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NEEDS AND STATE OF THE ART IN CRITICALITY DOSIMETRY AND DOSE RECONSTRUCTION TECHNIQUES FOR MEDICAL MANAGEMENT OF CRITICALITY ACCIDENT'S CASUALTIES

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ABSTRACT

The medical management of victims of a radiological accident is often driven by the information on the dose distribution or dose at organs at risk that is the main pertinent information expected. Since the Chernobyl accident with the feedback experience on the medical management of highly exposed liquidators, there is nowadays a medical management to treat patients if possible before clinical signs appear and therefore to develop a treatment strategy based in particular on dosimetry information. For criticality accidents, dosimetry is more complex, because of the possible high doses, high dose rates and complex gamma/neutron fields [1].

A high dose from a criticality accident requires dose estimation with a short delay to be effective. It is important to segregate the different contributions of the radiation field, due to the difference in biological detriment. As the neutron dose is mainly deposited in the first few cm of the body that implies to take into account the morphology specificity, difference in organ doses could be up to 30%.

This article presents the various technics used (physical retrospective dosimetry, cytogenetic, activation of blood and hairs and nails, Monte Carlo simulation, etc.) to estimate doses in case of criticality accident. Then, the needs for this specific field of dosimetry will be presented, including firstly the necessity for an international collaboration and cooperation, in order to maintain and to share the few facilities still available, and secondly to have scientific cooperation for future developments and improvements.

KEY WORDS

Dosimetry, Criticality Accident, NAD.

1. INTRODUCTION

The medical management of victims of a radiological accident is often guided by information on the dose received. More than the whole body dose, it is the distribution of the dose in the body and the absorbed dose at organs at risk that is one of the main relevant information expected. It is important to remember that even in the case of a whole-body irradiation, the dose distribution is always heterogeneous, even with high-energy photons. The dose to at-risk organs can be very different from the average dose in the body. In the case of a criticality accident, this axiom is even more true if we consider the high absorption of neutrons in the body that induce very high heterogeneity (see for example (Endo 2010), [2]), which differs greatly according to the radiation field and the morphology and orientation of the person in the irradiation field. With the feedback on the medical management of the liquidators of the Chernobyl nuclear accident, there is now an international consensus for the medical care of highly exposed people [3-7]. It is recommended to treat patients as early as possible and if possible before clinical signs appear in order to improve the effectiveness of treatment and recovery. Therefore, the medical strategy is based on dosimetric information that must be as accurate as possible and available as quickly as possible.

In the field of radiological accident dosimetry, a multi-technical approach is recommended and necessary to best estimate the dose distribution, the only information from the individual dosimeter being far from sufficient. In addition to individual dosimeter, complementary dosimetric approaches are therefore used:

- measurements on biological samples (cytogenetics on blood, Electron Paramagnetic Resonance (EPR) spectroscopy on tooth and nail biopsy, activation on hair, nails and blood),
- personal effects or inert materials from the environment (EPR, thermoluminescence (TL), optically stimulated luminescence (OSL), and activation),
- Monte Carlo (MC) simulation with a numerical phantom.

The multi-technical approach has been successfully used for many accidents with gamma or X-ray sources [8-20], but has never been used in its full possibility in the case of irradiation with a neutron component. The presence of a neutron component makes dose assessments more complex than the classical accident scenario types as those with orphan sources for example. Most of the research work dedicated to accident dosimetry is nowadays dedicated to the large scale accidents and notably to the adaptation of biodosimetry methods for fast triage and neutron irradiation is only considered for scenarios with improvised nuclear device (IND).

For neutron irradiations and more particularly for criticality accidents, dosimetry is far more complex. It requires not only the knowledge of the orientation of the victim but also the neutron energy distribution. In addition to the conventional personal dosimeter, an additional specific dosimetry system is also implemented: a nuclear accident dosimeter (NAD) capable of estimating at minimum, thermal and fast neutron dose components and gamma dose over a wide range of doses and providing some minimum information on the neutron spectrum. As the determination of the person's orientation is crucial for the determination of the dose, a belt is recommended with usually 4 or 6 dosimeters, although hair activation may also provide useful information on orientation (when possible), as demonstrated by a recently organized criticality dosimetry exercises (IER-148 [21] and IER-253). As knowledge of the neutron spectrum is essential for dose assessment (especially at depth in the body), it may be also recommended to use area dosimetry systems that provide neutron spectra, even if sophisticated NADs can provide some information (it remains limited due to the influence of the body and the difficulty of correcting orientation). Over time, the understanding of the challenges in this field and the technical constraints were deteriorated. In addition, the absence, in most of the countries concerned, of a regulatory framework for system testing and evaluation criteria may allowed the deployment of systems that are not adapted or do not meet needs.

A high level of exposure in criticality accident requires to provide a first doses estimation in a short delay. It is important to segregate the different contributions of the radiation field, due to the difference in biological detriment. As the neutron dose is mainly deposited in the first centimetres in the body [22], that implies to take into account the morphology specificity, difference in organ doses could be up to a factor of 4 [23]. Example of dose distribution within the body for an actual accident case can be found in Endo (2010) [2] and Endo and Yamaguchi (2003) [24] for the two most exposed workers of the Tokai-Mura accident.

Most NADs are able to provide an estimation of the maximal dose for each component for an anteroposterior (AP) configuration, but correction from orientation of NAD doses remains a critical issue needing further studies. The implementation of all these techniques needs to be tested in an exercise mimicking realistic conditions, especially for integrating the newly developed approaches. The last critical point is the determination of organs dose that is commonly done by simulation taken into account all other dosimetric assays. The combined approach was successfully used in several radiological accidents with gamma exposure only [8-20]. For criticality accident, the task would be more complex especially considering the short delay imparted and the identified need to take into account the morphology of the individual, leading to the necessity to use voxel phantom or to adapted mathematical phantom. Thus, a new approach could be to establish a database of dose conversion factors from dose in NAD to organ doses for different morphologies, particle types, particle energies and of course orientation to be able to provide quickly an accurate estimation of organ doses. The demonstration of efficacy of such tool should be part of future exercise.

The aim of this paper is to provide an overview of the specificity of criticality dosimetry, the techniques used and envisaged and a discussion of the critical issues in this field.

2. JUSTIFICATION AND NEEDS FOR DOSIMETRY INPUT FOR MEDICAL MANAGEMENT

The main objective of dosimetry in the event of a radiological accident is to be able to estimate the health consequences as accurately as possible and thus to determine the best therapeutic strategy to be implemented, if necessary. To do this, the dosimetric information required is therefore the doses absorbed in the most exposed and radiosensitive organs or tissues. It is important to segregate the different contributions of the radiation field, due to the difference in biological detriment. The relative contribution of the neutron and gamma components varies with depth in tissue. As shown in Figure 1, one can see that the neutron component is rapidly attenuated in the tissue traversed with a maximum dose in the first few centimeters of tissue. For gamma, in addition of direct gamma, secondary gamma are produced in the body mainly by capture reactions with neutrons on hydrogen atoms. The gamma component reported in Figure 1 is only secondary gamma from neutron interaction in tissue. One can easily understand that the gamma dose profile in the body should not only take into account the attenuation of direct gamma, but also the production of secondary gamma. This is one of the reasons why the knowledge of the neutron spectrum is important. The standard thickness of the human body reduces the photon doses by about a factor of 2 to 3 for photon energy around 1 MeV, and by a factor of 10 to 20 for neutrons with a fission spectrum. Since the distribution of the dose is very heterogeneous in the body, particularly in the case of irradiation with a neutron component (Figure 1), knowledge of the whole-body dose (as given by cytogenetic method) or the maximum dose (given by NAD) alone is obviously not sufficient. A second step in the dose evaluation is then needed.

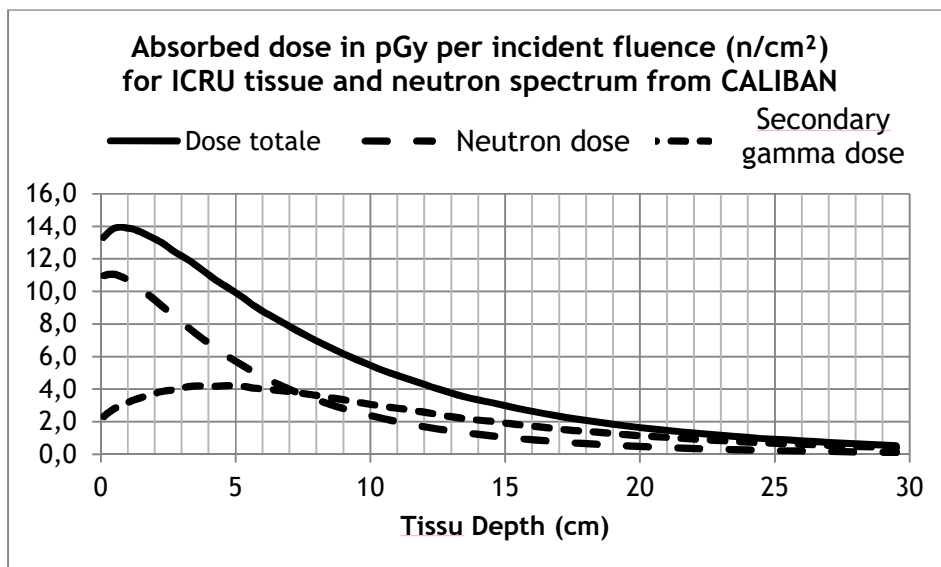


Figure 1. Calculated variation of the neutron dose and secondary gamma dose as a function of the penetrated tissue depth for a neutron fission spectrum measured at the CALIBAN (CEA, Valduc, France) (neutron spectrum can be found in [25]). Calculations were performed with MCNP [26]

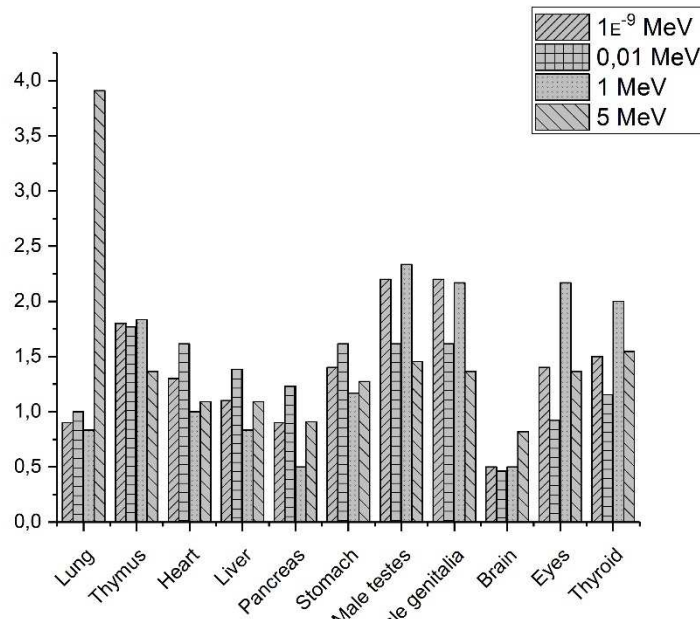


Figure 2. Variation of the ratio of organ dose to whole body dose for different neutron energies calculated with MCNP with numerical mathematical standard phantom (data calculated from data for AP configuration presented in [27])

Thus, the data provided by dosimetry systems, including maximum doses in the body (gamma and neutron) and neutron spectrum, are only input data to a more complete dosimetry assessment that will also take into account retrospective dosimetry data to ultimately estimate doses to the most critical organs. To do this, simulation techniques will most certainly have to be implemented. As shown in Figure 2, the difference in dose to deep organs can be as much as a factor 4.5 depending on the neutron energy. Orientation has also a significant influence on organ dose. Variation in organ doses can reach 20% between anteroposterior (AP) and posterior-anterior (PA) configuration for 1 MeV neutron [23]. The largest variation is observed when comparing lateral irradiation. For example, doses to left and right lung can differ in that case by a factor 100 for 1 MeV neutron and by a factor of 10 compared to AP or PA configuration. If simulation techniques based in particular on MC calculation codes are efficient, they can take into account all influence parameters and make it possible to estimate organ doses as accurately as possible. Nevertheless, these techniques require a precise knowledge of the circumstances of the accident (neutron spectrum, number of fission, maximum dose, orientation of the victim, morphology of the victim, distance, environment (e.g. wall)). This technique was used to evaluate the dose distribution in the body of the two most exposed workers of the Tokai-Mura criticality accident, but afterwards to provide knowledge regarding the link between the observed injuries and the deposited doses [24]. Wilson et al. (2012) have pointed out the importance to consider this method in the dose reconstruction process together with data from NAD [28]. A simplified approach could be to use the neutron spectrum and the maximum dose measured by dosimetry systems as input and normalization data for numerical simulation of the neutron dose component. However, the use of standard numerical phantoms of the human body will not always allow an accurate estimation of doses due to the influence of morphology on dose distribution. Difference in calculated organ doses depending on phantom morphology can reach a factor of 4 [23]. Therefore, the use of phantoms close to the morphologies of the victims becomes necessary. Voxelized phantom can be built from scanner or magnetic resonance images from the victims or pre-built from pre-existing phantom libraries [23].

Therefore, criticality dosimetry system and retrospective dosimetry aim to provide all the needed input data for final dose estimation based on simulation. To do so, at least the following minimum input should be provided:

- Orientation of the victim;
- Neutron spectra;
- Maximal dose (neutron and gamma) or tissue kerma (neutron tissue kerma provide a good estimation of the maximal neutron dose).

One could argue that neutron spectrum could be assessed by MC simulation when information on source terms will be available and therefore there is no need to make criticality dosimetry system complex (to get the neutron spectrum information) or even to have such system. First of all, even in benchmark studies with perfect knowledge of the description of the reactor, significant difference (few 10%) can be observed between measurements and simulations, these difference are even more important with the close presence of wall for example, the composition of concrete being definitely an issue. Secondly, due to the short delay imparted for the dose estimation and the accuracy expected in such circumstances (< 25%), it is not yet demonstrated (by an exercise for example) that accurate dose estimate could be provided by MC in such delay. For the Tokai-Mura accident, if MC were performed to assess organ doses, it was not done in the emergency phase but more to understand afterwards the biological effect [2]. The MC method could be also used to create radiation dose maps for the environment around the criticality accident site, to ensure that lightly exposed personnel on the periphery of the accident zone are assigned a conservative dose.

All additional input, especially those from retrospective techniques, could be valuable because helping to confirm exposure level and the scenario of exposure, providing additional data on dose heterogeneity. For example, doses estimated for nails by EPR (gamma dose) and activation (neutron dose) could be of value when hands are highly exposed, as for example in the Sarov accident [29]. It is worth noting that NAD may simply not worn as in the Tokai-Mura accident for example [30]. Therefore, one could argue that the human body is itself a dosimeter (applying retrospective dosimetry technique) and that no dosimetric system is therefore needed. As a matter of fact, all these retrospective dosimetry techniques have some limitations (availability of samples, calibration (knowledge of neutron spectra and neutron to gamma ratio may be needed), availability and rapidity of techniques). The performances of these techniques are described in the next section and in review papers [31, 32]. Overall, due to these limitations, even if the debate can be opened up, it is difficult to consider to abandon NAD.

3. OVERVIEW OF DOSIMETRY TECHNIQUES

After the quick sorting based on activation measurement and the analysis of NAD and other dosimetric systems, the second dose evaluation step will not only take into account data provide by the NAD (when available), but also data provided by the so called retrospective (or accident) dosimetry techniques to provide organ doses, as it is usually done for other context of radiological accident [8-20]. Overall, in case of radiological accident, it is recommended to accumulate the maximum of data, knowing that it is difficult at first sight to know which ones will ultimately be relevant.

a. Dosimetry system

Depending on countries and laboratories, the dosimetry system proposed can be composed at minimum by a NAD that is specifically design for criticality accident. The range of dose is higher than with techniques used for individual dose monitoring, with dose range from few tens of mGy to maximal dose of about 10 Gy. As these dosimeters are not routinely read (only in case of accident), they must require only a minimum of maintenance. NAD can be supplemented by a “criticality belt” as for example in France and UK nowadays and in USA (in the past) in order to provide the orientation of the victim. The knowledge of the orientation is a key parameter in the dose reconstruction process, as discussed in the previous section. Criticality belts were largely used in the past and gradually abandoned. In addition of belt and NAD, an area neutron spectrometer can be also deployed as it is still the case in France and in Italy for example.

NAD

For the neutron component, most of NAD used are based on activation techniques using foils or pellets of materials that can be activated. The most usual dosimeters include gold, copper, indium and sulphur. With these detectors, the main activation reactions are (n,γ) reactions (thermal and intermediate neutrons) and (n,n') or (n,p) reactions (threshold detectors for fast neutrons). A review of current design of NAD can be found in the IAEA technical report series n°211 [33]. Using multiple foils with different shielding, such as cadmium, provide information on neutron spectrum or at least provide the fast and thermal neutron components. One of the advantages of the NAD with activation is to allow with a simple survey meter to perform a quick sorting of people.

Chemical dosimeters are marginally used, but it provides only the total dose. Fission detectors (in the form of fission track detectors) are also marginally used [34] as well as silicon diodes (neutron energy threshold ~ 0.2 MeV) capable of measuring doses in the range of 0.2 Gy up to 10 Gy with a very negligible response to gamma rays but without providing any information on the spectrum shape [35]. New type of dosimeter based on free radical productions by ionization are also proposed to assess the neutron maximal dose. Typically, amino acid such as alanine, presenting the interest to be tissue equivalent are proposed [25, 36]. The reading is performed using EPR spectrometer able to identify and quantified the radio-induced free radicals. The signal can be considered as stable over long periods (months, years) and as reading is not erasing the signal (as for TL/OSL), the dosimeter can be read again as many times as necessary. This advantage is nevertheless a disadvantage regarding maintenance since contrary to activation, alanine pellets need to be replaced time to time. As alanine is also sensitive to photon, to get only the neutron dose, it also requires to have a gamma dose assessment from another dosimeter to subtract the photon dose delivered to alanine.

The design of NAD is more or less complex depending on the strategy retained for the neutron dose assessment. The gamma dose assessment uses same techniques (TL, OSL, radiophotoluminescent (RPL)) as for individual monitoring. Simple design for the NAD (for the neutron component) minimizing number of foils or pellets to read, presents the advantages of faster analysis and therefore larger capacity of measurement and to minimize the risk of human error in this process. The simplest design is usually composed of sulfur for the fast neutron component, gold foils bare and under cadmium shield to assess the thermal component and a gamma dosimeter such as TL, OSL or RPL. Such dosimeters may need additional information on neutron spectrum to tune the calibration and therefore need a neutron area dosimeter/spectrometer (usually based on activation foils). A more complex NAD design, by adding foils and shielding can provide more complete information on neutron spectra and is therefore less spectrum dependent. Therefore, in this case, area dosimeter may not be necessary at first glance. The complexity implies lower measurement capacity. Moreover, the effect of the body by the albedo phenomena is usually not corrected. Both approaches are valid and the choice of a technique or an approach is not only based on technical considerations, but also take into account the availability of measurement devices (gamma spectrometer, beta counter, EPR spectrometer, etc.), the competences available to use devices, the cost to maintain competences and devices if not used for other purposes.

Criticality belt

Orientation system aims to determine the orientation of the victim in the radiation field. More or less complex system were proposed and still used. The system is based on a belt supplied with dosimeter placed at known angle. It is highly important that the different dosimeters used are positioned always at the same angle (0° defining the front position) whatever the morphology of the wearer. Therefore, elastic belt are preferred, because keeping always the same orientation for dosimeter whatever waist circumference of the wearer. In UK, the criticality belt included in the past 4 dosimetric systems, similar to the NAD, placed around the belt by step of 90° (with multi-foils) and nowadays two dosimetric systems with a rigid belt (front and back). In France, the belt historically was designed with 6 pellets of ebonite (with sulfur) measuring therefore only the fast neutron component. Ebonite was also used in all the different French NAD type and nowadays only in one type of NAD. Activities measured in each of the dosimeters of the belt combined in a simple algorithm provide an estimation of the orientation. This information is then used to correct the NAD reading if needed to take into account the angular response in order to provide the maximal dose even when the NAD is not exposed face to the source. When irradiate by the back, in PA configuration, the dose is estimated from the dosimetric elements of the belt in the back, correction on NAD estimation being highly inaccurate in that case.

Area dosimeter/spectrometer

Area doseimeters installed at known locations and easily collectable in case of criticality accident allow to know the characteristics of the mixed field at this particular location. These systems were used for two main reasons. Firstly, to provide information on neutron spectrum with higher accuracy than a worn NAD in order to be able to correct the NAD results. Nowadays, this information is assumed to be also extremely useful for the second step of dose estimation with MC simulation (that were not foreseen when these systems were developed). Secondly, in some facilities, individuals have no NAD and only area dosimetric systems are positioned to map the facility and estimate the dose to individuals in case of accident.

One of the most difficulties with all these systems is to maintain operational the measurement capacities and the competences. That's why selecting techniques that are used for others purposed in routine is wise. Gamma

spectrometers or beta counter of measuring environmental samples could be also used to estimate foil activity if properly calibrated. Alanine dosimetry was also selected because used in routine in quality control of X-rays irradiators. To maintain competences, the organization of regular exercise is necessary.

b. Retrospective dosimetry

The unique feature of radiological accidents with neutron exposure is the induced radioactivity in body tissue, as well as from metal objects and clothing [37-41]. This feature has been used for decades to provide neutron dose estimation, mainly in the case of criticality accidents [41].

Neutron activation

Neutron activation techniques are based on the measurement of radioactivity induced by neutron interaction with biological tissues, such as blood, hair or nails, or with metallic elements worn by the victims, such as coins, jewelry or belt buckles. Activation techniques have been used for decades in the emergency management of criticality accidents, complementing other individual dosimetry methods [33, 42-47]. The same methods can also be used in cases of accidents with a neutron source or a neutron beam. One advantage of neutron activation is its specificity to neutrons, in other words, the absence of perturbations from the direct gamma-ray components on the neutron dose evaluation. On the other hand, neutron activation products with short half-lives require that measurements are performed after only short delays following the exposure and it is necessary to know the time and duration of the exposure to estimate correctly the induced activity.

Activation techniques permit very rapid dose estimation and are also used to complement individual dosimetry by giving pertinent information on dose heterogeneity. Thus, in the early phase of the management of a radiological accident, rapid and efficient triage can be performed using the measurement of sodium activation in human blood [$^{23}\text{Na}(n,\gamma)^{24}\text{Na}$, $T_{1/2}=14,96$ h, $E_{\gamma}=1.36$ MeV (100 %) and 2.75 MeV (99.85 %)] [46, 47]. Precaution should be taken when measuring ^{24}Na because of the presence of Cl in blood. ^{23}Na in blood appears mostly in the form of NaCl. Main activation products is ^{38}Cl blood [$^{37}\text{Cl}(n,\gamma)^{38}\text{Cl}$, $T_{1/2}=33$ min, $E_{\gamma}=1.64$ MeV (31 %) and 2.17 MeV (47 %)].

At the site of an accident, very rapid measurements of gamma radiation emitted by ^{24}Na with a simple direct gamma survey instrument positioned against the abdominal area of victims are considered as a good way to identify exposed persons. Nevertheless, it should be noted that the induced activity in ^{24}Na is mainly due to thermal neutron interaction. This has several consequences:

- The total sodium activity is dependent on the surface of the body exposed. For an identical thermal neutron fluence, an AP or PA irradiation configuration will generate more activation than a lateral configuration. Activation for lateral irradiation can be as low as 60% compared to a frontal irradiation. The sodium activity also depends on the mass of the body (on average, 1.4 g of ^{23}Na per kg of body weight [47]);
- The sodium activity or gamma-ray dose rate emitted by ^{24}Na cannot be related directly to the severity of the exposure. The neutron capture probabilities by sodium in the human body do not vary significantly from thermal neutron to up to 5 MeV, but as the neutron kerma is predominantly from fast neutrons, the ^{24}Na activity in the blood is not proportional to the neutron kerma [37]. For a same given total neutron fluence, fast neutrons compared to thermal neutrons will generate a lower level of activated sodium but a much higher level of dose. The amount of activated sodium is thus strongly dependent of the neutron fluence energy distribution. Typical coefficients from dose rate measured with gamma survey instruments at the contact and at 1 m of the abdominal area to ^{24}Na activity are respectively about $2.6 \cdot 10^5$ Bq. $\mu\text{Gy}^{-1}.\text{h}$ and $1.9 \cdot 10^6$ Bq. $\mu\text{Gy}^{-1}.\text{h}$;
- The neutron tissue kerma or maximal neutron dose and the total dose can be only deduced if the neutron spectrum, the orientation and the gamma-to-neutron dose ratio are known (1 Bq of ^{24}Na is related to a range of 0.5–3 μGy of neutron tissue kerma for a reference body weight of 68 kg). Without information on neutron spectrum, it is recommended to take a value of 0.97 $\mu\text{Gy}.\text{Bq}^{-1}$ calculated from the average of coefficients for neutron spectra usually encountered in nuclear facilities [47]. A more precise estimate of the sodium activity in victims can be obtained with a whole-body counter or by gamma spectrometry of blood samples. Whole-body counting provides the lowest detection limit. With a modern whole-body counter, the detection limit for thermal neutron doses is approximately a few tens of μGy but is somewhat higher for fast neutrons.

In addition to activated sodium, measurement of activated sulfur in hair, nails and wool [$^{32}\text{S}(n,p)^{32}\text{P}$, $T_{1/2}=14,28$ days, $E_{\beta\text{max}}=1.710$ MeV (100 %)] has also been used for dose reconstruction following accidents. The threshold for the reaction on sulfur is about 3 MeV. Therefore, the detection of ^{32}P is an obvious sign of exposure to fast neutrons. Since the cross sections of this reaction remains almost constant between 3 MeV to up to 20 MeV the sulfur activity is about proportional to the neutron tissue kerma. The counting of hair, nails or wool with Geiger-Müller counter, proportional counter or by liquid scintillation techniques requires a chemical preparation of samples to isolate phosphorus [33, 40]. Hair can be collected from different parts of the victim's body and thus useful information on dose distribution and the victim's orientation can be derived. Using sulfur, the detection limit is about 0.05 Gy for 1 mg of hair (0.05 g of sulfur per g of hair). In absence of any information on the neutron spectra, the total neutron dose can be estimated using a coefficient of 1.23 Gy per Bq of ^{32}P in 1 g of hair [47].

These techniques were mainly used in the context of criticality accident since the mid-1950s (see for example the accident at Los Alamos in 1956) [41]. The associated procedures and protocols have been established for several decades. All procedures for sample preparation, measurements, data analysis and dose estimation are described the IAEA technical report series n°211 [33]. In the past, regular exercises were organized to train technical staff and maintain the competences and results of this latest inter-comparison between laboratories can be found in [48], [49] and [50] for example.

Biological dosimetry

In addition of activation techniques, other techniques of retrospective dosimetry have to be considered. The gold standard methods are based on cytogenetic approach. Evaluation of chromosomal aberration (dicentric chromosome) yield per lymphocyte from blood collected on victims is one of the most standardized approach. This technique was used in very large number of expertise for dose evaluation after acute exposure [8-13]. To estimate dose from counting dicentric yield per cell, pre-established calibration curves are used. As the calibration curve is dependent on dose rate and radiation quality, in the specific case of criticality accident, it is necessary for laboratory to have different calibration curves for different neutron spectra and different gamma dose to neutron dose ratio. Calibration curve for low photon are linear quadratic and tend to become linear with a neutron component. This method provides the dose in the circulating blood that is a good approximation of the whole-body dose. The distribution of chromosomal aberration in cell can also provide some information on the level of heterogeneity of the dose distribution in the body [51]. This method has been considered for criticality accident [47, 52-54]. In case of dose above 5-6 Gy, other cytogenetic techniques as prematurely condensed ring chromosome (PCC-ring). The PCC-ring method are used because of saturation of the dicentric assay method. The Dicentric and PCC-ring method were used for the Tokai-Mura accident [52].

EPR dosimetry

Other types of biological samples could be also analyzed to estimate dose. EPR spectroscopy, by its ability to detect and quantify radio-induced radicals and defects, makes possible to estimate a dose from an EPR spectrum. Tooth enamel mini-biopsies (1-5 mg) measured by EPR Q-band have been recently developed and used for radiological accident dosimetry [17, 55]. Minimal detectable dose (MDD) is about 200 mGy. Enamel has a very low sensitivity to neutron. Therefore, with this approach only the gamma dose can be estimated. An approach using the difference of sensitivity to neutron and photon between enamel and dentin (inner part of tooth) was proposed but it necessitates a much more invasive sampling that may be difficult to perform in that case [56]. Nails was also recently and successfully used for dose estimation by EPR in two recent case of overexposure to hands [57, 58]. If the sensitivity of the EPR signals to neutron is known (not yet the case), thus estimating the neutron dose component with sulfur activation in nails, will make possible to estimate the gamma dose component by EPR. A same biological sampling in that case, with two different analysis techniques would provide a separate dose estimation to hands and feet that could be useful in scenario similar to the Sarov accident with hand closer to the source than the body and also useful to estimate the heterogeneity of dose. EPR technique is also applicable to various type of materials such as polymers (eyeglasses, badges, etc.), mineral glass, sugars, cotton, etc. [59]. Materials sensitivity to neutrons have investigated in details only for the different type of sugars commonly found in food [60]. Therefore, all the materials worn or found on the victims should be consider for EPR analysis and kept at low temperature because some material may exhibit a signal fading. Luminescence technique are more and more investigated for also application in radiological dosimetry and could be also applied even if this technique was up to now almost never applied for accident dosimetry.

MC methods

Developments of Monte Carlo codes simulating particle transport and dose deposition combined with an increased capacity of calculation has made possible the use of mathematical phantoms to describe the geometry of the irradiation and the human body, for example, the Medical Internal Radiation Dose (MIRD) software package. These capacities have been largely used in emergency situations. In a perfect world, knowing with exactitude all the parameters of the accident, these techniques could provide dose to organs and isodose in the body with acceptable accuracy. Nevertheless, as testimonies from victims are usually not reliable, and considering that even if the accident is immediately known, it is usually difficult to collect all the necessary information with accuracy. That is why numerical approaches are often combined with physical or biodosimetry. For example, if the duration of an irradiation is not known but the position of a victim is then, using physical or biodosimetry, one can normalize the relative dose distribution within the body to the measured dose (e.g., [16]).

Recent progress in computational tool development has provided numerical phantoms with a high degree of anatomical sophistication. Voxel phantoms, elaborated from X-rays, CT images or MRI scans, can provide numerical phantom(s) describing with accuracy the anatomy of the victim(s). This point is crucial when the morphology has a significant influence for the determination of the organ doses, especially in the case of neutron irradiation. Since neutrons are highly attenuated in the body, especially by superficial layers of tissue, one understands that variable amounts of fat can significantly modify the dose at depth, i.e. to internal organs. New types of phantoms can provide a higher level of anatomical description, using MESH methodology. MESH-type phantoms provide a better representation of thin tissue such as skin [61]. Moreover, this type of phantom can be deformed making possible changes to the geometry and so adapt the phantom to the real victim's position. Voxel phantoms can also be deformed and modified using specific software [62].

These techniques could be expanded to create neutron dose maps for the environment around a criticality accident, to ensure that lightly exposed personnel on the periphery of the accident zone are assigned a conservative dose.

4. CRITICAL ISSUES IN CRITICALITY ACCIDENT DOSIMETRY

The problem already mentioned in the previous section to maintain operational capacity and competences is one of the most critical issues in this field. The performance of given system is depending on the inherent performance of the dosimetry system but also, as nothing is automated as in individual dosimetry analysis process, on the training and competences of technicians and good maintenance of reading devices. The infrequency of criticality accidents has resulted in a dwindling of expertise in the area of criticality accident dosimetry over the past decades. Regular exercises are necessary if possible in conditions as close as possible to real conditions of expertise. If some national exercises were recently organized in USA with the involvement of a few European laboratories, the last large international exercises were organized in 1993, 2002 and 2010. The closing of most of facilities (see for example Valduc facilities in France: Silene, Caliban, Prospero reactors), in which such exercises can be organized, is problematic. Reborn activities in this field in USA were beneficial [21]. In ideal world, national or regional exercise should take place every year or two years. Exercises are not only mandatory to maintain an evaluate competences and dosimetric system performances, but it is also, as for example in France, for maintaining official accreditation of biological analysis laboratory in charge of activated blood analysis. A cooperation at international level is essential to maintain capacity. Most of approaches and techniques were developed in the 60's or 70's. Despite this fact, there is still a lack of harmonization and standardization in this field. New techniques and retrospective dosimetry techniques as described here, should be also implemented in the exercises. That would be interesting to evaluate the complementarity of all techniques (NAD and retrospective dosimetry), especially with complex exercise scenarios (not only AP irradiation). Experience and knowledge should be shared and compiled, as done within the framework of IAEA in the past. In some countries (for example in France), as no other system in dosimetry, there is neither approval procedure, nor technical referential, nor standard for criticality dosimetry system. In other hand, in the United Kingdom for example, a dosimetry service may be approved by the Health and Safety Executive (HSE) to provide special accident dosimetry in order to assess whole-body dose exceeding 0.5 Gy [63]. The requirement for the approval of such dosimetry is that the system used must be capable of assessing dose exceeding 1 Gy within 8 hours of exposure. In addition, the system must be capable of determining any dose exceeding 0.25 Gy, with an uncertainty no greater than 30 %, within 1 week of an incident [63]. In USA, ANSI provided a standard for criticality dosimetry [64].

Most of criticality dosimetry systems were initially developed in the 60's. These dosimetric systems were frequently tested and evaluated in the frame of international or international exercise program and were thus continuously improved. Therefore, performances of those system were quite well known. For new systems, especially, when no performance tests are required for releasing on the market, validation testing can be limited.

Nevertheless, the approach developed 40-30 years ago should be reevaluated in the light of the most recent knowledge and feedback from exercises. Especially exercises allow evaluating the performance of the dosimetric systems in non-standard configuration (lateral phantom irradiation for example). It is important to improve competences and the knowledge on system performances, to play more complex scenario of exposure. The training and evaluation should not only concern the reporting of dose, but also how all these data are compiled and used to provide the pertinent dose data to medical team. The part dealing with MC simulation is never played and should be evaluated. Practical issue as quick sorting, sample collection should be evaluated and played. If some materials worn by individuals can be used for dosimetry, it should be implemented in the local procedure and laboratory with expertise in retrospective dosimetry should be identified. Fortunately, international network in retrospective dosimetry exist for long years, but are insufficiently aware of the problematic of criticality accident and are not trained or do not have appropriated calibration curve.

5. CONCLUSIONS

Criticality accident are nowadays rare but usually with heavy health consequences requiring immediate medical care. Medical care would benefit from accurate dose estimation to the most sensitive organs to define the best therapeutic strategy. The dose estimation has to be provided in short delay because of the medical emergency and also because of the short time window for some techniques (see activation with short life radionuclide). Beside the technical issue, the emergency response organization needs also to be reevaluated notably to implemented new techniques, to gain in efficiency with probably lower human and financial cost. The availability of facility able to mimic a criticality accident is of high importance for maintaining and developing capacity, competences and to develop and validate new techniques or approaches.

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