Radiation Dosimetry: Why Internal Emitters Are Different

When ionising radiation passes through biological tissue it generates reactive chemical species, which may subsequently interact with crucial biochemical processes and generate adverse biological effects. The science of radiation dosimetry seeks to relate these biological outcomes to the radiation energy absorbed by the tissues, the so-called absorbed dose.
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These relationships are used to establish safety limits for radiation dose, say for the medical use of X-rays, exposure of workers in nuclear industries, the levels of radioactivity in food, etc. However, because of the way that the methodology of radiation dosimetry has developed, it is now recognised that there are a number of potential flaws in the established procedures.

One of these arises because an individual may receive a dose of ionising radiation either from a source external to the body - which may be nuclear fallout, but could be an X-ray machine - or from a source within the body - which would arise if a radioactive substance were ingested or inhaled. The two types of irradiation sources are described as external and internal emitters, respectively. It is the latter with which we are concerned here.

The potential flaws in radiation dosimetry to which I referred earlier can now be more clearly understood. Firstly, much of the science relating radiation dose to biological effect has been based on the effects of the medical use of X-rays and the incidence of disease amongst the survivors of the atomic bombs dropped on Hiroshima and Nagasaki in 1945.

These are both external sources of irradiation. Much less information has come from the effects of internal emitters, and in these cases the radiation doses received are often much less well defined. Secondly, radiation sources can be of several types, but crucially one of these can only irradiate the body if located inside it - these are the alpha emitters and, as described below, the type of radiation they emit has a very short range only.

Thus, when located inside a person, the full radiation dose from an alpha emitter will be received by the immediately surrounding tissue, but when located externally, no dose will be received at all. Whilst this might seem to render alpha emitters of lesser importance, this is not the case as the intensity of radiation received from this type of radioactive source is far greater, as indeed may be the biological effects.

To take all this into account, the standard methods of radiation dosimetry allocate a quality factor to this type of radiation, which is held to be 20 times more damaging than the radiation dose received from gamma radiation, usually from external sources.

Unfortunately, things are probably not that simple. The biological effects of the internal alpha emitters will depend crucially on where, precisely, they are located, and the use of a single quality factor to encompass all situations is far from ideal - in some cases, the appropriate factor may be 20, or even less than 20, but in some cases an appropriate number might be far greater. It is now realised by many that the logical basis for the use of this quality factor approach is fundamentally flawed, and that a radical re-appraisal to the evaluation of the radiation effects of internal emitters may be needed.

There are 3 principal types of ionising radiation emitted by radioactive substances, namely alpha, beta, and gamma, and these all have characteristic - and radically different - properties. Alpha radiation arises when a relatively heavy nucleus undergoes radioactive decay emitting relatively heavy positively charged particles. It was shown early in the 20th century by Earnest Rutherford, who discovered them, that these particles are identical to helium nuclei, having relative mass and charge 4 and +2 (atomic units), respectively.

Although alpha particles are usually emitted with relatively high kinetic energies (3 to 6 MeV per particle), because of their high mass the corresponding velocity is relatively low. Travelling through the surrounding matter, the massive, lumbering particles lose their energy and momentum continuously, by multiple collisions with electrons in the surrounding atoms, without deviating appreciably from a straight track. Alpha particles thus lose their high energies over rather short distances - a few thousandths of a millimetre - and for these reasons are classed as high linear energy transfer radiation (high LET radiation).

This type of radiation (which also includes other charged nuclei and also neutrons) gives rise to intense chemical ionisation and hence potentially a large amount of biochemical damage over a relatively small volume. For example, the typical energy of ionisation in a biological tissue is around 40 eV, so that a 4 MeV alpha particle will give rise to around 105 such ionisations along a track length of at most 100 micrometres (μm), producing several thousand ion-pairs in each cell. Consequently, an alpha emitter located internally will irradiate a small number of adjacent cells to a high intensity, killing some and causing major biochemical changes in others.

Radioactive decay by beta radiation also consist in the emission of charged particles, in this case electrons of relative charge -1 and very low mass (around one the thousandth that of an alpha particle). Beta particle kinetic energies generally range up to around 1 to 2 MeV, but because of their low mass, to achieve this energy beta particles start at relatively high velocities.

However, when a beta particle undergoes a collision with an atomic electron - which has the same mass as itself - the beta particle may well be deflected from its initial track direction, and the momentum (and energy) transferred depends greatly on the angle of impact - rather like a snooker ball colliding with a loose pack of other snooker balls. In general, a beta particle will lose its energy over far longer distance than an alpha particle of the same initial kinetic energy.

For this reason, beta radiation is categorised as being low linear energy transfer (low LET) radiation and in passing through tissues, the number of ionisations generated within a given distance - the density of ionisation - is much lower than for alpha radiation, and the track is not straight and may have many branches.

Thus, in contrast to alpha radiation, beta radiation will penetrate longer distances - maybe a few mm - in tissue and can be of importance as an external radiation source, although mainly to the skin or any other tissues in immediate contact. Because the density of ionisation is much lower, the number of ion pairs generated per cell is far less than for alpha radiation, and the biological effects may be qualitatively, as well as quantitatively, different.

Gamma radiation contrasts strongly with both alpha and beta particle radiation as described above. Firstly, gamma radiation is true electromagnetic radiation, consisting of bundles of

energy (photons), which lose energy to matter in a very different manner to the collisions described for alpha and beta particles.

Secondly, gamma radiation is highly penetrating and important both as a source of external and of internal radiation. Gamma photons do not leave a "track" of ionisation in the same way as alpha or beta particles. Instead, they behave on a probabilistic basis - that is, they have a certain (rather low) probability of being absorbed at any particular point along their track, but if a gamma photon is absorbed, its entire energy is absorbed at the one point and converted into a high energy electron - a so-called photoelectron - in practice indistinguishable from a beta particle. A beam of gamma rays - that is, many photons - will, of course, leave a ionisation path because a vast number of photoelectrons will be released at random intervals along the track.

In summary then, gamma radiation will pass through material over quite long distances, and is of primary importance as an external irradiation source, although of course a gamma emitter absorbed internally will also irradiate the body in which it is absorbed. Alpha radiation is absorbed over very short distances and is important only as an internal emitter.

Beta radiation is intermediate in these respects. In conventional dosimetry, radiation doses are averaged over relatively large volumes of similar tissue, for example whole organs, and herein lies the problem. Because alpha particles are absorbed over short distances, they generate a very high density of ionisation and hence chemical damage along their tracks. Consequently, an alpha emitter and to a lesser extent a beta emitter, located internally, will irradiate relatively small numbers of adjacent cells to a high intensity, causing major biochemical changes in localised clusters.

This contrasts with the conventional approach, appropriate to external sources of radiation, in which uniformity of dose, and consequently of biological damage, is assumed. These problems have, of course, long been recognised by radiobiologists, and has led to the development of the science of microdosimetry, in which short range effects of the type described are taken specifically into account.

However, the prediction of radiation damage from internal emitters also requires other factors - biological and biochemical - to be taken into account. Because radiation induced changes from alpha emitters are highly localised, the exact location of the alpha source within the tissue, or even within the cell, becomes an important factor.

Not all alpha emitters react biochemically in the same way, and as a consequence different elements will end up at different locations: maybe in different organs, maybe in different cells in the same organ, or maybe at different locations in the same cell. For example, when bone into which plutonium or radium has been incorporated is examined by autoradiography, a photographic technique which identifies the positions of the radiating atoms, the pattern of uptake is very different: radium is found to locate generally throughout the bone mass, whereas plutonium is located particularly at the growing bone surfaces.

Thus, for the same amount of each radioactive element (in terms of amount of radioactivity present) the doses to the bone surface and to the bone interior will be radically different for the two elements and consequently the risks for the initiation of different types of cancer may well be different. However, standard dosimetry would not distinguish between the two cases: for the same amount of radioactivity the average radiation dose over the whole bone will be

the same in each case, and the predicted (but not the actual) cancer risks would be the same for each element.

Thus, when considering biological outcome - for example, the initiation of a particular form of cancer - not only the gross structural difference between the radiation damage generated by alpha, beta and gamma radiation must be taken into account, but also - particularly in the case of alpha emitters - the molecular location of the radiating atoms. For these reasons, the biological effects of radiation from alpha, and to a lesser extent beta, emitters, absorbed internally, cannot reasonably be equated with the damage generated by gamma emitters, sited externally, even with the application of a quality factor to account for the difference in effectiveness. A more fundamental approach, and one taking both the chemistry and biology into account, needs to be adopted.

There is, of course, nothing new in these claims, nor indeed to the rationale I have advanced in support. Radiation dosimetry is, essentially, a pragmatic science and was originally devised as a rough and ready means to protect workers in the nuclear industry. As the scientific understanding of the affects of ionising radiation have advanced, and as the potential applications of dosimetry have multiplied, so have the basic flaws in the methodology become more apparent.

At each stage, emerging defects have been - in part - remedied by applying "factors" (for example, the radiation quality factors) to compensate for potential problems. However, there comes a stage at which the whole edifice becomes so complex, the exceptions so numerous, and the adjusting factors so apparently arbitrary, that the whole logical structure for the science becomes open to question. This stage may now have been reached.

Finally, the question: does it matter? Is this merely an academic quibble, nice to put right maybe, but of no practical consequence? The answer is firmly no, for several reasons. Quite simply, that the application of current methods of dosimetry may lead to the wrong conclusions with essentially practical consequences: the allowed levels of certain radionuclides in food, the levels of discharge allowed from a certain industrial site, the need or otherwise to evacuate an area after a nuclear accident.

There are cases where standard dosimetry has led to startling conclusions, which might not have been reached had a more scientifically rational approach been adopted. Clusters of leukemia or other cancers which have no apparent cause, and for which ionising radiation has been categorically dismissed as a potential cause, might take on a different aspect if radiation doses and radiation effects were evaluated taking the microdosimetry into account. It is important to recognise that this would not necessarily be the outcome of such a re-evaluation; but, whatever the outcome, it would certainly be more convincing for being based on a rational and scientific analysis rather than by the application of a number of empirical rules.

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