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Radiation exposure to medical staff in interventional and cardiac radiology

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Abstract. The aim of this work has been to determine typical occupational dose levels in interventional radiology and cardiology installations and to relate doses to patient and occupational dosimetry through the dose–area product. An experimental correlation between environmental dosimetric records and dose–area products in the centres studied was established. The study covered a sample of 83 procedures performed by 10 specialists in six laboratories. The radiologists and cardiologists monitored wore nine thermoluminescent chips next to eyes, forehead, neck, hands, left shoulder, left forearm and left arm during each single procedure. In addition, direct reading electronic devices for environmental dosimetry were placed in the C-arm of the X-ray system, to estimate roughly the occupational radiation risk level. Typical shoulder doses derived from electronic dosimetry range between 300 and 500 μSv per procedure, assuming no lead protective screens were used. Using these values and patient dose–area data from two laboratories, averaged ratios of 84 and 120 μSv per 1000 cGy cm^2 are obtained for cardiology procedures. Finally, occupational dose reductions of approximately 20% when using highly filtered X-ray beams with automatic tube potential (kV) reduction (available in some facilities), and by a factor of about three when using ceiling mounted screens, have been found.

Radiological risk to medical staff in interventional radiology (IR) is a topic of major concern in hospital occupational radiation protection (RP) [1–5], due to the rapidly increasing use of fluoroscopy. Furthermore, the fast development of IR in recent years has seldom, if ever, been matched by a parallel increase in the number of specialists. Thus, workloads supported by IR staff are often great. In addition, since fluoroscopic image quality can improve as radiation intensity increases, IR is prone to overexposure, both of patient and staff. Various studies have been performed to optimize IR [6–8].

Optimization procedures can involve significant reductions in staff doses. However, some measures may detrimentally affect the RP of staff in difficult situations. For example, manufacturers of IR X-ray equipment include elements to reduce doses to patients while keeping or improving the image quality [9], but some of these elements may entail an occupational dose (OD) increase if adjusted incorrectly or used improperly. Thus, the availability and regular use of protective tools such as aprons, glasses, gloves and screens, allows important dose savings. Image quality control must be carried out on a regularly scheduled basis. Practices based on performing the procedures at the most suitable location with reference to the patient, with well collimated beams, using magnification only when strictly needed and low cine frame rates should be recognized as critical to RP optimization strategies. A recent paper addressing staff radiation exposure in catheterization laboratories [10], stresses once again the importance of ability, good training and RP awareness as key factors. Unfortunately, discomfort of staff when using protective tools and/or some of these measures may impair the image quality, thereby slowing down the procedure [6, 11–13].

Given the above, the occasional measurement of large doses and the high workloads being undertaken by some staff make comprehensive OD monitoring on a routine basis advisable. Most studies aimed at assessing OD levels in IR procedures make use of thermoluminescent dosimetry (TLD) at different locations of the body [7, 14, 15]. However, the uneven radiation field found at short distances from the patient [16, 17] makes an investigation using large numbers of TLD chips desirable. Multiple site measurement (not achievable on a routine basis) is expensive and uncomfortable for the specialist, but allows a reasonable estimation of the spatial dose distribution. A single dosemeter may lead to underestimation of effective dose, since the unsuitable use of protective tools or bad practice (*e.g.* placing the

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hands in the direct X-ray beam) could lead to high doses to unexpected positions and poor correlation amongst dosimetric data. Previous authors suggest the use of three dosemeters: under the lead apron for whole body estimation, outside the apron at the shoulder level or on the thyroid protector, and the third one located at the hand [14, 18].

Since legal dose limits may be exceeded in IR, some radiologists may tend to avoid the regular use of radiation dosemeters to avoid possible problems with the regulatory authority, as suggested in a previous work [18]. This may explain the finding that personnel dosimetry files from regulatory bodies may show an occasional lack of reliability, and stresses the need for research on OD ranges in IR.

Given that IR staff in some centres wear only a dosemeter under the apron, the estimation of doses to eye lenses and shoulder could be achieved by measuring the environmental dose using single direct reading electronic devices properly placed at fixed locations on the X-ray facility. Assuming that no use is made of RP lead screens, this alternative has the great advantage of being able to supply results irrespective of geometrical factors or details such as protective elements, different uses of the possibilities offered by the equipment [1] or others such as choice of projection, which could mistake the relevance of the OD values measured.

A relation between patient doses (usually evaluated from the dose–area product (DAP) and OD is difficult to establish, especially in cardiology [13, 19], since OD are contingent upon given practices (use of protective devices, choice of projections, position with respect to the patient etc.). However, it could provide a good reference for dosimetric control of staff, as demonstrated recently by Williams [5].

This work presents data from OD using both TLD chips placed in nine sites on the specialist and electronic dosimetry (ED) devices located on the arm of the X-ray tube and image intensifier assembly. The relationship between occupational and patient doses for some of the X-ray equipment studied is also discussed.

Materials and methods

This study was undertaken on a sample of 83 common procedures, diagnostic and therapeutic, in interventional cardiology (IC) (coronary angiography, percutaneous transluminal coronary angioplasty (PTCA)), and in lower extremity arteriography, iliac arteriography, angioplasty and other typical procedures in vascular radiology (VR). The procedures were performed by 10 specialists. Six rooms specifically designed for IR, with different X-ray systems and RP elements, were monitored (Table 1). Staff always wore protective aprons, either 0.35 or 0.5 mm lead equivalent. No additional protective element (screen) was available in VR rooms, in contrast with the cardiac catheter suites where screens, glasses and thyroid protectors existed (although their use was irregular).

Distances between specialist and patient in VR rooms were variable (sometimes under 0.5 m); however, a distance of 0.5 m from the centre of the patient's scatter volume has been regarded as typical. Usually distances in cardiac procedures were larger, the typical value adopted for IC being 0.75 m from the isocentre.

TLD-100 chips from Harshaw TLD/Bicron/NE-Technology (BICRON-NE, Solon, OH, USA), individually calibrated, were located in all the cases on the specialist closest to the patient throughout the procedure. Eyes, forehead, neck, hands, left shoulder, left forearm and left arm were monitored.

Environmental doses were measured in three rooms, one devoted to VR and two to cardiac work, using direct reading ED devices based on three silicon detectors (Siemens-NRPB, model EPD1, Siemens, Erlangen, Germany). The device was attached to the C-shaped arm of the X-ray tube and image intensifier assembly. Assuming the C-arm was in a vertical plane and the X-ray tube in an undercouch position, the dosemeter lay under the horizontal plane intersecting the isocentre and at some 45° measured with the vertex in the same point (Figure 1). In this way, doses recorded are not affected by shielding devices in use (therefore they correspond to the highest intensity levels at that distance). Data from ED are easily comparable among different rooms as they become roughly independent of the arm orientation. It is possible to relate them to room workloads and OD values (although the high dose gradients lead to major differences for staff) and to check reliability.

ED readings in terms of deep dose, at 10 mm depth, and surface dose, at 0.07 mm depth (tissue equivalent) were normalized to the typical distances mentioned above. Periodical readouts from ED devices and zero reset made it possible to keep sensitivity in the μSv range.

At the same time, DAP values were measured for a sample of over 1300 patients, using transmission ionization chambers (Diamentor, PTW, Freiburg, Germany) calibrated with a reference ion chamber RADCAL (RADCAL Corp., Monrovia, CA, USA) model 2025AC. Measurement uncertainty was verified to be within 8%.

DAP results were used to relate contributions to OD from different projections. For a large number of coronary procedures, about 30% of the total DAP reading was recorded in the lateral projection, in which the ED device lies at a distance from the isocentre approximately similar to the shoulder of the physician (particularly in IC). Thus,

Table 1. Details of the IR laboratories studied

Manufacturer and model	Use	Available protective elements
Siemens Polydoros 100	Vascular	Apron/gloves
Philips Optimus M200	Cardiology	Apron/screen/glasses/thyroid
Philips Integris HM3000	Cardiology	Apron/screen/glasses/thyroid
GE Advantx LCV	Cardiovascular	Apron
GE Advantx	Cardiovascular	Apron
GE CPG 20	Cardiology	Apron

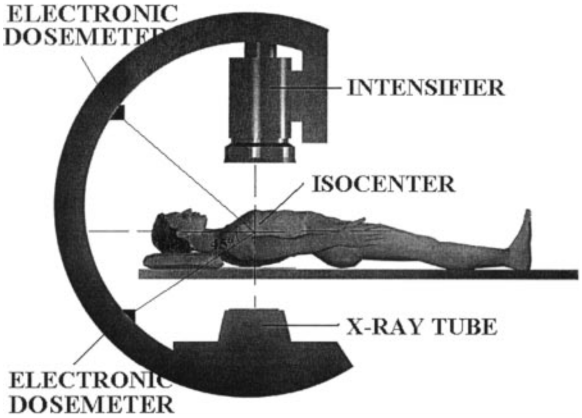

Figure 1. Electronic dosemeter layout for environmental measurements performed in one room for vascular radiology and two rooms for cardiac catheter studies. In the plot, the arm supporting the X-ray tube and the image intensifier stands in a vertical plane and two electronic dosemeters lie in symmetric positions, under and above the horizontal plan intersecting the centre of the scatter volume, at some 45° measured with vertex in that point.

nearly 30% of the OD (registered by a dosemeter commonly placed on the left shoulder) was received in the lateral projection. The rest could be attributed mostly to the undercouch vertical projection. Other oblique projections contributed doses which reasonably match the dose in vertical position.

Additional measurements were made by placing another ED monitor on the C-arm, at a symmetrical angular site with reference to the one described earlier (see Figure 1). The latter provides readings (comparable to the irradiation of the radiologist's shoulder) lower than those recorded by the undercouch device by a factor of around 3. This factor corrects both the angular dependence of scatter radiation and the X-ray beam absorption in the scatter volume, with regard to the radiation intensity received by the undercouch dosemeter. This is in fairly good agreement with an earlier estimation where a comparison between overcouch and undercouch tube fluoroscopy dose rates was made [20].

Accordingly, OD in the shoulder throughout the procedure should amount to 30% of the reading supplied by the undercouch dosemeter plus 70% of one-third of the same reading for IC (if the specialist does not use protective tools); that is, nearly 55% of the electronic dosemeter reading. Meanwhile, using a similar approach, a value of about 45% should be found at shoulder level in rooms employed for VR. In this case, the figure may exhibit major changes. In fact, it applies only to the room studied, the changes depending on the prevalence of cranial procedures, with frequent use of the lateral projection, in contrast to abdominal procedures where the lateral projection is seldom used and the doses would fall to 30% of the ED reading.

Results

Table 2 shows results from TLD in VR. The lowest dose values, close to background, are explained by radiologists occasionally being away from the immediate patient area (for diagnostic procedures), controlling the image acquisition from the system console.

Table 3 presents results from IC, arranged as general data for the whole sample. Doses are split into values measured in rooms with and without

Table 2. Values of dose per procedure in vascular IR, measured by TLD. Radiologists were occasionally out of the room controlling the image acquisition from the system console, giving rise to the lowest dose values, close to background

TLD location	Sample size	Average (μSv)	Median (μSv)	Range (μSv)
Left shoulder	21	283	182	45–1214
Right eye	18	296	122	45–2103
Left eye	19	284	95	40–1683
Forehead	19	222	159	19–1013
Neck	19	325	138	48–2104
Right hand	23	260	120	47–974
Left hand	23	396	184	40–2150
Left forearm	22	326	225	40–1886
Arm	29	365	243	50–1068

Table 3. Values of dose per procedure in interventional cardiology, measured by TLD. Doses are arranged for the whole sample and split into values measured with and without protective lead screen. The lowest values correspond to staff who made regular use of the protective screen

TLD location	Sample size	Average (μSv)	Median (μSv)	Range (μSv)
Whole sample				
Left shoulder	55	252	185	30–1031
Right eye	53	167	140	39–742
Left eye	54	294	193	53–1005
Forehead	53	236	178	40–934
Neck	54	269	214	43–816
Right hand	54	191	144	45–921
Left hand	58	364	256	60–1500
Left forearm	54	646	445	88–2890
Arm	54	618	414	70–1919
With lead screen				
Left shoulder	29	136	145	30–250
Right eye	29	136	140	52–252
Left eye	29	170	148	53–460
Forehead	29	145	150	40–415
Neck	29	163	160	43–398
Right hand	28	147	128	45–466
Left hand	31	235	195	60–740
Left forearm	29	440	350	88–2890
Arm	30	265	237	70–727
Without lead screen				
Left shoulder	26	382	308	125–1031
Right eye	24	205	138	39–742
Left eye	25	439	425	158–1005
Forehead	26	344	330	103–934
Neck	27	392	389	60–816
Right hand	25	242	149	45–921
Left hand	25	514	372	65–1500
Left forearm	25	885	801	168–2006
Arm	24	1061	1027	108–1919

a protective lead screen. Here, the lowest values correspond to staff regularly using a protective screen. As in Table 2, the data spread is broad because of its dependence on so many factors (distance, technical parameters used, equipment features, protective tools used, patient size etc.). Thus, average, median and range values are quoted.

ED readings reach values of 729, 587 and 492 μSv per procedure, respectively, for the Philips Optimus M200, Philips Integris HM3000 and Siemens Polydoros 100, when normalized to 0.75 m (though the usual working distance for the Siemens facility is 0.5 m). Using the lateral projection rates mentioned earlier and the percentages of the ED derived from them, the above values lead to OD on the shoulder of the specialist of 401, 323 and 228 μSv per procedure, respectively, for the same rooms. Since typical procedures carried out with the Siemens facility are shorter, compared with those performed in the other systems, dose values may also look lower.

The difference of about 20% observed between Optimus and Integris facilities arises because the Integris HM 3000 model includes a high filtration "Spectrabeam" system. Depending on the operation mode selected (normal, low or high dose), an automatic choice of different copper filters in the X-ray beam and tube potential (kV) is made, enabling suitable spectrum attenuation at the low energy side, while keeping the image quality virtually unchanged. The dose saving has been checked by ED over the period of a year and although data cannot be assigned directly to values of shoulder dose, they can be used without restriction to compare scatter radiation levels in corresponding rooms, as procedures and staff are the same in both facilities.

Table 4 presents values for IC procedures of the ratio between OD and DAP (in μSv per 1000 cGy cm^2) as proposed earlier [5], from the TLD readings at nine locations on staff, also showing the ratio (normalized at 75 cm from the isocentre) obtained from ED data.

Discussion

Figures 2a and b show the doses at the sites monitored for radiologists and cardiologists, respectively, taken from Tables 2 and 3. A more homogeneous distribution can be seen in the VR than in the IC group. The difference arises from

Table 4. Averaged values of the ratio between occupational doses and DAP in μSv/1000 cGy cm^2 from TLD readings at nine locations on staff, and from electronic dosimetry (ED) referred to left shoulder (in μSv). In the last row, number of procedures controlled (between brackets) and averaged DAP values in cGy cm^2

	Philips Optimus M200	Philips Integris HM3000
Left shoulder	43	32
Right eye	45	36
Left eye	60	33
Forehead	53	36
Neck	58	38
Right hand	63	29
Left hand	103	42
Left forearm	120	99
Arm	112	53
ED at the left shoulder (normalized at 0.75 m)	120	84
Number of procedures and average DAP (Gy cm^2)	(8)	(24)
	65.83	47.59

the variable positions usually adopted by the radiologist with respect to the patient. In IC procedures, doses are mainly received at the left-hand side, which remains closer to the scatter volume throughout the procedure. Therefore, a suitable use of the articulated screen between patient and staff should yield large dose savings (nearly 50%) to cardiologists. Note that data correspond to median values, which explains the lack of compatibility between some values at anatomical sites in close proximity.

The use of the protective screen is not constant throughout intervention and, when used, its location is appropriate only occasionally (even by staff most aware of the RP benefits). This explains why differences between mean values of the samples with and without screen use are lower than expected. For VR staff, the most adequate protection (as no screen is available in the rooms monitored) should be based on suitably large distances from the patient.

Eye lenses are inside a zone where doses may exceed the annual limits (50 mSv year^{-1} for whole body and 150 mSv year^{-1} for lenses) if between 30 and 40 procedures per month are performed; albeit the rest of monitored sites would impose a practical limit at 50–60 procedures per month, unless more intensive use of protective tools is not made. A dose of about 2150 μSv per procedure to the left hand of the vascular radiologist is consistent with that hand being in the direct beam. Values of about 3000 μSv per procedure at the forearm of those cardiologists who claim to use the screen denote an improper use of that tool, together with too short a distance from the patient.

ED readings corrected for distance and projection compared with TLD data exhibit good compatibility, bearing in mind that ED values depict typical expected shoulder doses to staff working at normal distances, with a standard protocol and without protective screen. Therefore, TLD mean doses to shoulder, eyes and neck remain below the typical ED value in some cases, depending on the use of RP tools. Also, TLD values above the ED reading can be explained as an effect of changes in working distance and protocol, together with neglecting the use of a ceiling mounted screen.

A fairly good compatibility is also observed between the present results and previous data from fluoroscopy [21]. Assuming that a typical procedure lasted half an hour and that the posteroanterior (PA) and anteroposterior (AP) projections used by Boone [21] correspond roughly to the vertical undercouch and lateral ones described here, the typical doses arrived at are of 0.6 mGy. Since digital/cine acquisition is not taken into account, this estimate is in agreement with the range values obtained.

Contrary to data obtained from TLD, which are affected by distances at different locations on staff, protective elements and protocols, ED values are nearly independent of external factors (equipment parameter choice and patient). Therefore, ratios between OD, derived from ED, and DAP supply information which is more comprehensive, and make it possible to establish an upper threshold of the occupational risk, assuming normal values of both quantities. This provides, in addition, an assessment of the working procedure of a specialist in respect of RP and of some equipment operation conditions (level of scatter radiation). In particular, the ratio between ED and TLD shoulder dose values in Table 4 is about 3, for IC units, which denotes a fairly regular use of the protective ceiling screen in these rooms.

Specific values of 84 and 120 μSv/1000 cGy cm^2 (at 0.75 m from the isocentre) in the two Philips facilities used for IC partially show the difference due to the selectable Spectrabeam system commented on earlier and confirm the need for estimation in each facility. Once this ratio has been obtained, the method suggested elsewhere [22] to relate DAP and patient skin dose values provides the simplest way to estimate approximately both the patient and occupational doses per procedure (if protective tools are not used).

Anyway, the situation depicted by the average ratios between OD and DAP should not hide other less typical situations in which OD values disagree strongly. For example, a dose to the arm of 1.9 mGy was measured in a coronary angiogram performed without the use of a ceiling articulated screen, with a DAP of some 240 Gy cm^2. In similar conditions and for 67 Gy cm^2, a dose to forearm

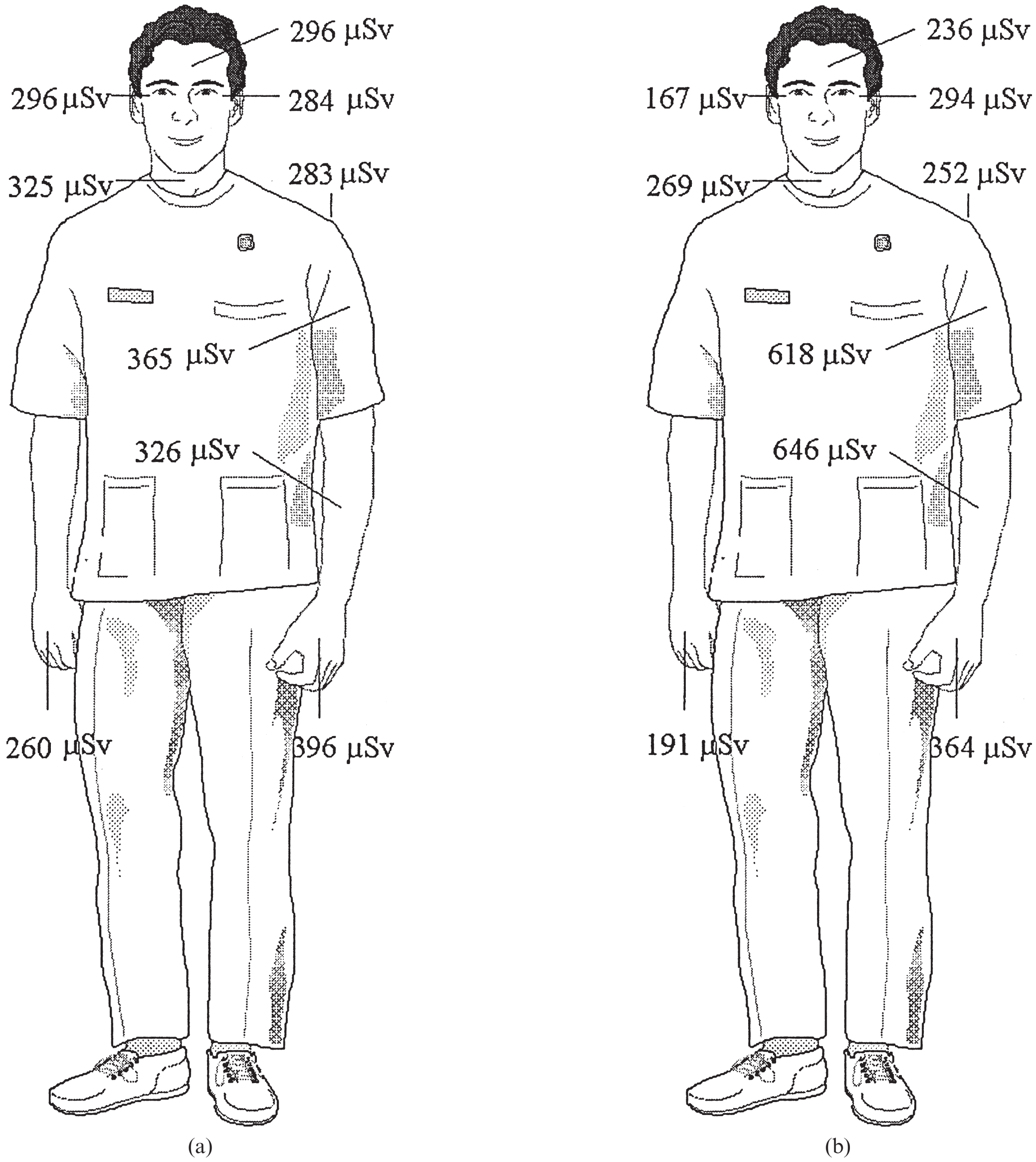

Figure 2. Graphic presentation of the mean values of doses per procedure found at the sites monitored for radiologists and cardiologists, taken from Tables 2 and 3. A more homogeneous distribution can be seen for vascular radiologists (a) than for interventional cardiologists (b), because of the variable positions usually adopted by the radiologist with respect to the patient, while in IC procedures doses are mainly received at the left-hand side, the closest to the scatter volume throughout the procedure.

of 2.9 mGy was recorded. Also, a "check of Hickman catheter" procedure can involve doses to eye lens level of about 2 mGy. These examples illustrate the need for a careful use of global results, keeping in mind features related to procedure type, radiologist skills and X-ray system used.

Conclusions

Our results show an ample range of variation in OD at all the locations monitored on the staff, which confirms the influence on the risk level of the equipment features, its adjustment and use. Ceiling mounted screens are very efficient protective tools, although they yield poorer protection in daily practice than expected, considering their theoretical attenuation factor, as their use is uneven or they are misused. Instead of a radiation absorption effect through 1 or 2 mm lead equivalent shielding, an average value of 382 μSv per procedure to the shoulder of the specialist falls to 136 μSv per procedure as the screen is used. This is a rather low decrease, albeit higher reduction factors could be found in other body zones of the medical specialist performing the intervention.

In some IR rooms where no articulated screen is available and in the case of radiologists not wearing protective elements, doses up to 2 mSv to shoulder and eye lens have been measured in a single procedure. Thus the threshold for deterministic effects could probably be exceeded by working for several years in these conditions.

The use of a direct reading ED device or TLD chips located on the C-arm X-ray assembly provides an effective option to estimate the occupational risk (once suitable corrections on angle and distance are applied) assuming no protective tools are used by the specialist. This establishes the typical risk level at the usual distances from the patient. Average values range between 300 and 500 μSv per procedure at the shoulder, depending on room and equipment, although doses may increase at distances shorter than the one considered usual. The protection improvement due to highly filtered beams produced by some commercial equipment has been verified in daily practice, with reductions in average doses of between 20 and 25%.

It is possible to relate dose values from dosimetry at a fixed location on the X-ray C-arm assembly with DAP data, both independent of protective elements and beam orientations. Since some systems include DAP meters, this way suggests a good possibility to estimate both occupational and patient doses.

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