Risks Associated with Ionizing Radiations

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SUMMARY

Medical use of ionizing radiations implies certain risks which are widely balanced by their diagnostic and therapeutic benefits. Nevertheless, knowledge about these risks and how to diagnose and prevent them minimizes their disadvantages and optimizes the quality and safety of the method. This article describes the aspects related to skin dose (nonstochastic effects), the importance of dose limit, the physiopathology of biological damage and, finally, the prevention measures.

CASE REPORT

A 48-year old male patient asked for medical advice due to new onset angina in functional class III-IV. He had a history of hypertension, dyslipemia and previous anterior wall myocardial infarction. A coronary angiography showed the presence of two severe obstructions in the left anterior descending (LAD) coronary artery and left circumflex (LCx) artery, and he was transferred to a tertiary care center to undergo angioplasty of the two lesions. As the procedure in the LAD took more than four hours, the second angioplasty was deferred to the next day. A stent was implanted in the LCx artery; this procedure was also difficult and lasted more than four hours. Primary success was achieved in both procedures. The patient was discharged 48 hours later without complications.

Fifteen days later, his wife noted a small erythematous, circumscribed coin lesion on the scapular region. One month later the lesion became red, itchy especially at night and with dry desquamation. The patient visited a dermatologist who prescribed a topical steroid. As this treatment was not effective, one week later he consulted another dermatologist who prescribed a topical cream with antibiotics; however, pruritus persisted.

Five months later he presented an isolated, non flaky and clean pale ochre-colored lesion that measured 9 × 7 cm. The cardiologist made a diagnosis of lesion induced by ionizing radiation. The habitual substrate of these lesions is a proliferative small-vessel vasculitis.

THE PROBLEM

The significant advances achieved in cardiology with the use of diagnostic and therapeutic procedures that require fluoroscopic guidance is well-known; however, its use is not free of certain risks for the patients and health care professionals in charge of the procedure.

The first case of radiation-induced skin injury secondary to prolonged fluoroscopically-guided, invasive procedure in the interventional era was reported in 1990. However, by 1994, the Food and Drug Administration (FDA) published a health advisory in its Web site (http://www.fda.gov/cdrh/fluor.html) due to the increasing number of reports received. Subsequent research has demonstrated that the problem persists (1) and it represents “the tip of an iceberg”, considering that an important number of cases are not reported. (2)

The goal of radiological protection is to prevent the occurrence of deterministic effects (see later) in patients and health care providers, and to reduce probabilistic effects as much as possible in order to protect the individuals against the harmful effects of ionizing radiations (IR), without reducing the benefits associated with their use in the different environments. In this sense, the level of exposure to radiation should be kept as low as reasonably achievable (ALARA principle, introduced by the Council Directive 97/43/Euratom) to maintain an optimal image quality.

Radiation protection regulations are based on three basic principles: justification, optimization and dose limitation. (4) The first two recommendations are the mainstays of radiological protection of patients. Justification of a diagnostic practice means that the exposure will provide the necessary information to...
confirm a diagnosis or to guide a treatment strategy. In addition, the information provided should be the best of all available options involving lower dose exposure or absence of exposure to IR.

The increasing use of interventional radiology procedures (multivessel angioplasty, catheter ablation, cardioverter defibrillator and cardiac resynchronization therapy implantation, etc.) with long periods of exposure to radiation has increased the occurrence of deterministic effects produced by radiations.

In order to minimize these damages, current guidelines for radiological protection are focused on staff training, using sophisticated fluoroscopic equipments that minimize the dose delivered to the patient while maintaining the image quality, and improving digital techniques by setting up diagnostic reference levels to optimize radiation exposure.

**IMPORTANCE OF RADIATION DOSE**

In order to prevent the aforementioned risks, we should be aware of the radiation threshold below which the risk of damage could be considered minimal.

When ionizing radiation penetrates a material, its energy is absorbed. The amount of energy transferred per unit mass in the medium of interest is called KERMA (kinetic energy released in material).

In order to quantify the amount of energy delivered to a tissue or organ of the body, we use dose measures:

- **Absorbed dose**: energy imparted per unit mass by ionizing radiation to matter at a specified point. The special name for this unit is the Gray (Gy: J/kg).
- **Equivalent dose**: the radiation dose that takes into account the different probability of effects that occur with the same absorbed dose delivered by radiations with different radiation weighting factors. A sievert is a unit of radiation absorbed dose equivalent, defined as that producing the same biological effect in a specified tissue as 1 gray of high-energy x-rays.
- **Effective dose**: it takes into account the varying radiosensitivity of different tissues.

In patients undergoing radiological procedures, the risk of radiation depends on the entrance skin dose. The entrance skin dose is defined as the absorbed dose in the centre of the field at the surface of entry of radiation for a patient undergoing a radiodiagnostic examination, and is expressed in Gy o mGy (1Gy = 1000 mGy).

Professionals exposed to radiations should undergo measurement of the doses received in the eyes (optional), fingers, under the apron and neck (optional) (Figures 1 and 2).

A thermoluminescent dosimeter (TLD) is a small device used to measure ionizing radiation exposure that is worn near the area of incidence of the radiation beam without interfering with the procedure (Table 1).

**DOSE LIMITS**

In order to restrict and control the risks related to radiation exposure, the following dose limits received for whole-body exposure by occupationally exposed persons or members of the public have been established:

- **Dose limits for occupationally exposed persons**: an average of 20 mSv per year for 5 years.
- **Dose limits for members of the public**: 1 mSv per year.

Average annual exposure to natural radiation sources is 2.4 mSv per year.
Dose limits for occupationally exposed persons should not be exceeded under any circumstances. Annual dose limits for workers is 20 mSv for whole-body exposure, with equivalent dose of 150 mSv to lens of eye and 500 mSv to skin.

Although there are no dose limits for patients, all exposures should follow the ALARA principle (as low as reasonably achievable).

The European DIMOND approach proposed a reference level of 45 Gy/cm$^2$ for radiation doses delivered to patients during coronary angiography.

**MECHANISMS OF BIOLOGICAL DAMAGE**

The biological effects of ionizing radiations are related to several mechanisms triggered by the absorption of radiation by a material. Ionizing radiation causes atoms and molecules to become ionized or excited. Energy absorbed in living tissues brings about physical, biochemical and biological changes at molecular, subcellular, cellular, and tissue levels, according to the end point considered.

A cell compromised by an ionizing event can repair certain levels of cell damage; at higher levels, damage cannot be repaired and the cell may survive or die. If the cell survives, it can either keep on with its normal functions or present modifications that lead to the loss of the mechanisms of control of its capability of multiplication (carcinogenesis).

When the radiation causes excitation or ionization in a biological system, particularly at the level of critical molecules (proteins, enzymes, DNA, cell membranes, etc.) the energy delivered damages this system. This mechanism is called direct effect.

As biological systems are made up of a high percentage of water, the energy absorbed in that volume of water will generate intermediate molecules (free radicals, R-•) that are highly reactive species leading to secondary or indirect mechanisms of biological damage; these mechanisms are the most important ones.

Free radicals are molecules or fragments of molecules with an unpaired electron in the outermost electron orbit, and are therefore highly reactive. The cell damage produced by free radicals is known as indirect effect.

**BIological EFFECTS OF IONIZING RADIATIONS**

According to radiological protection, biological effects of IR can be classified in stochastic and deterministic effects.

*Stochastic effects* occurs by chance; the effect typically has no threshold* and its probability of occurrence is a function of the dose. They are considered severe effects, equivalent to fatal events. They are caused by DNA damage (mutations in oncogenes or tumor suppressor genes) that may lead to cancer or teratogenesis.

*Deterministic effects* are those that can be related directly to the dose received. The effect is more severe with a higher dose. It typically has a threshold, below which the effect will not occur (clinical level) (Figure 3).

Some examples of deterministic effects include radiation-induced cataracts or skin lesions such as erythema, epilation or necrosis (Table 2).

The interval between exposure to radiations and the clinical manifestation of the effect is called latent period (LP) and it may take hours, days or weeks (prompt effects) or months or years (delayed effects).

**Deterministic effects**

Deterministic effects are produced by overexposure to radiation above the threshold dose. Overexposure may be external (i.e. exposure to a source of X-rays) or internal (ingestion of $^{131}$I); it may last seconds or may be prolonged; and it may be delivered to the whole body or to a portion of it. In these cases a great number of cells die and these deaths are not compensated by

<table>
<thead>
<tr>
<th>Class</th>
<th>Effective dose ranges (mSv)</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Ultrasound, magnetic resonance imaging</td>
</tr>
<tr>
<td>I</td>
<td>&lt; 1</td>
<td>Chest X-ray</td>
</tr>
<tr>
<td>II</td>
<td>1-5</td>
<td>Lumbar spine X-ray, head and neck computed tomography, thyroid and bone scans, renal scan, ventilation/perfusion scan</td>
</tr>
<tr>
<td>III</td>
<td>5-10</td>
<td>Computed tomography of chest, abdomen and pelvis, barium enema, SPECT</td>
</tr>
<tr>
<td>IV</td>
<td>&gt; 10</td>
<td>Certain nuclear medicine scans</td>
</tr>
</tbody>
</table>

* Threshold: amount of radiation necessary to produce an effect in at least 1% to 5% of the individuals exposed.
repopulation at the cellular level. The loss of cells may produce severe damage of the functions of an organ or tissue that is clinically detected.

During acute overexposure (i.e., during a prolonged fluoroscopy as in the case reported) the most probable deterministic effect is the interaction of radiations with the skin and it depends on the dose, the depth of radiation penetration and the area of skin irradiated.

The scale of symptoms severity is the same as for common burns: erythema, edema, blisters, ulcers, necrosis and sclerosis.

The study of the deterministic effects is based on the analysis of the spatial and temporal distribution of the dose in the body.

A single dose of 6-8 Gy to a field size of 5 cm² produces an initial erythema that increases during the first week and disappears progressively 10 days after. Then, the main erythema appears, increases in the following 2 weeks and lasts 20-30 days. Higher doses may produce dry or wet desquamation, and even necrosis. The presence of a latent period is the reason why these complications are underdiagnosed.

Analysis of the location and size of the blisters that appear with doses of 15-25 Gy is of interest for dosimetry; in addition, the chronology of the development of the blisters depends on the dose received by the basal layer: a greater dose reduces the latent period.

The threshold dose for deterministic effects in case of prolonged and fractionated fluoroscopies is higher due to partial healing of the tissue (sublethal damage repair). For example:

- 30 Gy or greater: erythema.
- 50-60 Gy: permanent epilation.

Nowadays these type of lesions are less frequent due to better fluoroscopic equipments; however, experts are worried about digital images obtained with modern digital systems as overexposure may pass unnoticed to the radiologist. Images are easily obtained and deleted with digital fluoroscopy and there is a trend towards obtaining more digital images than necessary with subsequent overradiation to the patient.

The following examples of the doses delivered by some procedures may serve to have adequate param-

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**Table 2. Biological effects of ionizing radiations**

<table>
<thead>
<tr>
<th><strong>Stochastic effects</strong></th>
<th><strong>Deterministic effects</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Severity</td>
<td>Dose-independent</td>
</tr>
<tr>
<td>Mechanism</td>
<td>sublethal cell injuries (one or a few cells)</td>
</tr>
<tr>
<td>Nature</td>
<td>Somatic or teratogenic effects</td>
</tr>
<tr>
<td>Dosis umbral</td>
<td>?</td>
</tr>
<tr>
<td>Dose-effect relation</td>
<td>Linear</td>
</tr>
<tr>
<td>Onset</td>
<td>Delayed</td>
</tr>
</tbody>
</table>

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**Fig. 3. A.** Lesion in the back of a patient 6-8 weeks after coronary angiography and multivessel angioplasty. **B.** Photograph of the same lesion 16 to 21 weeks after the procedure shows a small ulcer. **C.** Tissue necrosis 18-21 months after the procedure. **D.** Close-up picture of the lesion in c. **E.** Photograph of patient’s back after skin grafting (Photographs of T. Shope taken from ICRP Publication 85.)
ers. In July 2008, the Health Physics Society reported the following values:

### Table 3. Threshold dose and times of exposure to give rise to deterministic effects

<table>
<thead>
<tr>
<th>Effects</th>
<th>Threshold dose (Gy)</th>
<th>Time to onset</th>
<th>Minutes fluoroscopy at 0.02 Gy/min (20 mGy/min)*</th>
<th>Minutes fluoroscopy at high dose (2 Gy/min) (200 mGy/min)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early transient erythema</td>
<td>2</td>
<td>2-24 h</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>Temporary epilation</td>
<td>3</td>
<td>Approx. 3 weeks</td>
<td>150</td>
<td>15</td>
</tr>
<tr>
<td>Permanent epilation</td>
<td>7</td>
<td>Approx. 3 weeks</td>
<td>350</td>
<td>35</td>
</tr>
<tr>
<td>Dry desquamation</td>
<td>14</td>
<td>4 weeks</td>
<td>700</td>
<td>70</td>
</tr>
<tr>
<td>Secondary ulcers</td>
<td>24</td>
<td>6 weeks or greater</td>
<td>1,200</td>
<td>120</td>
</tr>
<tr>
<td>Necrosis</td>
<td>18</td>
<td>10 weeks</td>
<td>900</td>
<td>90</td>
</tr>
</tbody>
</table>

Conversely, dose-area product and effective dose for some angiographic studies in Newcastle are: (Br J Radiol 1998;71:634-639;)

The different doses in each center depend on the model of the equipment, the participation of medical dosimetrists, patients’ characteristics, number of exposures and education of staff; the standard deviations of all these variables are high.

Table 3 shows the ICRP-93 (International Commission on Radiation Protection) analysis on this issue (9).

### PREVENTION MEASURES

Firstly, risk factors likely to produce radiation lesions should be identified (Table 4).
It is essential to train personnel in charge of performing interventional radiology, to follow local protocols, particularly those concerning reading of dosemeters as they vary according to the procedure and the patient, and to include a medical dosimetrist in charge of implementing the necessary measures for radiological protection. In this way, dose limitation will optimize the cost-benefit principle.

**FINAL CONSIDERATIONS**

It should be emphasized that cardiologists should be aware of the effects of IR not only when they prescribe procedures that require fluoroscopy, especially angioplasties, catheter ablations, resynchronizing therapies, etc., but also during patients follow-up in order to diagnose and eventually treat a lesion due to radiation overexposure. All patients receiving skin doses of 3 Gy should be followed-up 10 to 14 days following the procedure. It is advisable for primary-care physicians to know about the procedures they prescribe to their patient, the duration of the procedure and, if possible, the dose received.

**RESUMEN**

**Riesgos asociados con las radiaciones ionizantes**

El uso médico de las radiaciones ionizantes implica ciertos riesgos, aunque están ampliamente compensados por sus beneficios diagnósticos y terapéuticos. No obstante, el conocimiento de esos riesgos, así como su diagnóstico y prevención, minimiza sus inconvenientes y optimiza la calidad y la seguridad de su empleo. En este artículo se discuten aspectos vinculados con la relación dosis-respuesta en la piel (efectos determinísticos), la importancia del límite de la dosis, la fisiopatología del daño biológico y, por último, con las medidas de prevención.

**Palabras clave** Radicales libres - Vigilancia - Fluoroscopia

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