direct FDs use a semiconductor material sandwiched between two electrodes to absorb and convert the X-ray energy directly into ion pairs. Currently, amorphous selenium (a-Se) is the only clinical choice.

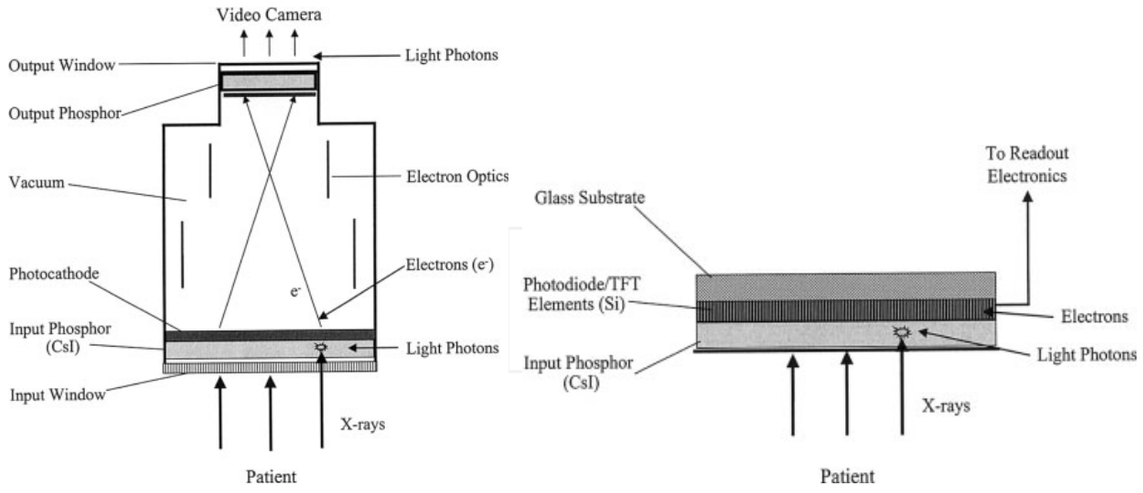


Fig. 2. X-ray detector technology. On the left, image intensifier (II) technology. On the right, flat-panel indirect detector (FD) technology.

There is a common consensus that FDs provides advantages in terms of image quality and dose efficiency comparing with II technology. Advantages include image uniformity, no geometrical distortions, no veiling glare and vignetting, wider dynamic range and better ergonomics for patient accessibility. On the other hand, for FDs, system noise remains a limiting factor and performance is rather limited for low exposure levels. (Holmes et at., 2004; Seibert, 2006; Davies et al., 2007).

### 2.1 Radiation quantities and units

Quantities describing patient dose from radiation exposures have been defined by the International Commission on Radiation Protection (ICRP, Publication 60, 1990 and ICRP, Publication 103, 2007) and by the International Commission on Radiation Units and Measurements (ICRU, Report 74, 2005). To make it simple, we will focus only on dose quantities and radiation units that are often used in interventional cardiology. We propose to divide them in three categories: dose quantities outside the patient's body, dose quantities to estimate risks of skin injuries and effects that have threshold and dose quantities to estimate stochastic risks.

Radiation quantities outside the patient's body are used to describe the beam of X-rays. These quantities can express total amount of radiation or can express radiation at a specific point. The X-ray beam is emitted from a small source (point) from the tube and is constantly spreading out as it moves away from the source. Absorbed dose, D, is the mean energy imparted per unit mass by ionizing radiation. The SI unit of D is the Gray (Gy), where 1 Gy = 1 J/Kg. The Kerma (Kinetic Energy Released in a MAterial) is the sum of the initial kinetic energies of all charged ionizing particles liberated by uncharged particles in a material of a specific mass. The SI unit is also Gray (Gy). To make it simply, in diagnostic radiology, absorbed dose D and Kerma are equal. It is possible to calculate the absorbed dose in a material if the exposure is known, by using a conversion coefficient depending on medium. Absorbed dose or air kerma in X-ray field can be measured with dosimeters. A practical quantity that gives an indication of the absorbed dose is dose-area product (DAP) or kerma-area product (KAP). It is the product of dose to air (air kerma) and the area of the X-ray beam, and it is expressed in units Gy*cm². The use of DAP-meter provides a complete

measurement of the total exposure of the patient. The DAP-meter is a flat large-area ionization chamber mounted at the exit window of the X-ray tube and intercepts the entire useful beam. In interventional cardiology, we work also with other quantities that influence radiation dose. One of them is fluoroscopy time, which can be adopted as starting unit in a quality assurance program (for comparison between operators, centers, procedures, for the evaluation of protocols, and for the evaluation of operator skills). Other quantity is the number of acquired cineangiographic images or number of series.

Entrance skin dose (ESD) includes the scatter from the patient. ESD = D*BF, where backscatter factor ranges from 1.2-1.4 as a function of field size. The SI unit for ESD is the Gray (Gy). Values of absorbed dose to tissue, compared with to air, will vary by a few percent depending on the exact composition of the medium that is taken to represent soft tissue. To evaluate the dose inside the patient's body, we use the mean absorbed dose in a tissue or organ, $D_T$, in fact the energy deposited in the organ divided by the mass of that organ. Organ doses cannot be measured on real patients. They can be measured in anthropomorphic phantoms simulating examinations or by dedicated software tools that simulates the interaction of X-rays on mathematical or realistic phantoms.

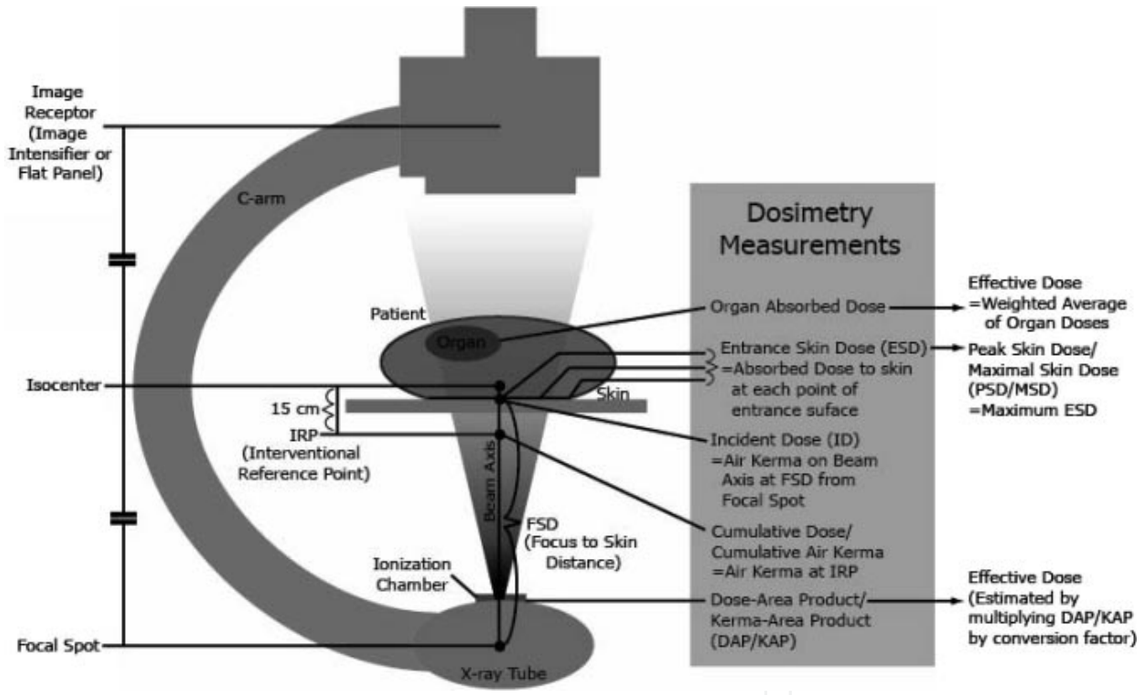


Fig. 3. Dosimetry terminology used in interventional cardiology (Adapted from ICRP Publication 85).

A second category of dose quantities are the ones related to estimate risks of skin injuries and effects that have threshold. Approximate entrance dose thresholds have been determined for various skin changes, ranging from early transient erythema at 2 Gy to painful dermal necrosis of about 18 Gy. For interventional procedures, maximal skin dose (MSD) can be assessed with different methodologies: (a) by direct calculation, with off or on-line techniques, (b) by direct measurements on the patient with point detectors (thermoluminescent detectors, TLDs, or other solid state detectors), (c) by direct

measurements on the patient with large area detectors (films and TLDs array), and (d) by portal monitoring with area or point/area detectors. The new cardiac X-ray systems are able to display on the monitors dosimetric parameters at the interventional reference point (IRP). The IRP is the reference point intended to be representative of the position of the patient's skin at the entrance site of the X-ray beam during an interventional procedure. For fluoroscopic systems with an isocentre, the IRP is located along the central ray of the X-ray beam at a distance of 15 cm from the isocentre in the direction of the focal spot (Figure 3).

Radiation exposure of the different organs and tissues in the body results in different probabilities of harm and different severity. The combination of probability and severity of harm is called detriment. For instance in young patients, organ doses may significantly increase the risk of radiation-induced cancer in later life. The equivalent dose (H) is the absorbed dose multiplied by a dimensionless radiation weighting factor, $w_R$, which expresses the biological effectiveness of a given type of radiation. $H = D \times w_R$ . The SI unit of H is the Sievert (Sv). For X-rays, the $w_R$ is 1 so H is equal to D. The mean equivalent dose in a tissue or organ $H_T$ is the energy deposited in the organ divided by the mass of that organ. To reflect the detriment from stochastic effects due to the equivalent doses in the different organs and tissues of the body, the equivalent dose is multiplied by a tissue weighting factor, $w_T$. The equivalent doses to organs and tissues weighted by the relative $w_T$ are summed over the whole body to give the effective dose, E. The SI unit of E is also the Sievert (Sv). $E = \sum_T w_T \times H_T$ . Till 2007 the tissue weighting factors of ICRP Publication 60 were used. A recent estimation of those factors was published in ICRP report 103. Main differences between publications for tissue weighting factors, $w_T$ are presented in Table 1. Stochastic risk is calculated multiplying effective dose by a risk factor specific for sex and age at the exposure.

Figure 3 illustrates the dosimetry terminology used in interventional cardiology. To summarize, the biological effects and risks from ionizing radiation are divided into deterministic and stochastic effects. Deterministic effects have a dose threshold, and the intensity of the effect increases with increasing dose. Stochastic effects include cancer and genetic risk. Probability of stochastic risks increases with increasing dose, but the intensity of the effect is not a function of the absorbed dose. For personnel working in cardiac catetherization laboratories, the major worries about radiation exposure are the potential risk of cancer, cataracts, and genetic birth defects of pregnant staff if the appropriate protective measures are not used. For patients, deterministic effects can be produced by high doses of fluoroscopic X-rays. In addition, stochastic effects can appear on patients with repeated interventional cardiac procedures, especially if are performed in young population.

Risks of exposure to ionizing radiation are contra balanced by the need for and potential benefit for a patient to have a cardiac interventional procedure. In fact medical use of radiation is a unique situation in which patients are intentionally irradiated. The risk should be minimised by utilizing techniques and procedures that keep exposure to a level *As Low As Reasonably Achievable* (ALARA principle). The principle of ALARA is the axiom for all radiation workers. Its successful implementation in catheterization laboratory require understanding of factors responsible for levels of radiation exposure and applying optimized procedures to obtain the medical diagnostic or therapeutic goal with minimum radiation risks.

| ICRP Report 60 (1990) | | ICRP Report 103 (2007) | |
|---|---|---|---|
| Tissue | Tissue weighting factor, $w_T$ | Tissue | Tissue weighting factor, $w_T$ |
| Lung | 0.12 | Lung | 0.12 |
| Stomach | | Stomach | |
| Colon | | Colon | |
| Bone Marrow | | Bone Marrow | |
| | | **Breast** | |
| | | **Remainder** | |
| Gonads | 0.20 | Gonads | 0.08 |
| Thyroid | 0.05 | Thyroid | 0.04 |
| Oesophagus | | Oesophagus | |
| Bladder | | Bladder | |
| Liver | | Liver | |
| Breast | | | |
| Remainder | | | |
| Bone surface | | Bone surface | |
| Skin | | Skin | |
| | | Brain | |
| | | Salivary glands | |

Table 1. Differences between $w_T$ tissue weighting factors in ICRP Publication 60 and Publication 103.

## 3. Literature review of patient and staff doses in clinical practice

Interventional cardiology procedures are usually fluoroscopy guided diagnostic and therapeutic interventions. Therapeutic interventions are often complex procedures and sometimes procedures are repeated for the same patient. In these situations patient high radiation dose levels occur. The specialized literature presents a series of case reports describing deterministic effects with growing incidence and more concern than stochastic long term risks. International Commission on Radiological Protection and World Health Organisation has requested attention to the skin dose problems of complicated radiological interventions. In this context, patient dosimetry approaches are an important issue. Many published dose data are expressed in terms of not particularly well defined dose quantities and without clear objective for the measurements performed. This section of the work aims to report and compare dosimetry approaches and eventually propose a classification of the different dosimetry objectives. Patient dosimetry methods currently used in interventional cardiology may be divided in three categories according to their purposes: (1) dosimetry for quality assurance; (2) dosimetry for stochastic risk evaluation, (3) dosimetry for deterministic effects evaluation.

**Dosimetry for quality assurance** is used to compare performance of equipment, operator skills or radiological practice among different teams or centers, to evaluate the optimization process or to establish diagnostic reference levels (DRL) for routine examinations. Useful dose quantity is the dose – area product, DAP. For cardiac

procedures, usually the total DAP for whole procedure is documented. Sometimes, the DAP for the fluoroscopy part ($DAP_{fluoro}$) and the DAP for the cineangiography part of a procedure ($DAP_{cine}$) are indicated. Some authors propose additional technical quantities like the total fluoroscopy time of a procedure, the total number of acquired images, the number of series of acquired images, the mean number of images per series in a procedure. **Dosimetry quantities for stochastic risk evaluation** are organ equivalent doses to organ/tissue and effective dose. These quantities are indicators of overall exposure in the assessment of stochastic effects of radiation exposure for population. Use of these quantities allows us to compare exposures from different types of procedure, radiation type, and radiation quality, and irradiation geometry. From effective dose, using correct risk coefficients (ICRP Report 103), we can estimate the detriment of individuals or population from medical exposure. **Dosimetry for deterministic effects** focuses on skin dose assessment. For complex interventional cardiology procedures, the knowledge of irradiated skin area is important with respect to the potential for deterministic effects of radiation exposure. Different methodologies are used to express the maximal skin dose (MSD): off-line or on-line calculation, direct measurements on the patient with point detectors (TLDs or solid state detectors), direct measurements on the patient with the area detectors (TLD array and film) or by portal monitoring with point or area detectors. Unfortunately not all methods are feasible for routine work, specially the on-line ones. An alternative approach on two levels can be used. The first level able to prevent deterministic effects is using a threshold. This can be fluoroscopy time or a measurable quantity like DAP, able to alert the operator that a certain value of skin dose, corresponding to a threshold for deterministic effects can be reached. The second level to assess MSD requires specific methods. In case of electrophysiology procedures where stationary fields are used, electronic point detectors or computational methods able to assess skin dose distribution can be employed.

We will present a summary of published patient doses in interventional cardiology. Any attempt to compare published studies must be performed with circumspection due to the lack of standardization of data acquisition and the uncontrolled variables (equipment differences, radiographic technique, complexity of procedure, patient characteristics (size, age, sex).

### 3.1 Patient radiation doses during diagnostic and interventional cardiac catheterization

The most frequent procedures in adults are coronary angiography (CA) for diagnostic and percutaneous coronary intervention (PCI) for therapeutic examinations. Consequently, there are a large number of articles that review the patient radiation doses. For CA procedures, some authors report data for subcategories of procedures like CA with left ventricular angiography, or/and cardiac catheterization. PCIs are more complicated to classify because of the large number of technical factors, like number of lesions treated, the wire technique, simple, ostial or bifurcation stenting, flow and pressure wire or any other special devices. The most common quantities used were: DAP, fluoroscopy time, cine frames, cine time (dosimetry for quality assurance), effective dose (dosimetry for stochastic risks), and skin dose (dosimetry for deterministic risks). Published results are presented in Table 2 for CA and in Table 3 for PCI procedures. The studies presented are a little part of the literature survey. We present only median values and, where available, the range. We looked for studies from different time periods. It is evident from the tabulated data that the reported

values for interventional cardiology procedures vary considerably. This can be attributed to procedural complexity, examination technique, use of radiation-reducing techniques, operator experience, workload, and catheterization laboratory examination. For example, Broadhead et al, 1997 compared patient dosimetry between single intensifier system and biplane image intensifier system, and found that the biplane system provides greater imaging capability but with increased dose. DAP for CA is 47.7 vs. 23.4 Gycm² (biplane vs. single system), and for PCI is 72.2 vs. 51.6 Gycm².

| Study | Sample (number cases) | DAP (Gycm²) | Fluoroscopy time (min) | Cine frames (images) | Maximum skin dose (mGy) | Effective dose (mSv) |
|---|---|---|---|---|---|---|
| | | Median ( Range min - max) | | | | |
| Zorzetto, 1997 | | 52.5 | 4.9 | 1350 | | |
| Broadhead, 1997 | 2174 | 58.8 | | | | 9.4 |
| van de Putte, 2000 | | 56.8 ( max 144) | | | 412 – 725 | |
| Eftathopoulos, 2003 | 20 | 29 | | | | 5 |
| Kuon, 2003 | 509 | 23.6 | 3.4 | 339 | | |
| Dragusin, 2005 | 78 | 25.6 (9 -115) | 4 (1 – 25) | 767 (318 – 1331) | | |
| Karambatsakiou, 2005 | 20 | (18 -107) | | | | |
| Vijakalakshmi, 2007 | 3752 | 19.1 | | | | 4.8 |
| D'Helft, 2008 | | 13.6 – 231 | 0.22 – 27.6 | | | |
| Tsapaki, 2008 | 549 | 31 ( 1 – 135) | 4 (0.8-57) | 688 (62 -2206) | | |
| Bogaert, 2008 | 200 | | | | | 7.3 |
| Dragusin, 2010 | 122 | 11.6 | 3 | 506 | | |
| Samara, 2010 | | 55 ( max 235) | 3.1 ( max 65) | | | |

Table 2. Short review of patient doses during coronary angiography (CA) examinations

Bernardi et al., 2000 and Padovani et al., 2001 investigated the effect of complexity of PCI interventions, by separating the procedures in "simple", "medium" and "complex" procedure, based on a set of technical and clinical factors. (Median DAP values 66.7,96.4 and 132.7 Gycm²). Sandborg et al, 2003 compared the radial arterial approach to the femoral approach in term of radiation dose. They found that radial approach yielded significant higher doses (51 and 75 Gycm² for CA, respectively PCI), compared with femoral approach (38 and 47 Gycm²). Tsapaki et al. 2004 and Trianni et al., 2005a compared the patient doses of flat-panel systems (FD) to image intensifier (II) systems. Despite of the potential of FD to produce images of higher quality with lower entrance detector dose rates, in clinical practice and terms of patient dose could give opposite results. Trianni et al., 2005a reported 33.4 Gycm² (for FD) and 31,1 Gycm² (for II) during CA examinations and 66.9 Gycm² (for FD) and 52 Gycm² (for II) during PCI examinations. Some publications presented patient dosimetry in term of contribution of fluoroscopy and image acquisition to the total DAP

(Efstathopoulos et al., 2003, Kuon et al., 2004). Mean DAP for fluoroscopy and image acquisition calculated from the values reported in these studies are 18% DAP fluoroscopy and 81% DAP image acquisition for CA procedures. For PCIs, DAP is 41% from fluoroscopy and 59% from image acquisition. The patient radiation doses vary widely among published studies. These differences are related to patient, procedure, X-ray equipment and physician.

| Study | Sample (number cases) | DAP ($Gycm^2$) | Fluoroscopy time (min) | Cine frames (images) | Maximum skin dose (mGy) | Effective dose (mSv) |
|---|---|---|---|---|---|---|
| | | Median ( Range min - max) | | | | |
| Zorzetto, 1997 | | 82.6 | 12.2 | 1500 | | |
| Broadhead, 1997 | 214 | 77.9 | | | | 14.2 |
| van de Putte, 2000 | | 108 – 131 | | | | |
| Eftathopoulos, 2003 | 20 | 75 | | | | 14 |
| Kuon, 2003 | 233 | 22.2 | 9.7 | 208 | | |
| Dragusin, 2005 | 23 | 9 – 148.4 | 1.4 -44.5 | 206 -1524 | | |
| Karambatsakiou, 2005 | 10 | 16 - 115 | | | | |
| Vijakalakshmi, 2007 | 646 | 35 | | | | 9.3 |
| D'Helft, 2008 | | 47.5 - 413 | 2-98 | | | |
| Tsapaki, 2008 | 549 | 62 | 10.4 (3.2-53) | 1257 (398-5940) | 799 (320-1660) | |
| Bogaert, 2008 | 118 | | | | | 11.6 |
| Dragusin, 2010 | 91 | 32.7 | 12.6 | 938 | | |
| Samara, 2010 | | 144 | 9.1 (max 52) | | | |

Table 3. Short review of patient doses during percutaneous coronary intervention (PCI) examinations

### 3.2 Patient radiation doses radiation doses during electrophysiology studies and pacemaker implantations

Cardiac electrophysiology is a subdiscipline of interventional cardiology that is focused on elucidating, diagnosing, and treating the electrical problems of the heart. The procedures are performed by invasive intracardiac catheter recordings of spontaneous activity as well as of cardiac responses to programmed electrical stimulation. These studies are performed to evaluate abnormal electrocardiograms and to assess complex arrhythmias. Typically therapeutic procedures are radiofrequency catheter ablations (RFCA). Patient doses are also influenced by the type of procedures. Diagnostic electrophysiological study (EPS) relies mainly on fluoroscopy. For therapeutic procedures, we can find different categories: RFCA without angiographic images using contrast medium, RFCA with angiographic images using contrast medium and RFCA of atrial fibrillation (AF) (Dragusin et al., 2005). The dosimetric data of this study is presented in Table 4. In the case of therapeutic examinations,

the radiation doses varied according to the location of the tachycardia. Ablations in which contrast medium is used to take images need more radiation exposure. RFCA of atrial fibrillation had longer examination times and yielded the maximum radiation doses.

| Parameter | Type of procedure (number cases) | Range | Mean ± SD | Median | Third quartile |
|---|---|---|---|---|---|
| DAP ($Gycm^2$) | EFO (72) | 0.5 – 77.5 | 13.8 ± 16 | 7.2 | 17.3 |
| | RFCA without contrast (85) | 1.5 – 93.2 | 21.9 ± 20.5 | 14.3 | 27.9 |
| | RFCA with contrast (52) | 1.5 – 102.1 | 34.3 ± 26 | 32.1 | 47.6 |
| | AF (36) | 33.6 – 440.2 | 156.3 ± 99.4 | 129.6 | 183.6 |
| Fluoroscopy time (min) | EFO (72) | 1.6 – 39 | 11.2±8.6 | 8 | 13.8 |
| | RFCA without contrast (85) | 4.4 – 48.8 | 23.7±11.2 | 20.7 | 30.3 |
| | RFCA with contrast (52) | 10 – 61.3 | 26.5±11.2 | 22.9 | 31.2 |
| | AF (36) | 27.6 - 130 | 67.6±24.7 | 66.4 | 85.5 |

Table 4. Summary of patient radiation data for electrophysiological procedures (Dragusin et al., 2005)

Trianni et al., 2005b collected patient skin doses from 90 electrophysiological procedures. Mean maximum local skin doses were 0.03 Gy for pacemaker insertion, 0.17 Gy for RFCA for nodal tachycardia and 0.22 Gy for atrial fibrillation. Ector et al., 2007 investigated the effect of body mass index on radiation doses in patients undergoing pulmonary vein isolation for atrial fibrillation. 85 patients undergoing AF ablation guided by biplane low-frequency pulsed fluoroscopy (3 frames/s). Mean DAP values per hour of fluoroscopy were 58, 110 and 184 $Gycm^2$ in normal, overweight, and obese patients. The corresponding effective dose for AF ablation procedures were 15.2, 26.7, and 39 mSv.

### 3.3 Patient radiation doses radiation doses during pediatric cardiovascular procedures

According to the Euratom Directive 97/43, exposures of children and procedures involving high doses to the patient, such as interventional radiology, should be given special attention. Both criteria apply to the pediatric cardiac catheterization laboratories, so patient dose evaluations should thus be established with priority. On pediatric patients both diagnostic and therapeutic procedures are performed. Diagnostic examinations study complex congenital heart diseases. Therapeutic procedures mainly involve dilatation of stenotic vessels or valves and occlusion of abnormal communications. The main therapeutic procedures are balloon dilatation of the pulmonary valve, balloon dilatation of peripheral pulmonary stenosis, balloon dilatation for coarctation of the aorta, stent implantation, occlusion of patent ductus anteriosus, closure of atrial septal defect and closure of ventricular septal defect. We will discuss the results of a study regarding pediatric radiation doses performed in a catheterization laboratory equipped with a biplane FD system (Dragusin et al., 2008a). In this study, the population was divided in six age groups (0-30 days, 1-12 months, 1-3 years, 3-5 years, 5-10 years and 10-15 years). Data from 273 patients are presented in terms of DAP, fluoroscopy time and number of image acquisition series. For diagnostic procedures the median values per age group are 2.7, 2.5, 5.1, 5.8, 7.1, 9.9 $Gycm^2$, 11, 6, 10, 8, 8, 5 minutes, and 8, 6, 6, 10, 8, 6 acquisition series. For therapeutic procedures the median values per age group are 4.8, 5.9, 7.5, 9.5, 17.1, 46.8 $Gycm^2$ for DAP,

16.5, 12, 16, 18, 21, 20 minutes for fluoroscopy time and 9, 14, 12, 18, 22, 19 acquisition series. The effective doses for each patient were estimated using PCXMC software (STUK, Finland). The 25th, 50th and 75th percentile per each age group for diagnostic procedure is presented in Figure 4 and for therapeutic procedures is presented in Figure 5.

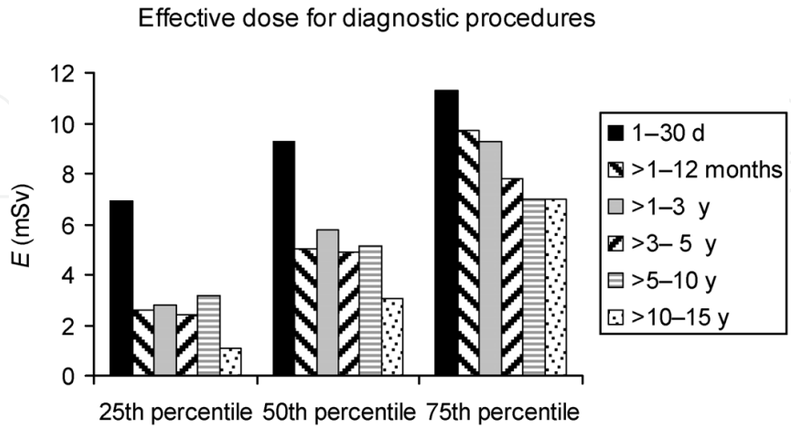


Fig. 4. Estimated effective doses for diagnostic procedures in pediatric interventional cardiology (Dragusin et al., 2008a)

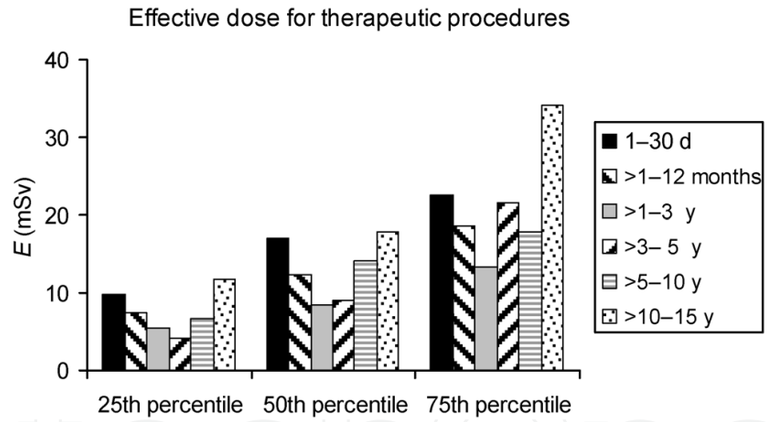


Fig. 5. Estimated effective doses for therapeutic procedures in pediatric interventional cardiology (Dragusin et al., 2008a)

Other study reported DAP values as 75th percentile of 6.2, 6.1, 9, 10, 15, 20, 27 and 36 Gycm² for 2114 patients divided in eight age groups from newborns to 21 y (Rassow et al.,2000). This study included diagnostic, therapeutic and myocardial biopsy procedures. Bacher et al., 2005 studied 60 patients of which 28 underwent diagnostic imaging. Patients age ranged from new born to 10 y. The DAP range for diagnostic was 0.96–14.6 Gycm2 and for therapeutic 0.4–20.4 Gycm2. Onnasch et al.,2007 expressed the results of dose data of a large population as DAP/body weight (Gycm²/kg) rather than DAPs for age groups. Using the 90th percentiles, he suggested as diagnostic reference level values of 0.81 Gycm²/kg for diagnostic procedures, and 1.16 Gycm²/kg for therapeutic interventions. Effective doses of 0.6 to 23.2 mSv for diagnostic procedures and from 1 to 37 mSv for therapeutic procedures were estimated by Bacher et al., 2005.

A number of specific conditions, such as higher heart rates, smaller cardiovascular structures, smaller body size, and wider variety of unusual anatomic variants with the potential need for relatively lengthy and complex studies, result in relatively high radiation doses to the patient. The improved survival of patients with complex anatomy (e.g., palliated single ventricle anatomies) implies that many such children with chronic cardiac disease require frequent catheterizations within the first few years of life. These factors, coupled with the increased radiosensitivity of children and a longer lifespan ahead of them in which to possibly develop radiation-related sequels, converge to create potentially unpleasant consequences.

### 3.4 Staff dosimetry

Occupational doses in interventional procedures guided by fluoroscopy are the highest doses registered among medical staff using X-rays. Interventional cardiologists experience radiation exposure with the patient, as they are close to the radiological source. Interventional cardiologists working in high-volume cardiac catheterization laboratories are exposed to significant occupational radiation risks of developing certain diseases, including hematopoietic cancers, thyroid diseases, skin diseases, cataracts, or upper respiratory disease (Venneri et al., 2009). Consequently, monitoring personnel exposure is compulsory and regulated for individual workers. Occupational doses limits apply, i.e a limit on effective dose of 20 mSv/year, averaged over 5 years. The equivalent dose should not exceed 150 mSv for lens of the eye, 500 mSv for the skin (average dose over 1 $cm^2$ of the most highly irradiated area of the skin) and 500 mSv for the hands and feet. Wraparound two-piece aprons, thyroid shields and eye protection are important personnel shields. Personnel dosimetry monitors include those using X-ray films (film badges) or thermoluminescent dosimeters (TLDs). Both detectors are placed in holders and the monitors are typically worn for one month before being submitted for processing. The laboratory readout the detectors and estimate the effective dose. For interventional cardiologists, it is recommended to wear two badges. One is worn outside the apron at the neck and one is worn under the apron at the waist. The second badge monitors the effectiveness of the lead apron. For other staff in the catheterization laboratory, a single badge is worn and it is usually placed outside the apron at collar level. The mean collar-level exposure per case for cardiologist who performs CA and PCI has been reported to be 0.04 to 0.16 mSv (Hujkens & Hummel, 1995, Zorzetto et al., 1997). Certain publications focus on the estimation of personnel doses for different anatomical locations by placing TLDs for each procedure. For example, Efstathopoulos et al, 2003 measured doses with five TLDs placed on the left branch of eyeglasses, the chest over and underneath the lead apron, the left hand and knee. The results of dose/procedure for cardiologists were 6 μGy (eyes), 0 μGy (chest under apron), 5.75 μGy (chest over apron), 22.5 μGy (left hand), 16.75 μGy (left knee). The assisting operator received less dose/procedure: 5.5 μGy (eyes), 0 μGy (chest under apron), 4 μGy (chest over apron), 17.5 μGy (left hand), 3.5 μGy (left knee). An interesting survey was performed by Vano et al, 2006, that evaluated the occupational doses of cardiologist for a period of 15 years (1989 to 2004). The mean values in mSv/year decreased from 11.6 (1989-1992) to 1.6 (1993-1998) and to 1.2 (1999-2004). The success of reduction in the effective dose by a factor of 10 is explained mainly by the training in radiation protection, optimization of procedures and improved performance of X-ray systems.

In conclusion, accumulation of radiation doses to interventional cardiologists has the potential of increasing risk of stochastic effects. To prevent radiation–associated diseases, radiation exposure to cardiologists should be reduced by using new generation cardiac X-

ray systems, performing diagnostic and interventional procedures with shorter fluoroscopic times, and using effective shielding to protect from radiation.

## 4. Optimization strategies of image quality and radiation dose

In cardiac catheterization laboratory, the goal of the ALARA (As Low As Reasonably Achievable) principle is to provide maximal diagnostic and therapeutic outcome while requiring the lowest possible radiation dose. The following discussion focuses on the compromise between radiation dose and image quality. There are few directions to follow. First element on the equation of the dose-image quality is the cardiac catheterization laboratory equipment. Taking into account the advances in technology, today modern cardiac catheterization systems are equipped with reliable X-ray generation tubes and flat panel detectors. If most of the laboratories are equipped with mono plane systems, for electrophysiology or pediatric applications biplane equipments are probably more appropriate. This choice depends on the cardiology practice. The imaging chain has an important feature, the Automatic Exposure Control (AEC) that ensures relatively constant image brightness. The AEC works as a feedback mechanism from the digital video processor to the X-ray generator. As mentioned before, the cardiac X-ray system is capable of different imaging modalities. Fluoroscopy mode is used for live, real-time viewing and provides sufficient image quality to visualize the catheters. For permanent storage and review, images of higher image quality are acquired in cineangiography mode. Nowadays, all systems are delivered with pulsed fluoroscopy, with a range of pulse rate from 30 to 3 pulses/second. Note that the lower the pulse frequency the less radiation dose, at the expense of a jerkier motion. The systems have the capability to store the last fluoroscopic images as film (option "fluoro store" or "hold last image"). Cineangiography mode rates vary from 60 to 15 or 30 frames/second. Most of adult angiograms are performed at 15 frames/second, but faster frame rates are necessary for pediatric patients to view rapidly moving structures throughout the cardiac cycle.

Optimization of new cardiac equipment with flat panel detector consists of finding the adapted configuration that offers an acceptable image quality with relatively low dose. The detector entrance dose is known to influence the image quality, at least in the clinically used dose range. In practice, various settings of the system lead to different patient dose levels. The spectrum of the beam can be influenced by the kV, added Cu filtration, thickness of the patient and the presence or absence of the grid. Dragusin et al., 2008b investigated influence on image quality of three factors: detector entrance dose, effect of antiscatter grid and patient thickness using two contrast phantoms (Leeds TO10 and CDRAD). These phantoms were imaged in fluoroscopy and cineangiography mode. For cineangiography mode six levels of detector entrance dose were used: 100, 120, 140, 170, 200 and 240 nGy/frame for a rate of 15 frames/second. For fluoroscopy mode, three levels: low (10 pulses/second, detector entrance dose 32 nGy/pulse), medium (15 pulses/second, 45 nGy/pulse) and high (15 pulses/second, 65 nGy/pulse). The average fitted contrast-detail curve for CDRAD phantom for different entrance detector doses is presented in Figure 6. The variation of the contrast-detail curve with patient thickness (9 cm, 13 cm, 17 cm and 21 cm equivalent plexiglass material) is presented in Figure 7. The configuration of X-ray system corresponds to the acquisition mode 15 frames/second and 170 nGy/frame detector entrance dose. When looking at graphically representation of contrast-detail curves, it should be noted that improved image quality makes the curve to shift to the lower part of the graph. In Figure 6,

it is evident that the poorest image quality corresponds to the fluoroscopy mode and the better image quality corresponds to acquisition mode with maximum detector entrance dose (240 nGy/frame).

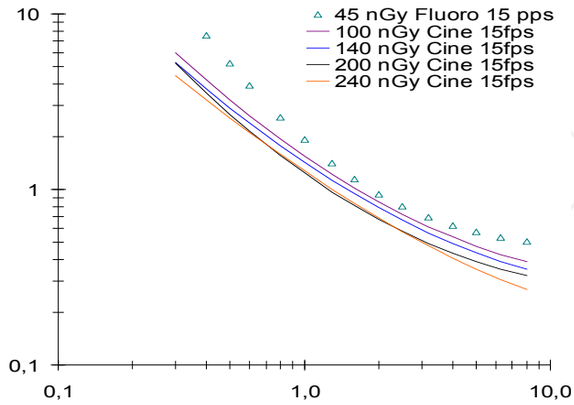


Fig. 6. Contrast-detail curves for CDRAD phantom for fluoroscopy mode and cine mode for different detector entrance doses.

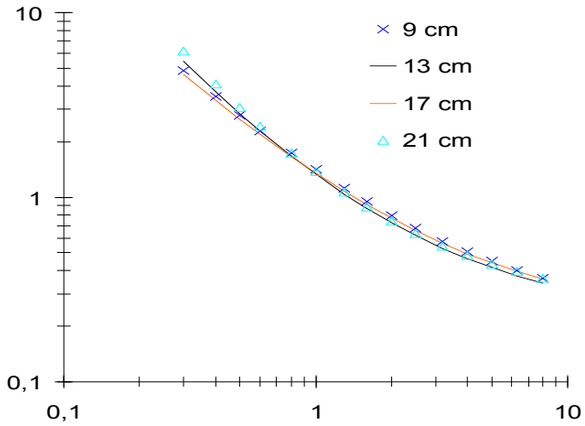


Fig. 7. Contrast-detail curves for CDRAD phantom for cine mode (15 frames/second; 170 nGy/frame) and different simulated patient thicknesses.

The improvement in image quality between settings is not very clearly visible because of the small changes in detector dose levels. Differences between detector dose settings are not significan (a factor of 2.4 between the minimum 100 nGy and maximum 240 nGy). This implies a little change in threshold contrast. Despite of the limitation of this study, the authors observed that just a simple change of the detector entrance dose from a superior to a next inferior setting (i.e. from 170 nGy/frame to 140 nGy/frame) will not dramatically change image quality. This simple action would potentially reduce the patient skin dose between 14-19% depending of the size of the patient. The limitation of the use of contrast detail phantoms consists of the difficulty to link with clinical image quality requirements. In particular for interventional cardiology, visualization of moving structures, visualization and grading of subtle lesions or anatomical structures during the passage of a contrast agent and the tracing of small catheters on the moving heart, implies the use of test objects that

simulates this environment. To visualize moving structures in cardiovascular fluoroscopy systems, some dynamic phantoms have been created. Guibelalde et al., 2001 have constructed the Patient Movement Simulation Test Object (PAMOSITO), a 2D motor-controlled test object holder to simulate clinical situations in which patient movement could be a cause of image degradation. The Society for Cardiac Angiography and Interventions (SCA&I) and the National Electrical Manufacturers Association (NEMA) developed a phantom that allows visualizing moving structures. The device is a rotating spoke that contains five steel wires of different diameters. Two lead dots are used to evaluate lag and recursive filtering (Balter et al.,2001). Both dynamic phantoms have the disadvantage that they do not incorporate details or features that are directly linked with critical issues in clinical cardiac images (i.e., circulation of contrast agent, anatomical background, lesions or pulsating arteries).

Dragusin et al., 2008c used a phantom that models the human anatomy from the knee to the neck. The modular design of the phantom contains also the heart (dimensions 15 cm (atria/apex) x 10 cm wide x 9 cm (anterior/posterior). The arterial tree model is fabricated in transparent polyurethane. Calcifications can be inserted into main arteries. Medical devices like catheters can be inserted into the model, positioned in a particular arterial branch and visualized on X-ray images. A pump circulates flow through the vasculature of the phantom. The contrast agent boluses are injected in the circuit via femoral catheters (Figure 8).

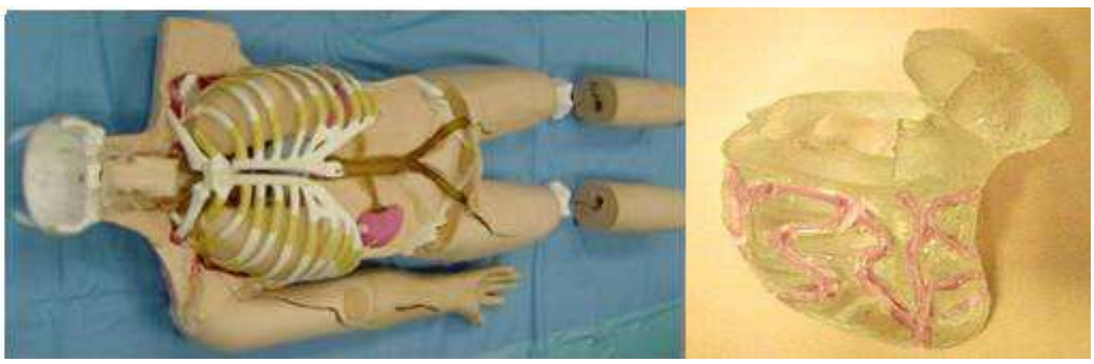

Fig. 8. (Left) Synthetic Arterial Model (SAM) integrated into phantom body. (Right) Close-up view of the heart model with coronary grooves highlighted

In this experiment were studied the effect of four technical variable of the X-ray equipment with an anticipated influence on image quality: tube voltage (kV), additional Copper filtration (mm Cu), detector entrance dose and dynamic density optimization (DDO). The last variable is particular to Siemens cardiac catheterization systems equipped with flat panel detector and is a image quality (post processing) parameter that works in real-time by harmonizing the distribution of gray steps in the image. The X-ray filming of the phantom allows the cardiologist to track the contrast agent circulation, to identify coronary lesions and evaluate their visibility in rapport with anatomical structures. In this study four calcified structures in the coronary arteries were used to simulate stenotic lesions. The first lesion was located on the proximal left anterior descending (LAD) segment, the second on the mid LAD segment, the third on the proximal circumflex segment (Cx) and the fourth on the distal Cx segment. Typical radiographic images, with indication of the lesions, are presented in Figure 9.

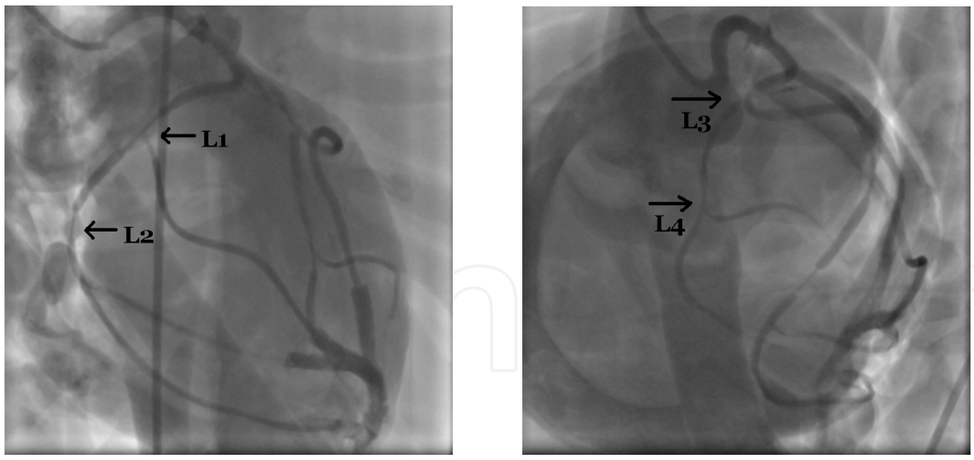


Fig. 9. X-ray images of the heart phantom under different experimental conditions. L1 to L4 indicate the location of simulated lesions.

The contrast media (Iodine) was injected in the phantom using the hand technique and a 6F catheter. 15 to 20 ml of iodine was used at the same flow rates and the image sequence is started a few seconds after the injection. For full characterization of the lesions, sets of two coronary angiograms from two viewing angle were recorded: RAO 30° and LAO 40°/CAUD20° (where RAO the right anterior oblique view, LAO the left anterior oblique direction and CAUD the caudal inclination). The duration of the angiograms was 5 seconds and was acquired at a rate of 15 frames/second. The angiograms were presented in a random order to eight interventional cardiologists (4 experienced interventional cardiologist and 4 residents). The observers were asked to subjectively assess the visibility of each simulated lesion and to give an overall score for each angiogram by using a five-point scale: 1 = not visible; 2 = poor visibility; 3 = acceptable visibility; 4 = good visibility and 5 = very good visibility. The evaluation of angiograms is presented in terms of image quality (IQ) scores. For every angiogram entrance skin dose was measured and an effective dose was estimated. Mean IQ scores ranged from 1.68 to 4.88. The highest IQ scores were obtained for the angiograms acquired with tube potential 80 kV, no added Cu filters, DDO 60%, RAO and LAO views and the highest entrance detector dose that has been used in the present study, namely 170 nGy/frame. Radiation doses (entrance skin dose approximately 40 mGy and effective dose of 1 mSv) were estimated for angiograms acquired at 15 frames/second, detector field-of-view 20 cm, and a length of 5 s. The following parameters improved the IQ factor significantly: a change in tube potential from 96 to 80 kV, detector entrance dose from 100 nGy/frame to 170 nGy/frame, the absence of Copper filtration. DDO variable which is a post-processing parameter should be carefully evaluated because it alters the quality of the images independently of radiation exposure settings. The SAM anthropomorphic phantom has the advantage of visualization of stenotic lesions during the injection of a contrast agent and using an anatomical background. In the future, this phantom could potentially bridge the gap between physics tests and the clinical reality in the catheterization laboratory. Future generation of phantoms should simulate the beating heart.

Optimization of X-ray equipment settings through experimental measurements is necessary, mainly when it involves new equipment or technology. The acceptance of optimized settings that affects image quality and radiation dose has to be accompanied by the training of the user. Authors of this work have experience in this area. In our center in Luxembourg

(Institut National de Chirurgie Cardiaque et de Cardiologie Interventionnelle), we perform continuously an internal audit related to radiation protection in clinical practice. Some results of our experience were already published (Bokou et al., 2008; Dragusin et al., 2010). All interventional cardiologists have taken part of two days continuous education course in radiation protection. The course was practically a discussion forum between cardiologists, radiation protection advisors and application specialist of X-ray equipment manufacturer, with theoretical and practical sessions demonstrating the different factors influencing patient and staff radiation doses. Before and after the course, a patient doses survey was performed. During that period the catheterization laboratories were equipped with image intensifiers. Later, the X-ray systems were upgraded and image intensifiers were replaced with new flat-panel detectors. The effects of education in radiation protection and new technology are visible on patient radiation doses (Figure 10). A decrease of 22% and 23% is noted for CA and, combined CA and PCI procedures. With FD system, the interventional procedures are performed with 6 pulses/second for fluoroscopy, compared with 15 pulses/second used on II system. For FD system, the entrance detector dose is 29 nGy/pulse for fluoroscopy, and 100 nGy/frame for cineangiography mode (lowest option available in our systems).

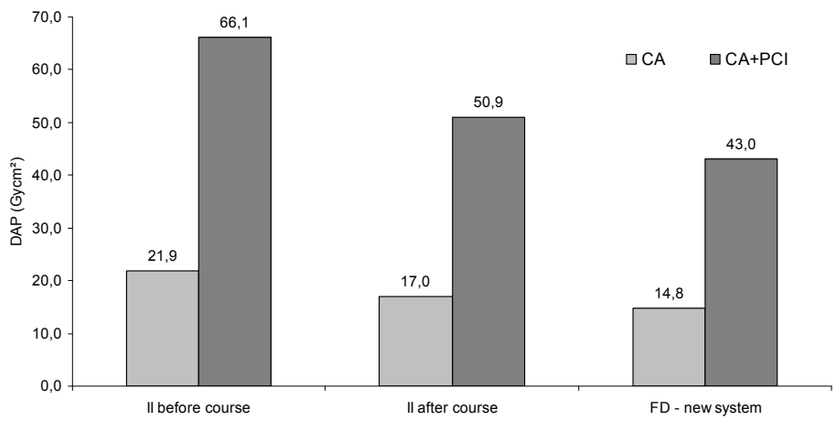


Fig. 10. Mean DAP patient values with II before and after training course and with FD for CA and PCI examinations.

Based on the survey of patient doses, we were able to establish reference levels (RL) for common interventional procedures. These indicators are DAP, fluoroscopy time and number of images, and give to the operator somehow the guideline of good and normal practice. Of course, higher doses might occur if the clinical status of the patient justifies the corresponding exposures to ionizing radiations. The goal to use RL is to control the level of optimization of the procedures. Once the dose indicators are collected, the RL are established as third quartile (75% percentile) of the distribution of observed data. In our center, INCCI Luxembourg, local RL values for CA procedures are: 23 Gycm² for DAP, 5 minutes for fluoroscopy time and 617 images. For PCI procedures, the RL values are 44 Gycm² for DAP, 15.5 minutes for fluoroscopy time and 1163 images. Our values were compared with reference levels at European level proposed by the SENTINEL consortium (Padovani et al., 2008). The data was collected from nine European centers, 672 CA and 662 PCI procedures. Comparison of our local reference values with the European values are shown in Figure 11 for CA procedures and in Figure 12 for PCI procedures.

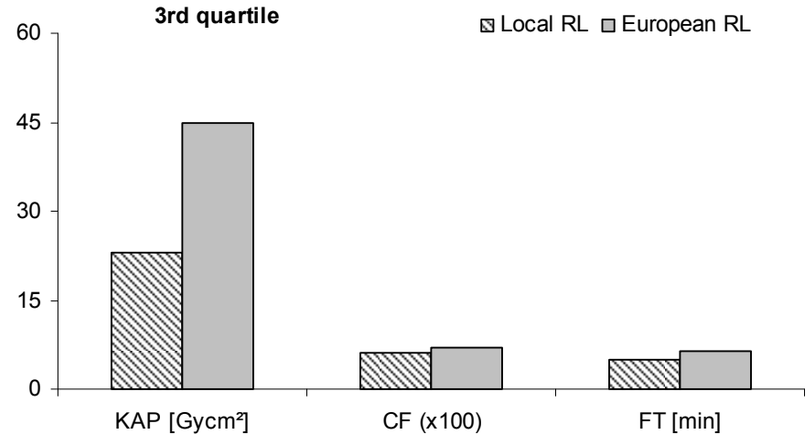


Fig. 11. Comparison of diagnostic reference levels for CA procedures between INCCI (local RL) and European study

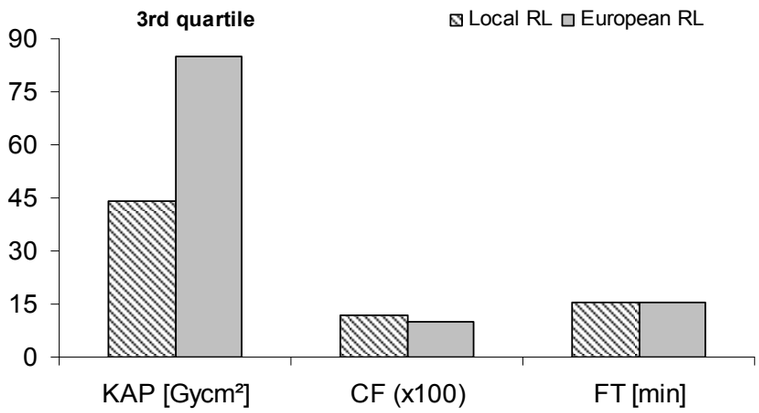


Fig. 12. Comparison of diagnostic reference levels for PCI procedures between INCCI (local RL) and European study

Strictly comparison between both studies is difficult to perform, because we do not have complete information about how the X-ray cardiac systems in the European study were configured. Also, we do not know if the cardiologist's experience and training education in radiation protection is uniform between centers.

Probably one of the factors that explain the difference is the configuration of the X-ray equipment for fluoroscopy mode. In our center the pulse rate is 6 pulses/s (low dose mode), where in European study, centers that submitted data work usually with 12.5 frames/s (for II systems) and 15 pulses/s (for FD systems). Our clinical experience shows that there is possible to optimize protocols when using new technology with little compromise on image quality but with benefit in reducing radiation dose levels to the patient.

## 5. Conclusion

Optimization of radiation dose - image quality and implementation of ALARA principle in catheterization laboratories are tasks that involve all actors: interventional cardiologists, auxiliary staff, medical physicist, and applications specialists. However, in daily practice

some tactics for radiation dose reduction and image quality improvement should be known by all interventional cardiologists. We create a list of little steps that have an impact in radiation safety in daily practice.

*Use the lowest acceptable clinical protocols during fluoroscopy and cineangiography*. Pulsed fluoroscopy and cineangiography at lowest radiation level should be used. If the equipment allows, different protocols must be created and used in function on the type of structure that is being imaged (venous vs. arterial, fast-moving vs. slow-moving).

*Correct placement of the patient in the isocenter on the table*. Having the patient correct positioned in the isocenter facilitates keeping the heart at the center of the X-ray field. In this way there is no need of prolonged fluoroscopy to adjust the patient's position with each change in angiographic projection.

*Avoid the use of fluoroscopy to make changes to the patient position or collimators*. Fluoroscopy should be used very briefly to check the patient position. Movements to the correct position should be avoided by using fluoroscopy constantly. Modern units have "virtual" markers that enable the positioning of the collimators. The correct position of collimators should be checked by brief fluoroscopy rather then constant visualization.

*Remove unnecessary instruments and body parts from the X-ray field.* Presence of the patient's arm, operator's hands or any external instruments should never be visible on a cardiac study. These structures or objects result in an overall increase in radiation dose to the patient because of the demand of AEC system to compensate with increased radiation output.

*Minimize the number of angiograms*. Limit the number of projections to provide an overview of the status of the coronary arterial tree and indentify the ideal projections to be used for coronary angioplasty. Always performs test injection of a small amount of contrast material using fluoroscopy prior to acquiring an angiogram. This approach prevents the wasted angiogram that is taken with the catheter inadvertently wedged deeply in a vessel. Also fluoroscopy of test injection can aid in determining the correct magnification mode. Keep in mind that few seconds of fluoroscopy and little quantity of contrast material are less irradiating the patient than a full wasted angiogram. During complicated interventions, limit the use of magnification, because of the substantial increase in radiation dose.

*Keep the detector (II or FD) as close to the patient as possible*. The X-ray tube should be as far away as possible. If the detector is far from patient, the input doses will be higher and the scatter radiation increases.

*Decrease beam on time*. This is probably one of the most important rules. Fluoroscopy must not be applied when discussing or doing other manoeuvre. If the eye is not on the screen, the foot should not be on the fluoroscopic pedal. Use stored images rather than live images for studying the case.

*Use angiographic projections that reduce operator exposure whenever possible*. For right oblique projections, the X-ray tube moves away from the operator, while for left anterior oblique projection moves it closer. Kuon et al., 2004 published an interesting paper focused on identification of less-irradiation tube angulations in invasive cardiology. Di Mario & Sutaria, 2005 published a review of techniques to obtain optimal views of all segments of the coronary arterial system.

*Remove anti-scatter grid when imaging small children*. New cardiac X-ray systems have possibility to remove the grid. In pediatric patients a significant reduction in radiation dose is possible without compromising image quality.

*Know your own cardiac X-ray equipment and its features*. Work with radiation physicist, the manufacturer to regularly test and maintain the equipment in optimal working conditions.

*Ensure protection of laboratory staff*. Before starting fluoroscopy, ensure that everyone in the room use radiation protection shielding. Ask of laboratory staff to keep distance during cine angiography. Remember the inverse square law: doubling the distance from a point source reduces the radiation exposure to one-quarter. Keep the proper use and storage of lead aprons. Aprons that are not proper storage might develop cracks, compromising their effectiveness. Always use personal dosimeters.

Technology of X-ray cardiac system is continuously adapting and optimization of radiation doses with less compromise on image quality is possible. On the other side, activity in cardiac catheterization laboratories increases and more complex procedures are performed. All the actors involved in catheterization laboratory should be trained and familiar with the basic principles of radiation safety. Developing a radiation safety culture should be a priority. Attention to the simple rules of radiation safety and the planning of an interventional procedure should enable the interventional cardiologist to produce high quality images at low radiation level to the patient.

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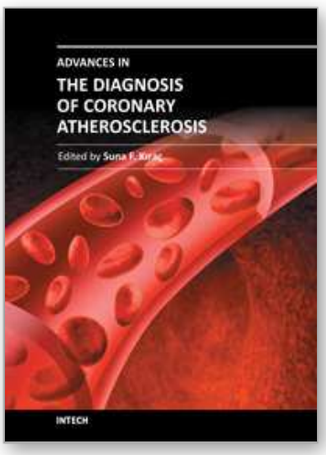


**Advances in the Diagnosis of Coronary Atherosclerosis**
Edited by Prof. Suna Kirac

ISBN 978-953-307-286-9
Hard cover, 378 pages
**Publisher** InTech
**Published online** 09, November, 2011
**Published in print edition** November, 2011

Coronary artery disease (CAD) and its consequences are most important morbidity and mortality reasons in the developed and developing countries. To prevent hard end-points, early definitive diagnosis and optimum therapy play significant role. Novel advanced diagnostic tests which are biomarkers of inflammation, cell adhesion, cell activation and imaging techniques provide to get the best result in the detection and characterization of calcified or uncalcified atherosclerotic plaques. In spite of last developments in the imaging methods, coronary catheterization is still frequently performed. Following the first cardiac catheterization performed in 1844, date by date historical developments and the mechanics of cardiac catheterization techniques, risks associated with coronary angiography, and also, preventions and treatments of possible complications have been presented in this book. Other important issue is radiation exposure of patients and staff during coronary angiography and scintigraphy. Radiation dose reduction techniques, general radiation protection principles have been discussed in related chapters.

**How to reference**
In order to correctly reference this scholarly work, feel free to copy and paste the following:

Octavian Dragusin, Christina Bokou, Daniel Wagner and Jean Beissel (2011). Optimization of Radiation Dose and Image Quality in Cardiac Catheterization Laboratories, Advances in the Diagnosis of Coronary Atherosclerosis, Prof. Suna Kirac (Ed.), ISBN: 978-953-307-286-9, InTech, Available from: http://www.intechopen.com/books/advances-in-the-diagnosis-of-coronary-atherosclerosis/optimization-of-radiation-dose-and-image-quality-in-cardiac-catheterization-laboratories

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