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Methods for measuring fluoroscopic skin dose

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Abstract This paper briefly reviews available technologies for measuring or estimating patient skin dose in the interventional fluoroscopic environment.

Keywords Fluoroscopic skin dose · Interventional radiography

Introduction

The substantial use of fluoroscopy to guide interventional procedures began in the 1980s. By 1990, radiation-induced skin injury became a concern. Deterministic effects were reported; attention was focused on malfunctioning equipment and high dose-rate techniques. By the mid 1990s the most likely cause was seen to be multiple procedures and long procedures conducted at normal dose rates.

Dosimetric information is helpful at multiple levels. Physics acceptance testing and QA processes assure dose-rate limits on clinical equipment. Real-time monitoring allows the operating physician to appropriately balance the expected clinical benefits and radiation risks of continuing a procedure. Postprocedure dose analysis provides valuable feedback into both the quality improvement process and the supervision of individual patients. These can be important either if a patent returns for a follow-up procedure or for continuing management if the index procedure was high-dose.

Indirect real-time dose monitoring

Indirect dose measurements yield a measure of dose at a defined location either using a physical dose measurement at a convenient point or by performing calculations based on equipment operating parameters and system geometry.

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Fluoroscopic time

Modern fluoroscopes still include a 5-minute timer. Fluoroscopic time is the traditional metric used for clinical radiation management. Even with better information readily available from the X-ray system, fluoroscopic time (with or without a count of the number of images or cine runs) is still the only dose metric routinely employed in many interventional fluoroscopy laboratories.

The fluoroscopic timer provides an inadequate skin-dose estimate in the interventional lab for several reasons. The most obvious of these is the total lack of information regarding fluoroscopic dose rate. In addition, fluorographic contributions are ignored. Finally, no account is taken of the beam's entrance ports.

Kerma area product (KAP), also known as dose area product (DAP)

KAP is defined as the integral of air kerma across the X-ray beam. Therefore, KAP includes field non-uniformity effects, such as anode-heel effect, and the use of semitransparent beam-equalizing shutters (lung shutter). KAP meters use large-area transmission ionization chambers placed between the final collimator shutters and the patient. KAP can also be calculated in real-time with an algorithm that uses the X-ray generator settings combined with collimator data.

The same KAP is observed with large fields and low skin doses as with small fields and high skin doses. Clinically, reasonable field size estimates can be made for many procedures. This can be used to obtain an estimate of skin dose. Even when applying a field size estimate, KAP provides no information regarding the spatial distribution of the entrance beam on the patient's skin. It produces an overestimate of the possibility of exceeding the deterministic threshold when there is significant beam movement

during the procedure. Estimates of beam motion can be made for typical cases.

Cumulative dose at the IEC reference point (C_{dose})

The International Electrotechnical Commission's (IEC) standard 60601-2-43 [1] defines an interventional reference point (IRP) at a location that is "representative" of the patient's skin. For typical isocentric interventional equipment, the default IRP is located on the central axis of the X-ray beam at 15 cm on the X-ray tube side of isocenter.

The cumulative air kerma (calibrated free in air) is reported. Effects, such as backscatter, table-top attenuation, and the conversion of air to tissue kerma need to be considered when comparing instrument readings with measurements obtained on the patient using film or a TLD.

Dose at a reference point also provides no information regarding the spatial distribution of the entrance beam over the patient's skin. Beam motion or variation in the location of the central beam axis and field size will cause the dose at a reference point to overestimate maximum skin dose.

Allowable uncertainties for KAP and C_{dose} are ±35% (FDA) and ±50% (IEC). This broad tolerance range was set after considering other major uncertainties in determining actual skin dose and predicting biological response. Closer tolerances can be maintained by a calibration procedure [2].

FDA "10 R/minute" point

FDA regulations limit table-top exposure rate to 10 R/min. Most C-arm and isocentric fluoroscopes will permit smaller source-to-skin distances (SSD) than is possible in a GI system. The FDA goes on to define its C-arm measurement point as 30 cm in front of the image receptor for any source-to-image-receptor distance (SID). Fluoroscopes with SID tracking maintain the 10 R/min limit 30 cm in front of the image receptor at any SID. Actual maximum skin exposure rates delivered by these systems will greatly exceed 10 R/min when operated at maximum SID. Figure 1 illustrates the relationships between the IEC and FDA measurement points.

Comparison of real-time indirect methods

Most interventional fluoroscopes can provide readouts of fluoroscopy time, KAP, and C_{dose}. The RAD-IR project reported [3, 4] these data for a total of 2,142 non-cardiac procedures (mostly in adults). PSD measurements were obtained in a subset of 800 of these procedures. The procedures studied differ substantially in how radiation is used, both in terms of spatial distribution of the incident radiation field and in the ratio between fluoroscopy and fluorography. The relationship among fluoroscopy time, DAP, cumulative dose at the reference point and peak skin dose (PSD) is a function of the type of procedure.

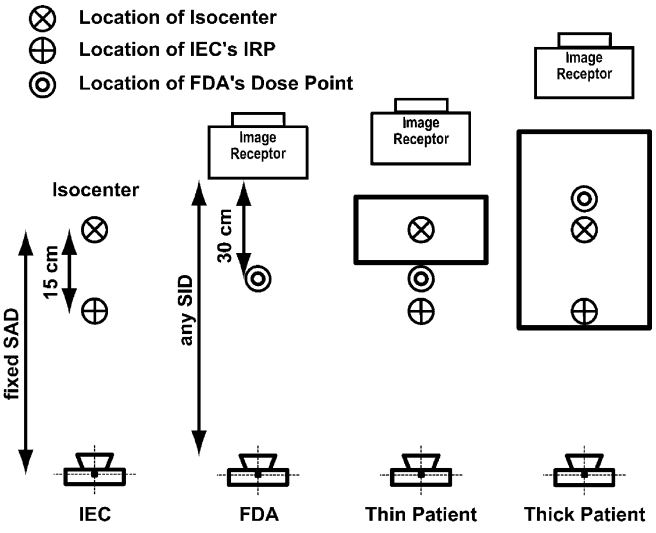

Fig. 1 Dose reference points. The IEC reference point is defined relative to the isocenter of the imaging system. It is independent of SID. The FDA measurement point is defined relative to the image receptor at any SID. This point moves away from the focal spot as SID increases

There was poor correlation between fluoroscopic time and the other metrics. There was reasonable correlation between KAP or C_{dose} and PSD for all procedures. The ratios PSD/C_{dose} and PSD/KAP differ from procedure to procedure. Based on RAD-IR, it seems reasonable to use either KAP or C_{dose} as a real-time indicator of the onset of deterministic injury. There is considerable patient-to-patient variability (Fig. 2). Other studies have shown similar variability [5–7]. Real-time PSD measurement is, therefore, the preferred technology. C_{dose} usually overestimates PSD by a factor that involves patient size, position, and beam motion during the procedure. Its use provides a conservative clinical skin-dose management tool.

DICOM DOSE (dose reporting)

The DICOM-DOSE project is a joint effort of the IEC and the DICOM Committee to improve accessibility to radiation dose information. The necessary standards documents are expected to be completed and published in early 2006. DICOM-DOSE-compliant fluoroscopes will generate an independent radiation dose structured report (RDSR) describing each procedure. Data from an interventional fluoroscope will include: beam geometry, KAP, C_{dose}, number of images, irradiation time, etc. These data are reported on a run-by-run basis (including fluoroscopic runs where no images are saved). The RDSR will be transferred to a repository (PACS, MIS, or stand-alone system) for analysis and archiving.

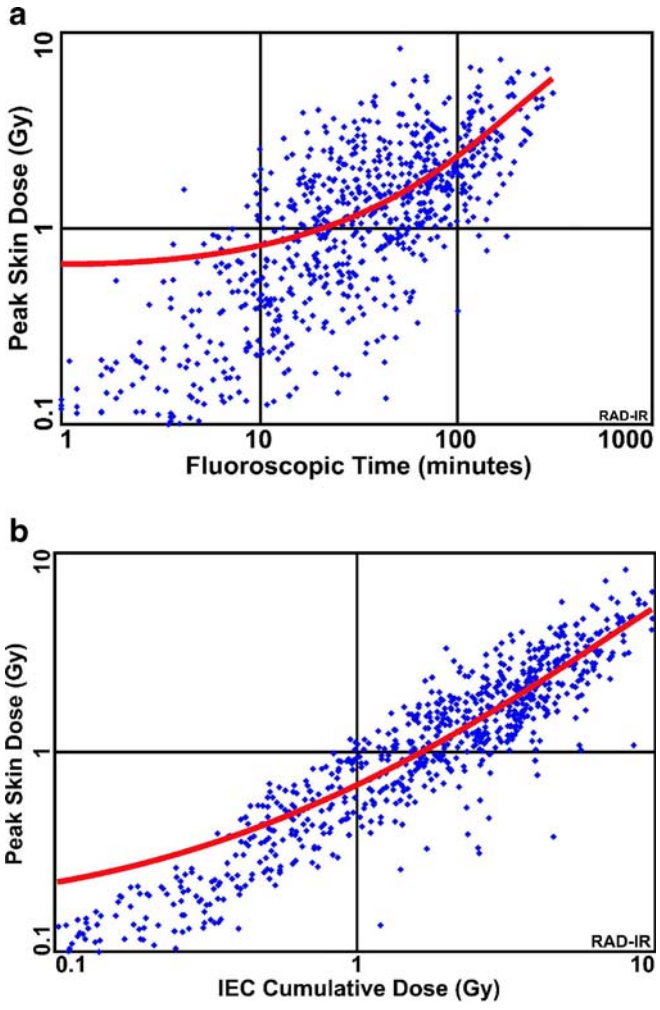

Fig. 2 Peak skin dose (PSD). **a** PSD vs. fluoroscopy time. Note that there is more than an order of magnitude variation in PSD for any fluoroscopy time. **b** PSD vs. cumulative dose (C_{dose}). Variability is reduced to about a factor of two

Real-time indirect skin-dose mapping

The PEMNET system

This is an example of an add-on device that provides real-time display of dose information and a permanent dose record. This instrument is electrically connected to the fluoroscopy system to obtain information on system technique parameters. These data, combined with geometrical and patient position information, are combined with calibration data via a microprocessor to provide a display and record of dose rate and cumulative dose to the patient's skin. This system, however, does not differentiate the dose to different locations on the skin. The use of the PEMNET system (Clinical Microsystems, Arlington, Va.) for patient dose monitoring has been described in a number of reports [8, 9].

The CareGraph system

This approach uses a mathematical model to combine data from a KAP meter with geometrical information on patient size and beam location. It provides a display of dose rate, cumulative dose and a real-time graphical display of the estimated dose distribution on the skin of the patient. The software models the shape and location of the patient's skin as an array of 0.5×0.5 cm patches. Every 500 ms, the software calculates the dose rate at each irradiated skin patch and the total dose delivered to that patch over time. The maximum dose at any point on the patient's skin is called the peak skin dose (PSD). A prototype has been described [10]. A commercial version was previously marketed as the CareGraph System (Siemens Medical Solutions, Malvern, Pa.). Figure 3 illustrates the CareGraph map and dosimetry film obtained during a RF cardiac ablation.

An interventionalist can monitor the distribution of skin dose during the procedure with a real-time skin dose map. In many cases a slight modification of the position of the X-ray beam on the patient's skin can dramatically reduce PSD. Final maps provide documentation for patient

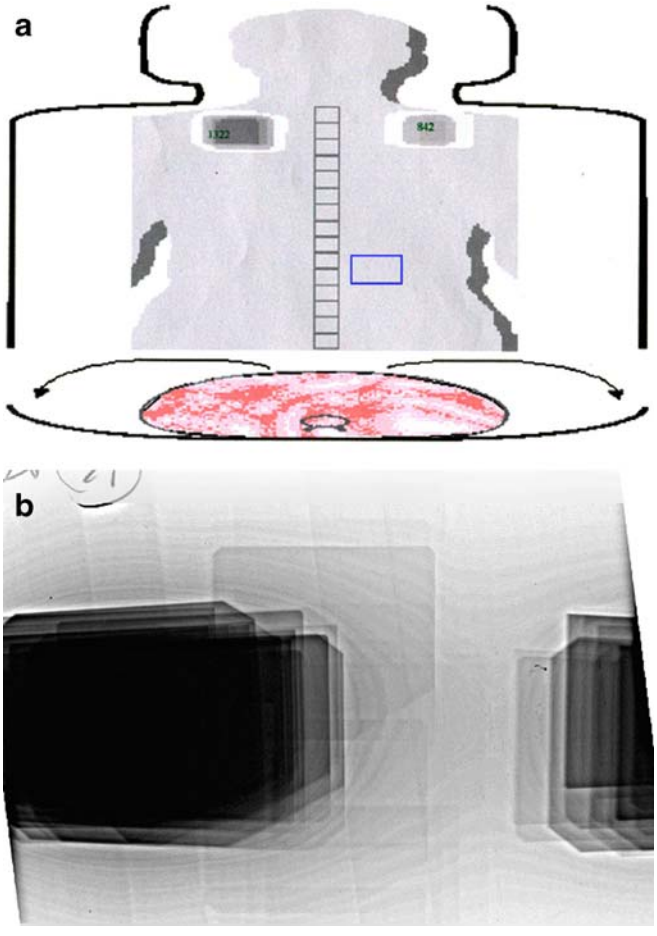

Fig. 3 Dose distributions from a dose mapping system (**a**) and from radiographic film (**b**). Procedure is a RF cardiac catheter ablation using 51 min of fluoroscopy. Both data sets were obtained simultaneously. The value and location of PSD are displayed. The open rectangle displays the current location and size of the X-ray beam (courtesy of Peter Kwan, Ph.D.)

management, for planning subsequent procedures and as part of a quality improvement program.

Direct real-time and non-real-time dose monitoring

A direct real-time probe placed at the location of PSD is the ideal dose measuring method. This is seldom possible in a clinical situation. Non-real-time film sheets or detector arrays produce dose maps without a-priori assumptions about beam position. Even though the dose maps are only available after the procedure, they can be extremely valuable.

Dose maps can be used to establish the ratios PSD/KAP and PSD/C_{dose} for classes of procedures performed at a particular institution. Locally established ratios, and the local variability of these ratios, can provide a better dose management tool than the uncritical acceptance of ratios obtained from other sources.

Real-time point dosimeters

There are several approaches to measuring dose during fluoroscopic procedures using geometrically small radiation detectors that provide immediate dose information via an electronic display. They should be positioned, a priori, at exactly the right location on the patient if they are to record the PSD. These instruments can provide real-time feedback to the physician during the procedure to optimize radiation usage.

Non-real-time point dosimeters

Point dosimeters (e.g. TLD chips, doped aluminum oxide chips; Landauer, Glenwood, Ill.) can be applied to the patient's skin prior to a procedure and read after the procedure. Read-out usually occurs hours to days after the procedure. Point dosimeters provide an accurate measurement of actual skin dose at the points that they are applied. This can be useful in circumstances such as when the location of the PSD is known a priori or when accurate measurement of the dose delivered to a critical tissue is needed, or to normalize indirect dose mapping technologies. Dosimeter arrays can provide a skin dose map (Fig. 4).

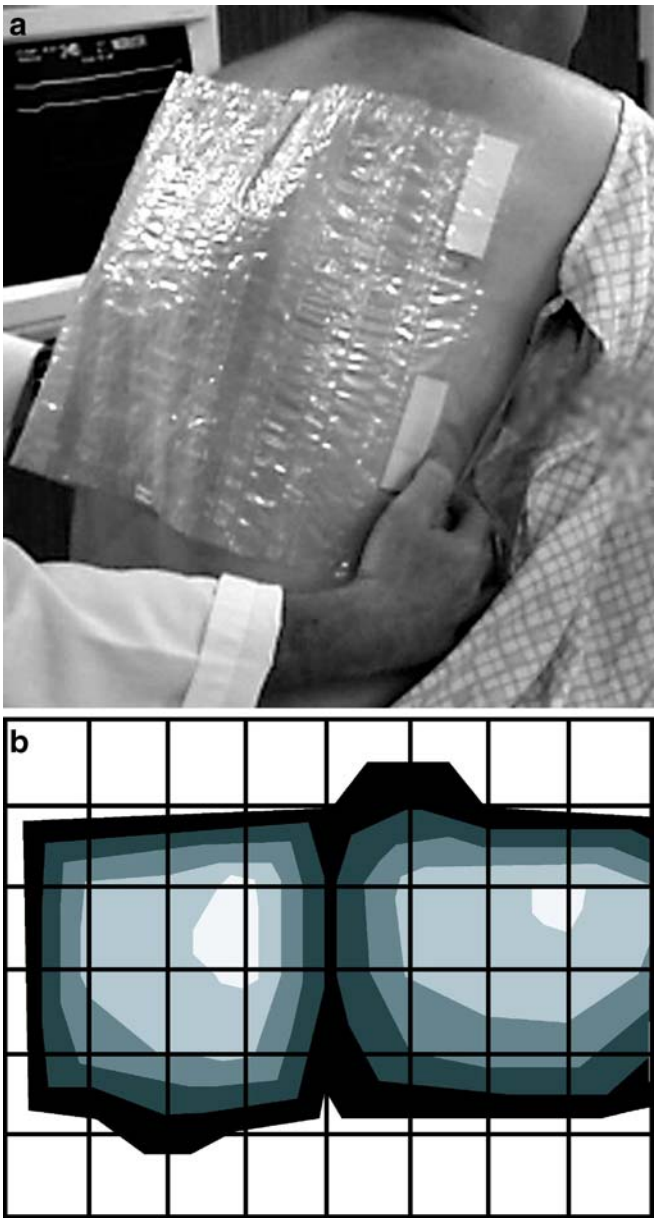

Fig. 4 TLD array (**a**) and an example (**b**) of the data reported for a RF cardiac catheter ablation procedure. The grid is 4×4 cm. Isodose curves are spaced 20 cGy apart. The PSD is between 100 and 120 cGy. (This is a different case from that illustrated in Fig. 3) (supplied by K and S Associates, Nashville, Tenn.)

Film dosimetry

Patient dosimetry for diagnostic and interventional X-ray procedures using various types of film has been described by a number of investigators. Dosimetry using film has the advantages of providing a detailed indication of the location of the skin dose, providing quantitative dose information with careful calibration and densitometry, and being used with any X-ray system.

Certain conventional X-ray films have a working range from 0.01 Gy to about 2 Gy. This is sufficient for many procedures but too sensitive for complex interventional procedures. Even in these cases, the film can demonstrate the distribution of dose and qualitatively indicate those skin locations where the dose exceeded the upper limit of the useful range of the film sensitivity.

A version of a radiochromic dosimetry film (GAF CHROMIC XR-type R; International Specialty Products, Wayne, N.J.) is available for quantitative mapping of patient skin dose during fluoroscopy. Its lower sensitivity makes it suitable for higher-dose fluoroscopy procedures. Radiochromic material changes color in proportion to dose. Sheets can be visually inspected after the procedure and quantitatively analyzed after digital scanning.

Dose information and patient management

Clinical fluoroscopic dosimetry is a component of good patient management. Direct and indirect dose measurements document the radiological footprint of a procedure. As such, they provide useful information regarding the possible occurrence of an acute injury. Given that many patients require multiple procedures, this documentation also aids in the planning of return visits. The nature of the measuring tool and its required accuracy are procedure-dependent. Simpler instrumentation is appropriate for fluoroscopes used only for known low-dose procedures. Advanced techniques using more extensive evaluation tools are indicated for higher-dose procedures and susceptible patients.

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