Radiation Protection education and training in several ionising radiation applications

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Abstract. Ionising radiation (IR) applications are quiet common among several areas of knowledge, medicine or industry. Medical X-rays, Nuclear Medicine, X-rays used in non-destructive testing or applications in research are a few examples. These radiations originate from radioactive materials or radiation emitting devices. Radiation Protection education and training (E&T) is of paramount importance to work safely in areas that imply the use of IR. The Technical Unit for Radiation Protection at the University of Barcelona has an extensive expertise in basic, initial and refresher training, in general or specific areas, as well as in courses validated by the Spanish Nuclear Safety Council or to satisfy specific needs with bespoke courses. These specific customer needs are evaluated and on-site courses can also be carried out.

1. Introduction

Ionising radiation (IR) applications are quiet common among several areas of knowledge, medicine or industry. The low intensity of some of them is counterbalanced by the huge number of people involved. Probably one of the most effective ways of keeping the risk at minimum is specific education and training (E&T) at different levels according to the area of application and responsibilities [1], thus spreading the radiation protection (RP) culture.

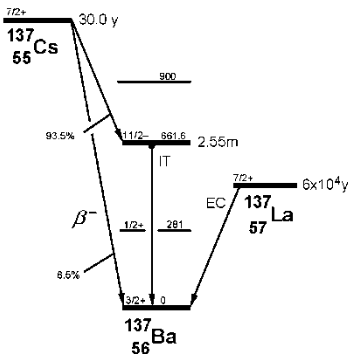
According to the International Radiation Protection Association (IRPA), the main objective of RP is to provide for the protection of man and his environment from hazards caused by radiation, and thereby to facilitate the safe use of medical, scientific, and industrial radiological practices for the benefit of mankind [2].

On the other hand, one of the pillars of RP is the ALARA concept. ALARA is the acronym for “As Low As Reasonably Achievable”, the radiation protection optimisation principle, defined by the International Commission on Radiation Protection (ICPR) as follows [3]: “the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept *as low as reasonably achievable*, taking into account economic and societal factors.” This goal can only be achieved by education and training programmes involving all stakeholders.

2. Ionising radiations nature and sources

2.1. Physical principles

It is said that “Radiation is a fact of life”, because of its ubiquity. As radiation simply defines the process in which a body emits energy or particles that propagate through a medium, this can be found in different physical forms, commonly separated in two main groups: ionising and non-ionising radiations [4]. Non-ionising radiations include most of the electromagnetic spectrum (photons), from radio waves to ultraviolet light; and ionising radiations include X and gamma-rays, as well as particle emissions (e.g. alpha or beta particles) (Figure 1). Photons are emitted in many natural processes. For example, when a charge is accelerated it emits synchrotron radiation. During a molecular, atomic or nuclear transition to a lower energy level, photons of various energies will be emitted, from infrared light to gamma rays. A photon can also be emitted when a particle and its corresponding antiparticle are annihilated (e.g. electron-positron annihilation).



Gammas from ^{137}Cs (30.07 y)

Eγ (keV)	Iγ (%)	Decay mode
283.53 *4*	0.00058 *8*	β^-
661.657 *3*	85.1 *2*	β^-

Betas from ^{137}Cs (30.07 y)

Eβ endpoint (keV)	Iβ (%)	Decay mode
513.97	94.4 *2*	β^-
892.22	0.00058 *8*	β^-
1175.63	5.6 *2*	β^-

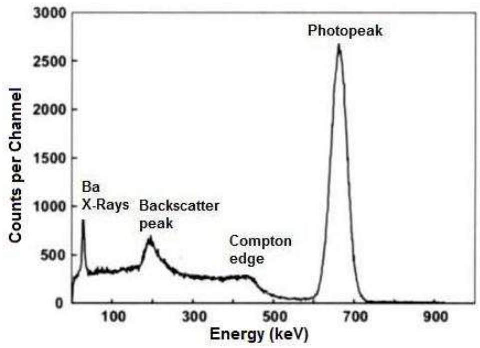


Figure 1: Decay scheme for Cesium-137 (^{137}Cs) (left); decay modes, energies and intensities (centre); and its corresponding Sodium iodide gamma spectrum (right).

The different kinds of electromagnetic radiation have different kinds of interactions with matter [5], and both ionising and non-ionising radiation can be harmful to organisms and can result in changes to the environment. But, non-ionising electromagnetic radiation has only sufficient energy to change the rotational, vibrational or electronic valence configurations of molecules and atoms; meanwhile ionising radiation has sufficiently high energy to ionise atoms that means to strip an electron from an electron shell, which leaves the atom with a net positive charge (ion).

2.2. Natural sources of ionising radiations

Ionising radiation surrenders us in our direct environment, because it arises from natural processes, mainly from cosmic radiation, radioactivity in soils, minerals and in our body (^{40}K), inhalation of radon gas or radionuclides present in food and drink [6]. The impact of these natural sources can also be enhanced by human activities; such as flights, mining and other activities that led to the production of by-products known as NORM materials (Naturally Occurring Radioactive Materials) [7].

2.3. Artificial sources of ionising radiations

Artificial processes, such as medical X-rays, Nuclear Medicine, X-rays used in non-destructive testing, nuclear power production or applications in research are some examples. In general, these radiations originate from two different kinds of sources: radioactive materials or radiation emitting devices.

2.3.1. Radioactive materials

Radioactive materials are those materials that contain radioactive elements (radionuclides), which are unstable atoms that spontaneously emit radiations as they decay. Artificial radioactive materials can be found in two forms, known as sealed and non-sealed sources respectively. *Unsealed sources* consist of radioactive chemical compounds that are directly accessible and can be manipulated directly. For example, radioactively labelled dissolutions used as radiotracers in life science research, to study biochemical pathways. Nearly any chemical compound can be radiolabeled [8]: carbohydrates, lipids, amino acids, nucleic acids, hormones, drugs…

On the other hand, *sealed sources* usually consist of a sealed capsule (of non-radioactive material) that contains solid radioactive materials. They can form a part of a device, as in some radiotherapy equipment, or constitute individual items, such as the little sealed radioactive sources for educational purposes.

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2.3.2. Radiation-emitting equipment. In contrast to radioactive materials, radiations emitted from this apparatus do not come from spontaneous decay but from an electric device (Figure 2), where radiation can only be generated and emitted as long as the device is switched on, so it depends on a power supply. Probably medical X-ray machines are the most widespread radiation emitting equipment [9], but devices such as electron microscopes and some type of cathode-ray tubes, generate ionising radiation as a by-product of some other function.

Particle accelerators also constitute radiation-emitting equipment. Linear accelerators (LINACs) are widely used in medicine, for radiotherapy and radiosurgery. Meanwhile circular accelerators can be used as synchrotrons to obtain synchrotron light or radiation (X-rays); or as cyclotrons, for proton therapy, or those used to produce the short-lived radionuclides for positron emission tomography (PET) in nuclear medicine imaging. Finally colliders, such as the Large Hadron Collider (LHC) at CERN are also sources of ionising radiation and particles [10].

3. Ionising radiations applications

3.1. Medical/Veterinary applications

Ionising radiation has two very different uses in medicine: for diagnosis and therapy. Both are intended to benefit the patients and, as with any use of radiation, the benefit must outweigh the risk.

Diagnostic X-ray examinations (Figure 3) are quite common and include a wide range of equipment variations. Simple X-rays are used in dental intraoral or panoramic examinations, traumatology, bone densitometry, mammography, etc. More specific equipment is needed in

Computed Tomography (CT) or in interventional radiology, which make use of C-arm apparatus in the operation theater [11].

Figure 2: Faxitron cabinet enclosed X-ray machine used in some X-ray UTPR-UB training courses

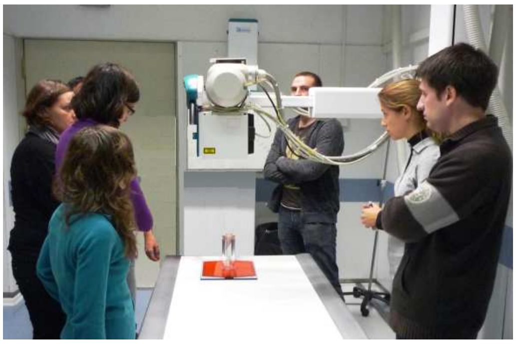

Figure 3: X-ray Quality control training session with UTPR-UB equipment

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Some diagnostic procedures involve the administration of radionuclides as non-sealed sources to patients in Nuclear Medicine [12], as in bone gammagraphy (using special radionuclides as ^{99m}Tc) in the form of radiopharmaceuticals. Or in Positron Emission Tomography (PET), which makes use of short-lived radionuclides, at present mainly ^{18}F, with a half-live shorter than 2 minutes, in the form of ^{18}F-FDG (Fluor-deoxy-glucose).

On the other hand, the aim of radiotherapy is to cause damage to cancerous cells to stop its reproduction and the cancer progression. Radiations used are high-energy gamma rays from ^{60}Co sources or high-energy X-rays generated by linear accelerators. Small sealed radioactive sources can also be implanted in the patient's body in brachytherapy. Finally, in a few centers around the world accelerated proton beams are used for radiation therapy (Proton therapy) that can be precisely delivered in depth [13] due to the presence of the characteristic Bragg peak.

3.2. Industrial applications

Ionising radiations are powerful tools in industry, mainly in the so called non-destructive testing (NDT), where gamma sources or high-energy X-rays are used to obtain an image of the inner parts of pieces to verify the integrity of components or flaws [14]. Non-destructive testing can be applied as a part of the final product quality control assurance, or later in used components to localize cracks or worn pieces. It is fairly used in automotive, aeronautic or electronic industries, for instance. With a similar aim radioactive tracers may allow to find a hole in a tube or to measure wear in a motor.

X-ray inspection systems can be applied in different areas, from final product quality control for a wide range of packaged items to the well known baggage control security systems in airports and official buildings. In this sense food in cans, jars or packets are systematically scanned to find foreign materials (Figure 4), underfills and verify package contents in the food, beverage and drug packaging industries [15]. Furthermore, lately some countries are implementing the use of full body scanners [16] in airports and train stations to look for hidden objects; some of these devices are based on direct X-ray technology and others on backscatter X-rays.

Another industrial use of ionising radiations concerns gauges [17]. They can be used for example to control the level of replenishment in tanks of liquids or grainy substances, or even packed beverages. Or thickness gauges, useful to control the product thickness in continuous production, like that of paper, rubber, etc.

Figure 4: Different radiographic conditions in an experimental example designed by the UTPR-UB for a specific X-ray equipment course. It consists of a jar of food where two thin foreign objects have been detected by means of X-ray technology, showing different image qualities

In industrial irradiation facilities radiation is used for sterilization of mainly sanitary tools and equipment, among others; this includes different kind of products used in agriculture and flower-growing (soils, substrates, fertilizers, plastic flower pots and seeds). An advantage is that the object may be sealed in plastic before sterilization. An emerging use in food production is the sterilization of food using food irradiation [18]. Food irradiation seems to provide optimum results for inhibition treatment of tuber shoots, elimination of insects from fruits and seeds, delaying the maturing process of fruits and elimination of alterative microorganisms and pathogens in any type of food [19], helping to improve food-related health worldwide. Electron accelerators as well as gamma sealed sources (^{60}Co) are currently in use. At present, in the Spanish legislation food irradiation is only allowed for dried aromatic herbs, spices and vegetal condiments [20].

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3.3. Scientific and biological Research applications

At the University of Barcelona (UB), as in all worldwide leader Research institutions, non-sealed radioactive sources are in use in low quantities as radioactive tracers, where radioactive atoms substitute its stable isotope in a molecule. Then as radioactive emissions from radioactive atoms can be relatively easily detected, this molecule can be followed in any physical, chemical or biological system (Figure 5). In biological systems radioactive tracers can be applied at the different study levels [21]: “in vivo” on different animal species, “in vitro” in cell culture systems, in nucleic acid or protein labeling techniques, Radioimmunoassay (RIA), as well as in subcelular localization of molecules, so in Molecular Biology; but also in drug discovery studies, Pharmacology, Biochemistry, Ecology and so on. A common and important aspect of most of these procedures is the detection technique, where Liquid Scintillation Counting (LSC) is a powerful technique [22] that is described elsewhere in this Handbook, as well as in the UTPR-UB training sessions (Figure 6).

A diagnostic-type X-ray machine or a cabinet enclosed X-ray machine may be used for imaging in research. For example at the UB’s Faculty of Biology Radioactive Facility it is currently in use with experimental animals (mouse, fish, squirrels, etc). X-ray techniques at UB facilities are also treated in depth elsewhere in this Handbook. The cabinet enclosed X-ray machine in Figure 2 is used in the corresponding UTPR-UB training courses.

3.4. Other uses

Many other applications of ionising radiations are in use, as ^{241}Am in ionic smoke detectors, measurement of humidity of soils in buildings and engineering technologies (nuclear gauges such as Troxler), precious stones irradiation to enhance its properties or for crosslinking of polymers. With a similar aim that ionising radiations are used in diagnostic imaging and NDT, they are applied to the study, conservation and restoration of art and cultural heritage [23].

In biology and agriculture, radiation is used to induce mutations to produce new or improved species. An interesting application in Biology/Agriculture is the “Sterile Insect Technique” to control pests [24], where male insects are mostly sterilized with radiation and released in the fields, so that they have no offspring, thus reducing the next generation's population. This constitutes a method of biological control of pets for crops and insect vectors for sickness (Anopheles and Aedes mosquitoes, tsetse fly, etc).

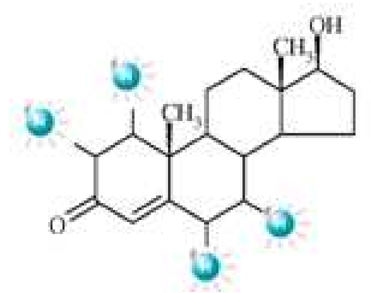

Figure 5: Example of tritium radiolabeled hormone *Testosterone, [1,2,6,7-^{3}H(N)]*

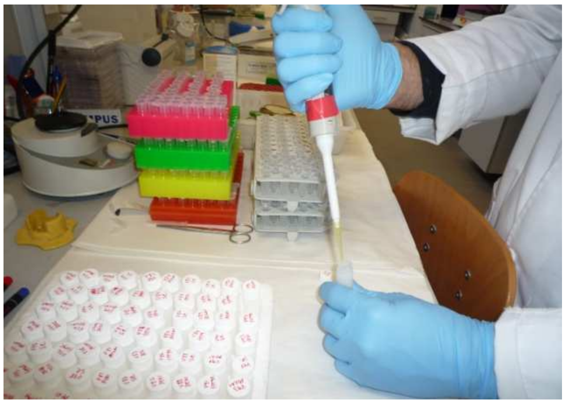

Figure 6: LSC sample preparation for its detection and quantification at a UB Radioactive Facility

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People enrolled in all this and other applications involving the manipulation of materials or equipment that emits ionising radiations need to be trained according to their level of responsibility, magnitude of used sources and the application itself.

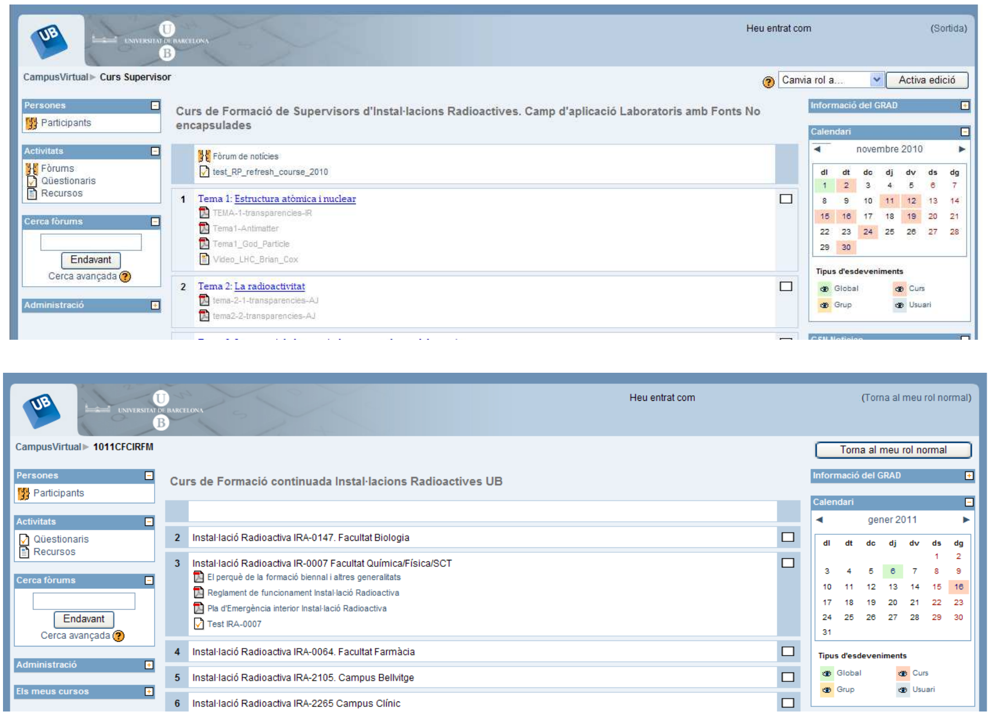

Figure 7: Two examples of web based UTPR-UB training courses implemented on the Moodle platform through the "UB Virtual Campus"

4. Methodology

4.1. Training levels

For practical reasons it is worth to distinguish between basic, initial and refresher training [25].

4.1.1. Basic training

It can be aimed at different collectives of non-exposed workers, for example:

- Workers who do not directly work with ionising radiations, but nevertheless work in the vicinity of radiation sources (including, for example, cleaning and maintenance staff) have to be trained in and informed of the potential hazards associated with radioactive sources and the basic protection and safety procedures.
- Personnel in management positions have responsibility to ensure that all workers, including contractors, receive adequate training in radiologic protection and safety.
- In this category information to stakeholders can also be included.

4.1.2. Initial training

This training is compulsory for any new exposed personnel:

- Students who are engaged in course work or research projects in which radioactive materials and radiation producing devices included in this category are used, and may need specific radiation safety training associated with their academic studies.
- Exposed workers with low level of responsibility need a training level similar to that mentioned above for students.
- Exposed workers with high level of responsibility in a lab or radioactive facility are required to have a licence by the regulatory body, usually as Operator or Supervisor. This is the case of the Spanish regulations [26], where these courses need to be validated previously by the Spanish Nuclear Safety Council (Consejo de Seguridad Nuclear, CSN).

4.1.3. Continuous training

In general the frequency of refresher training is determined by national regulations, but is quite common to establish an annual or biannual periodicity [27]. This can include or not, on the job training, as a means of training for a new practice or equipment.

4.2. Training methodology

Training methodology needs to fit the level and purpose of the training session or course, as well as its length and content. Presential courses or classroom based lectures are still one of the most effective methodology and face-to-face classes are irreplaceable for practicals. Therefore, in most cases, theoretical information is reinforced by the effective use of demonstrations, laboratory exercises, case studies, simulations and technical visits.

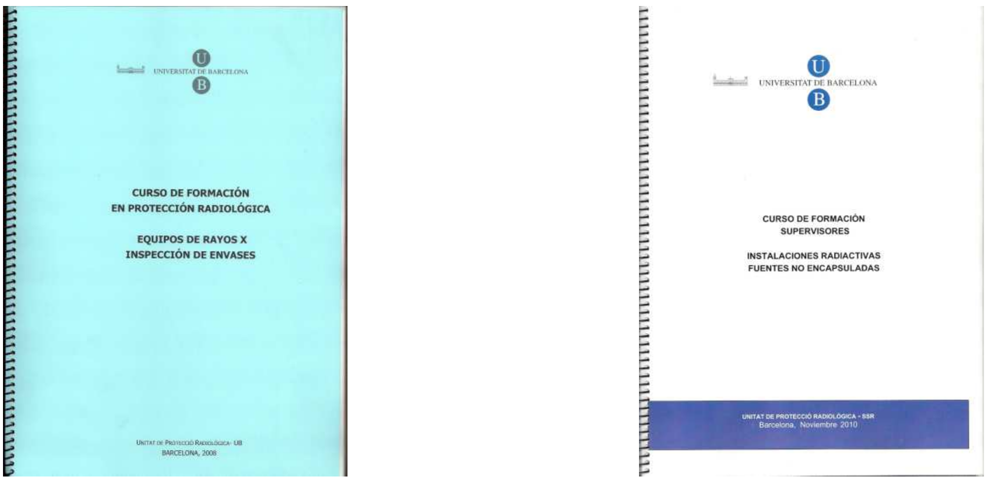

Figure 8: UTPR-UB Handbooks of several Radiation Protection training courses

But nowadays, web-based, on-line or e-learning (Figure 7) modalities have advantages in aspects such as minimizing timetable problems or time consuming trips to the formation centre. On the other hand, the availability of commercial platforms [28] and free, open-source platforms to implement these training modalities facilitates the widespread use of them.

4.3. Training in specific areas

Courses aimed at holding a validated license according to Spanish regulations, are divided in five specific areas [29]: 1) Radiotherapy, 2) Nuclear Medicine, 3) Labs holding non-sealed sources, 4) Industrial Radiography and 5) Processes control and analytical techniques. Furthermore, health professionals using X-ray equipment need to hold an official accreditation [30], to direct or to operate, an X-ray facility. But needs for training are constantly changing as at present health professionals on interventional radiology must undertake a more specific course (second level).

In spite of the improvement and specificity of the aforementioned areas, some cases are difficult to classify under one of the specific licences. For example, scientists in the Chemistry, Pharmacy or Biological applications very often need to hold a license under the specific area of "Labs holding non-sealed sources". But X-ray NDT on an art work needs to hold a licence on "Industrial Radiography".

Other professionals may need some kind of RP training and education [31]. This personnel can include staff of regulatory bodies, emergency response personnel, those involved in transport of radioactive materials, or dealing with the management of residual materials containing radioactive materials, technical staff from firms related to ionising emitting equipment, such as technical services from medical X-ray providing equipment, or X-ray inspection systems or staff operating a baggage control X-ray machine (EVAT firms).

It is worth mentioning that obviously members of a Radiation Protection Technical Unit (UTPR) must also undertake specific training, as Head of UTPR (official course in Spain exclusively organized at CIEMAT (Madrid)) or as RP expert (it can only be accredited by the UTPR Head). Their continuous training must be granted. On the other hand, at European level a wide diversity in the approaches of Member States as to the training and qualifications of radiation protection stakeholders has been described. This makes mutual recognition difficult between Member States and an improved level of harmonisation would be very useful [32].

Figure 9: UTPR-UB equipment used in RP training courses (radiation detectors and personal dosimeters)

5. UTPR-UB training expertise and capabilities

5.1. Training instrumentation and facilities at the UB

For practical exercises different kind of radiation detectors are available at the UTPR-UB (Figure 7), as well as several small calibration sources for demonstrating alpha, beta and gamma emissions, along with a set of absorbers. Also, samples of film badges, TLD dosimeter badges, and direct reading electronic personal dosimeters (Figure 9) are shown. Examples of personal shielding equipment such as Perspex screens and boxes, lead sheets and containers, or lead aprons are also on the spot.

Furthermore, the following big equipment can be used for more specific demonstrations: automatic liquid scintillation counters and spectrometers (LSC), NaI crystal spectrometers and counters, shielded X-ray cabinet (Figure 2) and automatic film processing equipment or electronic autoradiography plates and readers, just to mention some.

5.2. UTPR-UB training expertise and capabilities

Since 1988 training has been a central task of the UTPR-UB. Training ranges from initial training of new Radioactive Facility users (academic staff, researchers, technicians, students) to Supervisor courses validated by the CSN. Initial and refresh courses are of paramount importance in all contexts, especially in the research and university environment, where many people can be involved in low-level ionising radiation applications, but also where research personnel can have a high-turnover rate.

The first edition of a Supervisor accrediting training course at the UTPR-UB took place in 1990. Since then, more than three hundred people has been trained at this level in the application area of "Labs holding non-sealed sources" at their facilities.

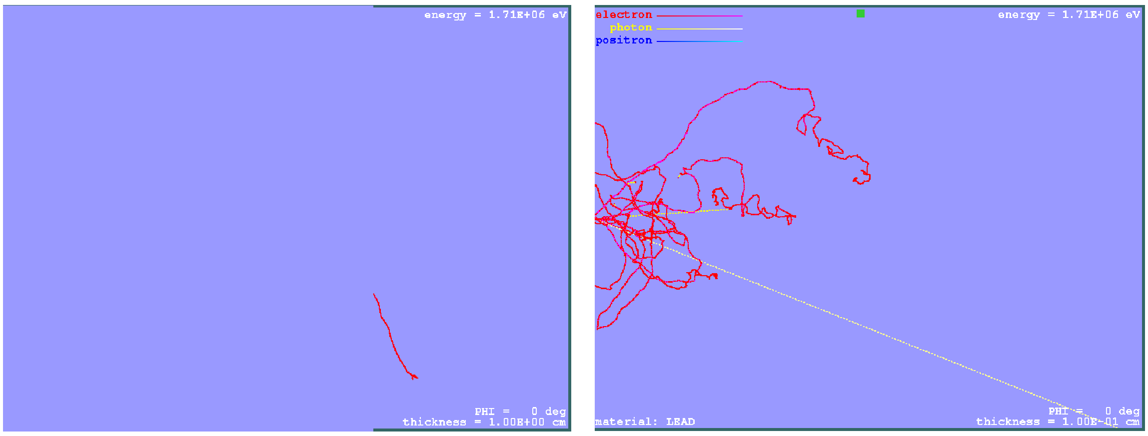

Figure 10: Images of Monte Carlo (PENLAYER) simulation used in RP training courses. In the example, 10 electrons with an energy equivalent to $E_{\beta max}$ of ^{32}P emissions interact with a 1-cm-thick slab of water (left) and a 1-mm-thick slab of lead (right). Notice Bremsstrahlung photon generation (yellow line) in the interaction of electrons with heavy materials.

Our training methodology is in constant evolution, and includes some simulation or web-based tools. For example, simple visual "electron-photon shower" simulation (e.g. the code PENLAYER from the general-purpose Monte Carlo program PENELOPE [33] developed at the UB) (Figure 10), or the use, as a complementary tool, of the Moodle platform by means of the "UB Virtual Campus" (Figure 7). Courses syllabus and contents are carefully revised prior to each edition, mainly to take into account the introduction of new Spanish/European legislation.

Furthermore, custom courses have also been developed on demand. For example, a specific course was organized for the technical staff from a supplier of enclosed cabinet X-Ray inspection systems for packed food. It included the development of a specific course handbook (Figure 8), attending classes, implementation of specific X-ray exercises, a final test and a satisfaction questionnaire. Also, initial training sessions for staff of dental clinics using X-ray equipment have been developed.

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