PRACTICAL APPROACHES TO DOSIMETRY FOR THE PATIENT AND STAFF FOR FLUOROSCOPIC PROCEDURES

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INTRODUCTION

Three recent developments that provide practical information on radiation dosimetry for patients or clinical staff for diagnostic or interventional fluoroscopy are presented. They are: (i) a Handbook for determining absorbed doses in tissues (for patients) from coronary artery procedures; (ii) recommendations on avoiding radiation-induced skin injuries (to patients) during fluoroscopically-guided interventional procedures: and (iii) a method for determining effective dose (to staff wearing protective aprons) from fluoroscopic procedures, using the results of personal monitors.

HANDBOOK OF SELECTED TISSUE DOSES FOR FLUOROSCOPIC AND CINEANGIOGRAPHIC EXAMINATION OF THE CORONARY ARTERIES

The Monte Carlo procedure and anthropomorphic phantoms (i.e., ADAM and EVA) used to produce the Handbook for examinations of the coronary arteries is the adaptation of the BRHGAM code (1) by the Gesellschaft für Strahlen-und Umweltforschung (2). The mathematical phantom for the reference male patient (ADAM) is a modification of the original MIRD-5 phantom (3), with the addition of an esophagus (4) and the addition of a supporting tabletop at the back of the phantoms (5). The reference female patient (EVA) is the ADAM phantom reduced uniformly to 83 percent of its original size, with the unique female tissues instead of the unique male tissues (2).

The simulated examinations of the coronary arteries are based on a series of distinct x-ray fields commonly used in coronary interventional radiology, derived from analyses of practice at the Institut de Cardiologie de Montréal (6,7). The views and arterial projections represented are generally applicable to a broad range of examinations following a variety of clinical protocols. For each arterial projection, a separate Monte Carlo calculation was made with ADAM and EVA for the relevant complex oblique x-ray field in divergent-beam geometry, with specific x-ray spectra representative of clinical practice (5).

The Handbook presents twelve tabulations, one tabulation for each of eleven arterial projections, and one tabulation that provides nominal data that can be used for an examination consisting of several views, in lieu of the individual tabulations. The nominal approach is acceptable for coronary artery examinations because all the views share the heart as a relatively small, common region intercepted by the central ray of each different x-ray field. The arterial projections are specified by view (e.g., RAO, right anterior oblique), angulation of image receptor (if different than 0 degrees) in the transverse and saggital planes, and location of the field center (left or right ventricle). Descriptions of the standard nomenclature used in the anatomy of the coronary arteries and to identify the arterial projections, the specifications for the irradiation geometry and complex oblique views, and the coefficients of variation for the Monte Carlo calculations are provided in the Handbook (5). Data are tabulated for the entrance skin in the primary field and 20 internal tissues or organs. The tabulated values (conversion coefficients) are tissue dose (mGy) per 1-Gy air kerma (free-in-air) at the skin-entrance plane.

In extended coronary artery examinations, cumulative absorbed doses to that portion of skin lying directly in the path of the incident primary field may approach or exceed the thresholds for deterministic injury. The entrance skin in the primary field is only a small fraction of the entire skin tissue; the extent is delimited and the location is determined by the collimation and irradiation geometry of the anatomical projections.

Except for the heart, the internal organs and tissues listed are those with which cancer, genetic effects or in utero effects have been associated (8). The heart surrounds the ventricle field centers and always lies within the field of view. It receives the highest absorbed doses per unit air kerma of the internal organs. The data for the heart are provided for reference purposes; there is no health effect yet established for absorbed doses in the heart for the ranges that occur in coronary artery examinations.

The data are presented for three beam qualities for each reference patient (i.e., ADAM, 2.5, 4.0 and 5.5 mm Al HVL; EVA, 2.0, 3.5 and 5.0 mm Al HVL). The range of beam qualities corresponds to that observed

in the study conducted at the Institut de Cardiologie de Montréal (7) and that observed in a nationwide survey of fluoroscopy practice in the United States (9). The beam qualities are without the presence of a supporting tabletop. For the usual ranges of kVp and aluminum filtration combinations used in fluoroscopy and cineangiography of the coronary arteries, the results should have uncertainties of less than 10 percent when half-value-layer (HVL) alone is used to describe beam quality (5).

When the actual diameter of field of view (FOV) at the image receptor plane differs from that used in the reference simulation by more than 20 percent, the following correction is recommended (5):

$$[\text{FOV(actual)}/\text{FOV(tabulated)}]^2.$$

The correction is not applicable to the entrance skin in the primary field, since the absorbed dose in that portion of skin is not dependent on the size of the area irradiated.

The tabulation for the nominal conversion coefficients is given in Table 1.

Table 1. Nominal Conversion Coefficients for Fluoroscopic and Cineangiographic Examinations of the Coronary Arteries (from reference 5): SSD = 60 cm; SID = 90 cm; FOV diameter at image receptor = 14 cm

	Tissue dose (mGy) per 1-Gy air kerma (free-in-air at the skin-entrance plane)					
	Male			Female		
HVL (mm Al)	2.5	4.0	5.5	2.0	3.5	5.0
Entrance Skin in Primary Field	1000	1120	1180	950	1090	1170
Brain	0.003	0.020	0.041	0.001	0.018	0.045
Thyroid	0.12	0.50	0.85	0.075	0.53	1.1
Thymus	2.2	6.5	9.9	1.6	6.7	12
Active Bone Marrow	6.1	12	16	5.2	12	17
Esophagus	14	33	47	11	32	51
Lungs	34	53	65	31	55	71
Breasts				3.0	9.4	15
Heart	30	62	86	23	63	95
Adrenals	36	62	78	32	64	87
Spleen	4.9	11	15	3.8	11	17
Pancreas	5.4	14	20	3.8	13	22
Stomach	2.4	6.3	9.3	1.7	6.3	10
Liver	4.4	9.7	14	3.5	9.9	15
Kidneys	3.2	6.8	9.3	2.7	7.1	11
Colon	0.071	0.31	0.56	0.043	0.32	0.67
Small Intestine	0.091	0.40	0.72	0.050	0.39	0.82
Ovaries				0.007	0.076	0.19
Uterus				0.005	0.071	0.17
Urinary Bladder	0.003	0.021	0.044	0.001	0.023	0.054
Testes	+	0.002	0.004			

+ less than 0.001 mGy absorbed dose per 1-Gy air kerma.

The Handbook can be used to perform a view-by-view or a nominal analysis of an examination. To use the nominal approach, the coronary artery examination is characterized in an overall sense. This permits a quick, but somewhat less accurate way to estimate nominal tissue doses for a complete examination without detailed specifications for the particular views applied clinically.

The complete examination is characterized with nominal values for four parameters:

(a) the beam quality (i.e., mm Al HVL);

(b) the total air kerma (free-in-air at skin-entrance plane) summed for all the fluoroscopic plus cineangiographic segments and for all skin-entrance planes;

(c) the field-of-view diameter at the image receptor plane; and

(d) the highest cumulative entrance air kerma (i.e., fluoroscopic plus cineangiographic) for any single skin location. Such a skin region may be irradiated in only one view or in multiple views that share a common locus of irradiation.

The example given below is for a left-heart study of an adult male entailing a left ventriculogram in biplanar mode followed by left and right coronary angiography. In a typical application of the nominal approach, the user will rely on estimated values of the parameters for the entire examination that may be truly nominal, developed at the level of detail and with the degree of accuracy available to the user.

Nominal Parameters for the Entire Examination (Example)
Half-value-layer: 3.6 mm Al
Total air kerma (free-in-air) for all skin-entrance planes: 1.6 Gy
Field-of-view (FOV) diameter at image-receptor plane: 20 cm
Highest cumulative entrance air kerma for any single skin location: 0.80 Gy

Notes: a correction factor of 2.0 is needed for the actual FOV (20 cm rather than the 14 cm in the reference tabulation); and linear interpolation is made between reference HVLs

Tissue	mGy per 1-Gy Air Kerma	Relevant Air Kerma (Gy)	FOV Correction	Tissue Dose (mGy)
Entrance skin in primary field (maximum)	1090	0.80	none	870
Active bone marrow (entire examination)	10	1.6	2.0	32
Lungs (entire examination)	48	1.6	2.0	150

The Handbook presents this same example evaluated by a method in which detailed specifications for the particular views applied clinically were obtained for the examination. The absorbed doses were:

Entrance skin in primary field (maximum), 830 mGy;
Active bone marrow (entire examination), 37 mGy;
Lungs (entire examination), 170 mGy;

which are close to the values obtained above by the nominal approach.

The following general observations for absorbed doses can be made for examinations of the coronary arteries:

(a) Since a variety of different views are used in any specific examination, no single area of entrance skin is uniquely irradiated throughout the examination. Therefore, the cumulative air kerma for all the views will be a significant overestimate of the maximum dose to any portion of the entrance skin. The largest single cumulative dose in a portion of the entrance skin occurs where a common region of skin is irradiated in multiple views. The maximum absorbed dose to a portion of entrance skin will need to be evaluated for each examination.

(b) For the fields used in coronary artery examinations, larger fractions of the heart, lung, esophageal and adrenal tissues are in the radiation fields than other internal tissues, although the heart is not subject to radiation risk at the doses involved. The magnitude of the absorbed dose in these tissues is much lower than the maximum absorbed dose in the entrance skin in the primary field (see value for the lungs in the example). The absorbed doses in other internal tissues are less than the absorbed doses in heart, lung, esophageal and adrenal tissues, some being an order of magnitude or more lower per 1-Gy air kerma (see Table 1).

RECOMMENDATIONS FOR AVOIDANCE OF SERIOUS X-RAY-INDUCED SKIN INJURIES TO PATIENTS DURING FLUOROSCOPICALLY-GUIDED PROCEDURES

An increasing number of invasive procedures, primarily therapeutic in nature and involving use of devices under fluoroscopic guidance, are becoming accepted medical practice. These procedures are performed by a variety of medical specialists and may provide significant advantages over alternate therapies in terms of improved clinical outcome and reduced patient risk. However, physicians performing these procedures should be aware of the potential for serious radiation-induced skin injury caused by long periods of fluoroscopy occurring with some of these procedures. Such injuries have been reported as a result of radiation exposure due to long fluoroscopic exposure times, high dose rates or both (10).

The types of injury to skin and adjacent tissues which result from x-ray irradiation are summarized in Table 2 along with the typical absorbed dose in the skin required to produce the injury. Appearance of the injury is dependent on variables other than cumulative absorbed dose in the skin, such as: the rate of delivery of the radiation; the fractionation of the absorbed dose; the age and characteristics of the exposed person; and the site on the skin of the exposure.

Table 2. Typical Threshold Doses for Radiation-induced Skin Injuries (adapted from reference 11)

Effect	Typical Threshold Absorbed Dose (Gy)	Fluoroscopic On Time (a) to reach Threshold (hours) at 0.02 Gy min^{-1}	at 0.20 Gy min^{-1}	Time (b) to Onset of Effect
Early transient erythema	2	1.7	0.17	hours
Temporary epilation	3	2.5	0.25	~3 weeks
Main erythema	6	5.0	0.50	~10 days
Permanent epilation	7	5.8	0.58	~3 weeks
Dry desquamation	10	8.3	0.83	~4 weeks
Invasive fibrosis	10	8.3	0.83	- - -
Dermal atrophy	11	9.2	0.92	>14 weeks
Telangiectasia	12	10.0	1.00	>52 weeks
Moist desquamation	15	12.5	1.25	~ 4 weeks
Late erythema	15	12.5	1.25	~6-10 weeks
Dermal necrosis	18	15.0	1.50	>10 weeks
Secondary ulceration	20	16.7	1.67	>6 weeks

(a) Time required to deliver the typical threshold absorbed dose to skin at the specified rate.
(b) Time after single irradiation to observation of effect.

The absorbed dose rate in the skin from the direct beam of a fluoroscopic x-ray system is typically between 0.02 and 0.05 Gy min^{-1}, but may range from 0.01 to more than 0.50 Gy min^{-1}, depending on the mode in which the fluoroscopic equipment is operated and the size of the patient. The times required to deliver the typical threshold dose shown in Table 2 are for fluoroscopic dose rates of 0.02 Gy min^{-1} (the usual dose rate for normal fluoroscopy for an average-sized patient) and 0.20 Gy min^{-1} (a dose rate near the maximum permitted for the high-level control mode of operation in the United States) (12). The times listed are for irradiation to a single skin area by a stationary, continuous fluoroscopic x-ray beam.

Other than the mildest symptoms, such as transient erythema, the injuries from the irradiation may not appear until weeks following the exposure. Physicians performing these procedures may not be in direct contact with the patients following the procedure and may not observe the symptoms when they occur. For this reason, it is recommended that information be placed in the patient's record which permits estimation of the absorbed dose to the skin, especially for patients who may receive a significant fraction of the threshold dose from single or multiple procedures. Physicians should counsel such patients on the possible symptoms and risks from these procedures.

Table 3 presents examples of the x-ray-induced skin injuries reported to the Food and Drug Adminstration in the United States that illustrate the range of procedures and the severity of the injuries. Details that would permit quantitative estimates of the absorbed doses to the skin were generally not available, since records were not maintained on the extent of fluoroscopic exposure times and other technical factors or the facility was unwilling to share additional information.

Table 3. Examples of Skin Injuries from Fluoroscopy Reported to the Food and Drug Administration (from reference 10)

Patient Sex and Age	Procedure	Nature of Injury	Fluoroscopic Exposure Time
male, 40	coronary angiography and PTCA followed by second coronary angiography	skin necrosis requiring 12 cm x 10 cm skin graft	unknown; estimated to exceed 120 min
female, ?	RF cardiac catheter ablation	7.5 cm x 12.5 cm second degree burn	unknown
female, 25	RF cardiac catheter ablation	skin breakdown 3 weeks post procedure	unknown; procedure time of 325 min
female, 34	RF cardiac catheter ablation	draining skin lesion on back 5 weeks post procedure	unknown; procedure time of 190 min
female, 62	balloon dilation of bile duct anastomosis	burn-like injury on back requiring skin graft	unknown
female, 61	renal angioplasty	skin necrosis requiring skin graft	unknown, procedure time of 165 min

PTCA is percutaneous transluminal coronary angioplasty; RF is radiofrequency

The Food and Drug Administration has issued a Public Health Advisory (13) with recommendations for avoiding such x-ray-induced skin injuries and additional advice (14) on recording information in the patient's record that identifies the potential for such injuries.

Recommendations to avoid serious x-ray-induced skin injuries during fluoroscopically-guided procedures

(a) Establish standard operating procedures and clinical protocols for each specific type of procedure performed. The protocols should address all aspects of the procedure, such as patient selection, normal conduct of the procedure, actions in response to complications and consideration of limits on fluoroscopy exposure times.

(b) Know the radiation dose rates for the specific fluoroscopic system and for each mode of operation used during the clinical protocol. These dose rates should be derived from measurements performed at the facility.

(c) Assess the impact of each procedure's protocol on the potential for radiation injury to the patient.

(d) Modify the protocol, as appropriate, to limit the cumulative absorbed dose to any irradiated area of the skin to the minimum necessary for the clinical tasks, and particularly to avoid approaching cumulative doses that would induce unacceptable adverse effects. Use equipment which aids in minimizing absorbed dose.

(e) Enlist a qualified medical physicist to assist in implementing these principles in such a manner so as not to adversely affect the clinical objectives of the procedure.

Additional advice on recording information in the patient's record that identifies the potential for skin injuries

(a) Each facility should establish a threshold dose for recording information. The Food and Drug Administration suggested a threshold absorbed dose in the skin of 1 Gy, but the facility may select another value (such as 2 Gy) based on its experience.

(b) Determine the fluoroscopically-guided procedures that will approach or exceed the selected threshold. The Food and Drug Administration stated that the list should include the following procedures:

Radiofrequency cardiac catheter ablation
Vascular embolization
Transjugular interhepatic portosystemic shunt
Percutaneous endovascular reconstruction

and any others that professional and medical specialty organizations suggest or the facility determines will approach or exceed the selected threshold.

(c) For these procedures, record an unambiguous identification of those areas of the patient's skin that received an absorbed dose that may approach or exceed the selected threshold. The facility may also wish to include in the patient or supplemental record an estimate of the cumulative absorbed dose (and an estimate of its uncertainty) to each irradiated area of the skin noted in the patient record, or sufficient data to permit estimating the absorbed dose to those areas of skin. Cumulative absorbed dose in skin refers to the dose accrued by any specific area of skin over the course of a single or possibly multiple procedures.

No consensus currently exists as to the most effective method for estimating skin dose. Absorbed dose in the skin from fluoroscopy may be estimated through: (i) direct measurements, such as placing radiation dosimeters on the patient during the procedure; or (ii) indirect means, such as collection of specific information for a patient on equipment technique factors combined with patient and procedure characteristics, or such as use of supplementary information obtained with measurement and recording devices attached to the x-ray equipment. Note, however, that the sum of all exposures (i.e., the cumulative value for air kerma) occurring in an entire procedure is likely to be a significant overestimate of the cumulative absorbed dose to a specific area of skin, except in the event that the x-ray beam is stationary during most of the procedure.

Each approach to dose estimation has advantages and disadvantages, and all of the approaches involve practical complexities. Fortunately, clinical decisions and patient management do not require highly accurate estimates of the cumulative absorbed dose to the skin. It is more important that the potential for approaching or exceeding the threshold for injury be recognized and avoided, if possible.

A METHOD FOR DETERMINING EFFECTIVE DOSE TO STAFF WEARING PROTECTIVE APRONS DURING FLUOROSCOPY AND INTERVENTIONAL RADIOLOGY

Clinical staff taking part in diagnostic and interventional procedures using fluoroscopy wear protective aprons to shield internal tissues and organs in the torso from scattered x rays. Use of the measurements from monitoring devices worn outside and above protective aprons as the record of effective dose (E) for these individuals results in significant overestimates of their actual risk (15).

Experimental determinations of E have been reported for simulated irradiation of clinical staff for conditions commonly encountered in fluoroscopy and interventional radiology (16). In that work, x-ray scatter radiation was produced at various x-ray tube potentials in the range of 70 to 110 kVp, with the x-ray tube in overtable or undertable position. The operational quantity, personal dose equivalent for strongly-penetrating radiation, $H_p(10)$, can be obtained from the film badge dosimeters that were placed on the neck and waist of a Rando phantom that simulated a clinical staff member. Absorbed doses to tissues and organs, when a protective apron was not present, were determined using numerous thermoluminescent dosimeters in the phantom. Absorbed doses to the tissues, when a protective apron was present, were estimated from the absorbed doses without a protective apron, as modified by transmission data for the appropriate x-ray tube potential and equivalent lead thickness of the apron. E was computed as described by the ICRP (8) for the noted range of x-ray tube potentials without an apron and with aprons having equivalent lead thicknesses from 0.1 to 0.5 mm.

The relationships between E and the $H_p(10)$ values obtained from the film badges are quite variable over the conditions studied. For example, for aprons of 0.3 and 0.5 mm lead equivalence, $H_p(10)$ for the neck film badge ranges from 21 to 72 times higher than the corresponding E, and $H_p(10)$ for the waist film badge ranges from 1.7 times higher (multiply by 0.60) to 67 times lower than the corresponding E (15). The fluctuations in kVp used during various fluoroscopy procedures render a direct use of the conversions for individual staff impractical. However, when a single personal monitor is worn at the neck outside and above a protective apron, dividing the $H_p(10)$ value for this personal monitor value by 21 (the minimum value in the range) will provide a conservatively high estimate of E. This modification gives appropriate credit for the protection afforded by the apron and does not overestimate the value of E by more than a factor of 3.4.

From the experimental results, one can produce an empirical formula for E (that uses the results of two personal monitors) of the form:

$$\text{estimate of } E = aH_1 + bH_2;$$

which is a weighted sum of the $H_p(10)$ values obtained with personal monitors worn under a protective apron at the waist (H_1) and at the neck above and outside a protective apron (H_2).

The procedure was to iterate values of the weighting factors a and b by trial and error until a desired approximation of E for radiation protection purposes is achieved for the clinical range of x-ray tube voltages, the two x-ray tube locations, and for aprons with 0.5 and 0.3-mm lead equivalent thicknesses.

The criteria for a desired formula for radiation protection purposes were: (i) minimize the underestimates of E, even at the expense of larger overestimates of E for some conditions, and (ii) obtain a close estimate of E at the combination most frequently encountered in clinical practice (i.e., 90 kVp, 0.5 mm lead equivalent apron and undertable x-ray tube).

The resulting formula, using the experimental conversion factors, is:

$$\text{estimate of } E = 0.5\ H_1 + 0.025\ H_2.$$

The estimates of E resulting from the formula are presented in Table 4. Over the stated range of conditions, the estimates range from 1.06 E to 2.03 E. The criteria for a desired formula are met. There are no underestimates and the largest overestimate is 2.03 E. The estimate for the most frequently encountered combination is 1.06 E. Use of the formula would be a simple and practical way to monitor E when both personal monitors are worn.

Table 4. Estimates for E Using Empirical Formula for Two Personal Monitors, Aprons Present, Over and Undertable X-ray Tubes (Derived from references 16 and 17)

Apron Thickness (mm lead equivalent)	Tube Voltage (kVp)	Estimate of E Relative to a Value of 1.0
0.5, overtable	70	1.49
	90	1.96
	110	1.13
0.5, undertable	70	1.10
	90	1.06
	110	1.34
0.3, overtable	70	1.56
	90	2.03
	110	1.26
0.3, undertable	70	1.27
	90	1.21
	110	1.44

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