Assessment of the potential impact of embedded radioactive fragments following the use of a crude radiological dispersal device (‘dirty bomb’)

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Abstract
This work was undertaken to understand what would happen if a high-activity radioactive fragment became embedded in an individual following the use of a crude radiological dispersal device (‘dirty bomb’). Two areas were addressed: how would a high-activity fragment be viewed on modern digital x-ray imaging systems; and, what would be the impact on medical management for the patient? A set of experimental trials were undertaken using an iridium-192 source and a DRagon mobile x-ray set equipped with a Canon CXDI-50G portable flat panel digital detector plate. In addition, the potential doses to a surgical team were calculated and potential doses to a patient were assessed using a Monte Carlo code, in which a radioactive point source of nil volume was located within a limb of an anthropomorphic voxel phantom. Three distinct effects on the digital imaging systems were observed, referred to in this paper as a localised ‘bloom’ effect, a ‘discontinuity’ effect towards the middle of the image and ‘fogging’ across the entire image. The first two of these effects were unexpected, and possible reasons for their appearance are discussed. The
Monte Carlo modelling showed that the patient exposure can potentially lead to very high localised absorbed doses, which may result in symptoms associated with acute radiation syndrome. While the dose clearly depends upon the activity of the fragment and the length of time that the fragment is present inside the patient, it is clear that radiation necrosis of bone, muscle and other tissues may threaten the medium term viability of the limb. The dose rates associated with high-activity fragments may also restrict the time a surgeon has to operate, leading to challenging ethical and surgical decisions. Low-activity fragments allow for conventional surgical management to be considered with appropriate control measures.

Keywords: radioactive fragment, RDD, dirty bomb, digital radiography

(Some figures may appear in colour only in the online journal)

1. Introduction

The aim of this study is to inform clinical guidelines for the management of chemical, biological, radiological and nuclear (CBRN) casualties [1, 2] by understanding what would happen if a high-activity radioactive fragment became embedded in a casualty following the detonation of a crude radiological dispersal device (RDD), also known as a ‘dirty bomb’.

During the NATO CBRN medical exercise CLEAN CARE 2016, a scenario was created to observe the management of a radiological casualty following an RDD incident. This generated a number of observations and two specific questions: how would a high-activity radioactive fragment be viewed on modern digital x-ray equipment (and could this be used as an indicator of the presence of a radioactive fragment); and what would be the implications for the medical management of the patient? The latter question includes estimation of the continuing localised radiological injury to the patient and risk of acute radiation syndrome (ARS), and the potential risk to the surgical team.

For this work it is assumed that use of a crude RDD has resulted in an explosive incident and has caused limited fragmentation of a radioactive source, rather than more widespread distribution of radioactive contamination. One of these fragments has become embedded in an individual patient.

Whilst standard x-ray imaging procedures would typically be expected to identify the presence of a fragment in such a scenario, it is possible that medical personnel have no reason to assume the fragment is radioactive. Some previous work has been undertaken on the imaging of radioactive fragments [3, 4], but the likely effect of high-activity fragments on digital imaging systems has not been previously reported.

The conventional management of contaminated wounds following an explosive incident includes the initial imaging of wounds to identify and locate any embedded foreign bodies, risk assessment based on size, location and localised damage, and surgery either as damage control surgery to preserve life or limb (ideally within 1–2 h), or primary surgery to restore function. Over the last decade, diagnostic imaging within both the military and civilian health sectors has transitioned from conventional ‘wet film’ radiography to direct digital radiography (DR) systems and computed tomography (CT). The detectors have evolved from traditional polyester film bases with photographic emulsion to state-of-the art flat panel detectors with an amorphous silicon core with caesium or gadolinium scintillators.
It is important to understand what triggers there may be that indicate the fragment is radioactive. X-ray imaging systems may be one potential such trigger, but it would be hoped that radiation monitoring equipment at the event would first alert responders to the presence of radioactive material. However, this may not be the case and the first casualties to present to a medical treatment facility are likely to be the walking wounded with small fragmentation injuries who can easily self-evacuate from the scene. Consequently, this work seeks to understand the likelihood of the response of the imaging system to the radioactive fragment acting as such a trigger. In addition, the extent to which exposure to a high-activity radioactive particle will affect the diagnostic operation of the imaging system has been investigated.

Having identified the presence of a high-activity radioactive fragment, the next questions to address are what are the clinical implications for the patient and what is the impact on patient management. Whilst foreign bodies are generally removed due to the risk of infection and poor healing, in certain circumstances they may be left in place as the position of these foreign bodies may mean that the risks of removal are greater than the risk of infection. In such a case, the fact that the fragment is radioactive will affect this risk balance approach. In addition, if the localised doses are sufficient to compromise the viability of the limb due to significant local tissue necrosis, amputation might be the more appropriate surgical option [5]. Hence, knowledge of what doses the patient may accrue from an embedded radioactive fragment is extremely important. There are also additional concerns, relating to what controls should be in place to protect the surgical team and the predicted occupational dose for the proposed procedure. In the UK, the relevant occupational limits according to the Ionising Radiations Regulations 2017 (IRR17) [6, 7] for the surgical team are: 500 mSv equivalent dose to the extremities and 20 mSv effective dose, both in a calendar year.

2. Radioactive materials

There are a wide range of radioactive materials that could be used within an RDD. For this study, it was decided to concentrate on iridium-192 (Ir-192) and cobalt-60 (Co-60). Both these sources are used for many applications within industry and medicine. The construction of a double-encapsulated Ir-192 industrial radiography source is shown in figure 1. In this example the iridium is present in the form of small metal discs approximately 2 mm in diameter, which are then held within two stainless steel capsules. This capsule is then placed within the end of the radiography source ‘pig tail’, as shown in figure 2.

Following an explosive incident, the size of any fragment is subject to many variables driven by the type of explosive, the design of the particular explosive device and the material which is fragmenting [8, 9]. It could result in the explosive projection of an intact source capsule, or a significant sized fragment of the source, or much smaller sized fragments of the source [10]. Ir-192 sources used for industrial radiography can have activities of up to 7.4 TBq (200 Ci) [11], although in the UK use of sources with an activity no greater than 1 TBq (27 Ci) is more common. Due to the half-life of Ir-192 (74 d), these sources typically have a working life of around 6–12 months before they are replaced. Co-60 sources used for industrial radiography can have activities of up to 7.4 TBq (200 Ci) [11] and have a working life of up to 15 yr.
3. Methods

Two distinct work packages were undertaken in this study. The first package (imagery trial) consisted of a set of experimental trials to obtain x-ray images representative of those that would be obtained when imaging a high-activity radioactive fragment embedded in a wound using DR. To achieve this, a 260 GBq Ir-192 industrial radiography source\(^1\) was inserted in a hind quarter taken from an existing pig carcass, and the resulting images recorded.

The second package of work (dose assessment) involved calculating what the dose would be to a patient who had a radioactive fragment embedded in their leg. These calculations involved Monte Carlo techniques to determine the local absorbed dose around the wound area, the equivalent dose to organs and the patient effective dose. Standard health physics techniques were then used to determine the likely exposures to the medical team.

Each of these two packages of work is discussed in this report.

For the purpose of this work, the imagery trial has used a complete source from a typical gamma radiography system. This was largely due to the practicalities involved in the imagery trial.

The dose assessment results are given in the first instance in terms of dose per GBq, and for Ir-192 and Co-60 sources. However, the results are also discussed in terms of a standard representative fragment, to provide some context to the results. At present there is no solid basis for choosing the activity of this representative fragment. The activity of such a fragment in an actual event will depend significantly on the explosive event leading to fragmentation, and the specific form of the source in the first instance. An activity of 370 GBq (10 Ci) has been chosen for this study. It is acknowledged that this fragment activity is somewhat arbitrary although, as it represents 5% of the maximum activity of a gamma radiography source (and around 40% of the maximum activity of an Ir-192 gamma radiography source typically used in the UK), it is not unreasonably large. The physical size of such a particle is somewhat difficult to estimate, as it depends on the radio-purity of the radioactive metal used in the source, and on potential amalgamation with other materials during the explosive event.

\(^1\) It was originally planned to use a 370 GBq Ir-192 source. However, the experiments were delayed by a few weeks by which time the source had decayed to an activity of 260 GBq.
3.1. Imagery trial

The presence of a high-activity radioactive fragment would cause significant fogging in traditional ‘wet film’ medical radiography and computed radiography (CR), rendering any image diagnostically useless. As an example, figure 3 shows a chest x-ray image using CR after injection of a low dose of technetium-99m (10 MBq) for sentinel node labelling.

However, many DR detectors only respond to radiation for the very short time frame of an x-ray exposure, and hence are not as susceptible to fogging issues. In a common type of DR x-ray imaging system, the x-rays are detected in a gadolinium oxysulphide scintillator, with the resulting light emissions then being detected by an array of amorphous silicon detectors. The size of the measured signal is proportional to the radiation dose to the scintillator. This signal is then turned into a number on a grey-scale for visualisation. The effects of radioactive sources on the resulting image are likely to depend to some extent on the specific electronics and image processing algorithms used, which in many cases are closely protected intellectual property of the equipment manufacturers.

Consequently, it was felt that the simplest way to determine the effect of a large radioactive source on the final image was through experimental trials. The set-up and implementation of this trial is outlined below.

3.1.1. Experimental set-up. This trial was undertaken within a purpose built structure on the Dstl range facility. The structure built was a simple three-sided concrete structure and lead castle, used to reduce exposure to trial staff and equipment.

A surgical pocket was created within the muscle next to the femur in the hind quarter taken from an existing pig carcass. To simulate a casualty with a radioactive fragment, a 260 GBq Ir-192 industrial radiography source was to be placed in this surgical pocket. This source was housed in a Sentinel Model 880 source projector, allowing its safe transportation and use. The source was ‘wound’ out of the exposure device, along a radiography guide tube, and into position within the experimental phantom. An industrial radiographer undertook all the work with the Ir-192 source and its projector. An image of the experimental set-up is shown in figure 4.
3.1.2. X-ray system. A DRagon mobile medical field x-ray set equipped with a Canon CXDI-50G portable flat panel gadolinium oxy sulphide and amorphous silicon digital imaging plate (supplied by Xograph) was used for the purpose of the trial. The DRagon imaging plate was covered in surgical drapes to protect it from any potential contamination with biological material. The experimental phantom was placed on top of the plate and the radiography guide tube inserted into the surgical pocket. The guide tube was connected to the Sentinel Model 880 source projector in readiness to wind the source out.

The DRagon set was positioned such that the x-ray head was 1 m above the imaging plate. It was taken through the warm-up procedures by a qualified medical radiographer experienced with the equipment. Only the medical radiographer operated the imaging equipment throughout the experiments.

Test radiographs were initially taken to establish the optimal operating parameters for imaging the experimental phantom. A tube voltage of 65 kV, current of 50 mA and exposure time of 0.1 s were identified as optimal. Test images included the appearance with the collimators closed.
3.1.3. Undertaking the trial  
The DRagon x-ray set was used to take the following series of radiographs:

- one test x-ray image without the Ir-192 source present;
- three x-ray images with the Ir-192 source deployed alongside the femur within the pig leg;
- three images with the Ir-192 source deployed alongside the femur within the pig leg but with the DRagon x-ray collimator in the closed position. A tube voltage of 65 kV, current of 50 mA and exposure time of 0.1 s were again used but, with the collimator closed, the only radiation reaching the imaging plate was from the Ir-192 source. This technique was required to trick the device into thinking an image was being acquired using the tube-head as the x-ray source and to activate the detector.

A £1 coin was placed on the imaging plate for use as a test object to provide some degree of scale on the images. All images were taken without the use of an anti-scatter grid. The radiographer was protected by lead and concrete radiation shielding while undertaking all the exposures.

3.2. Dose assessment

Dose assessments have been performed to: (1) estimate the dose to the patient and thereby predict the localised radiation injury and limb viability, and risk of acute radiation syndrome (ARS); and (2) estimate the dose to the surgical team. The assessments are based on the assumptions that surgery is performed 2 h after the incident using conventional surgical techniques.

Dose assessments have been performed for two isotopes: Ir-192 and Co-60. Calculated doses are given in terms of the dose per hour for 1 GBq sources and with sources of 370 GBq activity for the purpose of providing some context for the results.

3.2.1. Dose to patient. The gamma dose to the patient was calculated using the Monte Carlo N-Particle Transport Computational Code MCNPX 2.7.0 [12]. Two models were developed in which a radioactive point source of nil volume of either Ir-192 or Co-60 was located within the right thigh of an existing anthropomorphic voxel phantom, known as NORMAN [13]. The point source was located within an adjacent voxel to the anterior surface of the mid-point of the femur. Due to the presence of all organs within these voxel phantoms it is possible to calculate the effective dose from irradiation by the source. It should be noted that this is based upon the assumption that the patient is lying in a fully supine position.

Due to their very short range in tissues (a few millimetres), the dose from beta particles was calculated using deterministic methods in which it was assumed that 50% of the beta energy was deposited in the femur bone, and 50% in muscle next to the femur.

It was assumed that the source fragment would remain intact and would not dissolve and enter the blood. Consequently, calculation of the effective dose from absorption into the blood has not been performed.

3.2.2. Dose to the surgical team. Generally, doses to medical personnel are considered to be relatively minor during the management of radioactively contaminated casualties, as comparatively small amounts of activity will be present, and the early removal of clothing will further reduce the hazard [5]. However, in this scenario the doses to the surgical team have the potential to become considerable in relatively short time-scales, and hence example doses have been estimated. These example calculations assume that the surgeon is 60 cm from the
radioactive fragment, with extremities 15 cm from the radioactive fragment. Ambient dose equivalent values are then calculated based on published exposure factors [14].

4. Results

4.1. Imagery trial

4.1.1. Radiographs with DRagon x-ray exposure and Ir-192 source tube in place, but source not deployed. The image in figure 5 was taken with the DRagon x-ray set and the Ir-192 guide tube in place, but the source not deployed. Nothing unusual is observed in this image; it is used as an indication that the system was working as designed at the start of the trial.

4.1.2. Radiographs with DRagon x-ray exposure and Ir-192 source deployed. A series of three images were then taken with the Ir-192 source deployed, to determine what effect (if any) the radioactive source had on the detector and if that effect was consistent. These images are shown below in figures 6(a)–(c).

The presence of the radioactive source has clearly affected the x-ray image. There are three distinct effects observed in all three images, referred to in this paper as a localised ‘bloom’ effect, a ‘discontinuity’ effect towards the middle of the image and ‘fogging’ across the entire image.

The most immediately obvious of these effects is the bloom effect, observable as a white area in the position of the radioactive source at the end of the guide tube. Whilst the first two images are reasonably similar in this regard, the bloom in the third image is observably larger. Intuitively one would expect the radiation itself to create a dark area as in conventional radiographs or CR, rather than a lighter area, and it is therefore likely that the explanation for
Figure 6. (a)–(c) X-ray images with the Ir-192 source deployed. The arrows show areas of ‘discontinuity’ within the ‘bloom’.

this effect relies on an understanding of the image processing, rather than the physics of the system. This is explored in more detail in the discussion section of this paper.

The discontinuity effect is also quite apparent and is observed as a discontinuity corner type effect to the top right of the bloom area in figures 6(a) and (b), and as a cross type effect in figure 6(c) (marked with arrows). Again this effect was unexpected, and is explored in the discussion section of this paper.

The final effect, clearly observable in high-resolution versions of the images, is that there is a fogging or speckling effect across the image, more apparent closer to the source (although eventually covered by the white ‘bloom’ above the source). The fogging appears randomly over the image, indicating a higher level of radiation exposure. This is typical of what would
be expected from a radioactive source, and is almost certainly due to the random interaction of gamma emissions from the radioactive source with the imaging plate.

4.1.3. Radiographs with Ir-192 source deployed by tube-head collimators closed. Images taken with just the Ir-192 source deployed (i.e. the x-ray collimator closed) are shown below. A total of three images were taken in this trial, as shown in figures 7(a)–(c).

As with the results taken with the collimators open, there is a general fogging of the image. This is not unexpected, as darker areas would be expected where the radiation interacts with the detector.
However, there is again a second bloom-type effect observed in these images, although not in the same way as the images with the open collimators. Whilst there is again significant variation between the images, the general trend is for a lighter area towards the middle (as with the x-ray images), with this area surrounded by a darker ring. This darker ring is then surrounded by a second lighter area, of similar intensity to the inner bloom area, and finally a brighter area again towards the edge of the image. An explanation for this effect, or a reason for the variation between images, is not immediately obvious.

4.2. Dose assessment

4.2.1. Patient absorbed dose. The absorbed dose rate received by the patient from a 1 GBq Ir-192 fragment is shown in figure 8. The same results are shown for 1 GBq of Co-60 in figure 9.

The absorbed dose rates received by the patient from a 370 GBq Ir-192 fragment and a 370 GBq Co-60 fragment are shown in figures 10 and 11. As is to be expected, figures 8–11 show the dose rates from these sources are significant but rapidly fall off with distance from the source.

4.2.2. Patient equivalent dose The equivalent dose rate to the patient’s organs and the effective dose rate from 1 GBq sources are shown in table 1. Tissue weighting factors are taken from the International Commission for Radiological Protection (ICRP) 103 [15]. The voxel phantom used did not include salivary glands. Consequently the dose to this tissue is included within the remainder.

The equivalent dose rate to the patient’s organs and the effective dose rate from 370 GBq sources are shown in table 2. Tissue weighting factors are taken from ICRP 103 [15].
Figure 9. Dose rate contours (Gy/h) to tissue in leg from a 1 GBq fragment of Co-60.

Figure 10. Dose rate contours (Gy/h) to tissue in leg from a 370 GBq fragment of Ir-192.

The dose rates in tables 1 and 2 are the average dose rates to the tissue. Due to the highly localised nature of the exposure, for tissues such as the bone marrow that are distributed across a number of locations within the body, some parts of the tissue will receive dose rates orders of magnitude higher than this average while other parts will receive dose rates orders of magnitude lower. Figures 10 and 11 show that, with 370 GBq Ir-192 or Co-60 sources, the absorbed
Figure 11. Dose rate contours (Gy/h) to tissue in leg from a 370 GBq fragment of Co-60.

Table 1. The equivalent dose rate to tissue and effective dose rate from 1 GBq radioactive fragment of Ir-192 or Co-60.

| Tissue          | Tissue weighting factor | Equivalent dose rate (mSv h\(^{-1}\)) |
|-----------------|-------------------------|--------------------------------------|
|                 |                         | 1 GBq Co-60  | 1 GBq Ir-192   |
| Red bone marrow | 0.12                    | 2.34E+01    | 8.32E+00       |
| Colon           | 0.12                    | 1.39E+00    | 3.43E-01       |
| Lung            | 0.12                    | 7.46E-02    | 7.11E-03       |
| Stomach         | 0.12                    | 2.66E-01    | 3.54E-02       |
| Breast          | 0.12                    | 6.46E-02    | 4.97E-03       |
| Remainder       | 0.12                    | 3.04E+00    | 2.34E+00       |
| Gonads          | 0.08                    | 5.76E+00    | 1.66E+00       |
| Bladder         | 0.04                    | 3.57E+00    | 9.68E-01       |
| Oesophagus      | 0.04                    | 8.38E-02    | 8.65E-03       |
| Liver           | 0.04                    | 1.62E-01    | 1.85E-02       |
| Thyroid         | 0.04                    | 2.32E-02    | 1.55E-03       |
| Bone surface    | 0.01                    | 1.24E+01    | 1.25E+01       |
| Brain           | 0.01                    | 7.00E-03    | 4.92E-04       |
| Skin            | 0.01                    | 4.76E+00    | 1.49E+00       |

| Effective dose rate (mSv h\(^{-1}\)) | 4.17E+00 | 1.64E+00 |

The dose rate to the part of the bone marrow nearest to the source is in the order of 1000 Gy h\(^{-1}\). For the average equivalent dose rate to the whole of the bone marrow to be 8.67 Sv h\(^{-1}\) (Co-60) or 3.08 Sv h\(^{-1}\) (Ir-192), clearly the dose rate to this tissue in other body areas must be much lower than this average.
Table 2. The equivalent dose rate to tissue and effective dose rate from 370 GBq radioactive fragment of Ir-192 or Co-60.

| Tissue            | Tissue weighting factor | Equivalent dose rate (Sv/h) | 370 GBq Co-60 | 370 GBq Ir-192 |
|-------------------|-------------------------|----------------------------|----------------|----------------|
| Red bone marrow   | 0.12                    |                            | 8.67E+00       | 3.08E+00       |
| Colon             | 0.12                    |                            | 5.13E−01       | 1.27E−01       |
| Lung              | 0.12                    |                            | 2.76E−02       | 2.63E−03       |
| Stomach           | 0.12                    |                            | 9.83E−02       | 1.31E−02       |
| Breast            | 0.12                    |                            | 2.39E−02       | 1.84E−03       |
| Remainder         | 0.12                    |                            | 1.13E+00       | 8.67E−01       |
| Gonads            | 0.08                    |                            | 2.13E+00       | 6.14E−01       |
| Bladder           | 0.04                    |                            | 1.32E+00       | 3.58E−01       |
| Oesophagus        | 0.04                    |                            | 3.10E−02       | 3.20E−03       |
| Liver             | 0.04                    |                            | 6.00E−02       | 6.83E−03       |
| Thyroid           | 0.04                    |                            | 8.58E−03       | 5.75E−04       |
| Bone surface      | 0.01                    |                            | 4.59E+00       | 4.61E+00       |
| Brain             | 0.01                    |                            | 2.59E−03       | 1.82E−04       |
| Skin              | 0.01                    |                            | 1.76E+00       | 5.50E−01       |
| Effective dose rate (Sv h\(^{-1}\)) |                  |                            | 1.55E+00       | 6.06E−01       |

Table 3. Potential ambient dose equivalent rates to the surgical team.

| Distance from source | 1 GBq Co-60 | 1 GBq Ir-192 | 370 GBq Co-60 | 370 GBq Ir-192 |
|----------------------|-------------|-------------|----------------|----------------|
| 15 cm                | 15          | 6.2         | 5700           | 2300           |
| 60 cm                | 0.97        | 0.38        | 360            | 140            |
| 100 cm               | 0.35        | 0.14        | 130            | 51             |
| 200 cm               | 0.09        | 0.04        | 32             | 13             |

4.2.3. Dose to surgical team The dose to the surgical team ultimately depends on the activity of the fragment. Table 3 shows the potential ambient dose equivalent rates [H\(^{*}\)(10)] to the surgical team at different distances from the sources [14]. The dose rates at 60 cm and 100 cm in table 3 are comparable to a previously published assessment of the effective dose rate to a surgeon of 25 mSv h\(^{-1}\) from a 37 GBq fragment of Co-60 deeply embedded (20 cm) within the patient [10].

5. Discussion

5.1. Imagery trial

The images indicate that the presence of a gamma source of the activity used in these trials (260 GBq) has a clear effect on the image. The striking observation is the inversion of a black artefact for CR and conventional radiography to one where the exposed area is a white artefact on DR. The Ir-192 source affects the image in a number of ways. One of these (the fogging effect) is potentially attributable to the direct effects of radioactivity on the imaging plate. The additional effects (the local bloom and the discontinuity) are not directly attributable to the radiation itself, and are hence most likely to be an artefact of the image processing.
Discussions with the equipment manufacturers indicate that the ‘bloom’ effect is a result of the inherent background correction mechanisms used in the image collection. In this imaging system, after every primary image is taken using the tube-head, a brief second image is then automatically collected without any x-rays being generated. The final displayed image is based on the difference between these two images. As part of this process, if during the background exposure certain pixels reach the maximum intensity of the grey-scale (i.e. are saturated) then the end result of this will be that the displayed image will always show as white for this pixel. Clearly this effect is more likely where the radiation dose to the imaging systems during the background exposure is higher, which is the area around the radioactive source.

If (as seems likely) this is the explanation for this observed effect one would expect there to be a ‘threshold’ gamma exposure rate, dependent on the algorithms and detectors used, below which the background image is not saturated and the bloom effect would not be observed. For exposures below that threshold, the deciding factor in whether the x-ray user can deduce the presence of a radioactive source may then depend on the magnitude of the fogging effect, the operator’s ability to identify this effect, and then to be able to attribute the effect to a radioactive fragment. This will be primarily a human factor issue, as it depends on a person and their training, rather than the technology.

For this reason a series of further trials are now planned, with the primary aim of identifying the gamma dose at which this bloom is not observed, and how that threshold dose relates to fragment activities that can reasonably be expected in an RDD event.

The above discussion may provide some indication as to the cause of the discontinuity effects, although at present a complete understanding of this has not been reached in conjunction with the technology developers. It is possible that the image generated is broken into several sections for the purpose of background correction. The difference in the focal distances between the x-rays and the gamma rays may also be a factor. This is to be explored as part of the planned further work.

There is a noticeable difference between image 6(c) and the previous two images 6(a) and (b). There are also clear variations between the three images 7(a), (b) and (c). An explanation for the variation between the images is not obvious and will likely require further work.

5.2. Dose assessment

5.2.1. Patient dose estimation and effect prediction. Deterministic effects are dependent, among other factors, on the dose to a particular tissue and that tissue’s threshold dose for health effects. The prediction of tissue tolerance to radiation even in therapeutic situations is an imprecise science that challenges radiation oncologists, especially when partial organ volumes are irradiated. Therapeutic irradiation is often given in fractions, which also means that tolerance thresholds recorded for that means of delivery (such as those published by Emami [16] or the QUANTEC group [17]) are not representative of the situation with embedded radioactive fragments.

Descriptions of the deterministic effects that high-dose radiation has on tissues have been published by the Health Protection Agency (HPA) [18], ICRP [19] and other texts such as ‘Medical Effects of Ionising Radiation’ by Mettler and Upton [20]. These publications provide useful guidance, whilst noting the gaps in scientific knowledge that still exist. Case studies of accidents involving industrial radiography sources, such as the ones that occurred at Yanango [21] and Gilan [22], also give insight into local injuries from ionising radiation (although in these incidents radiography sources were placed adjacent to an area of skin rather than being embedded within tissue).
In this paper, the doses to a patient who had a radioactive fragment embedded within their right thigh have been assessed. Consequently, the tissues within this area will include bone, bone marrow, muscle, vasculature, peripheral nerves and the skin. Threshold doses for bone marrow and skin have been extensively studied and reported [18–20]. For bone marrow, whole body irradiation of about 0.5–1 Gy is normally sufficient to initiate a characteristic effect on haematopoiesis. For skin, the threshold for necrosis is a dose of greater than 25 Gy. For the other tissues, there is much less information.

For bone itself, radiation necrosis, spontaneous fracture, or fracture following uncharacteristically light trauma, are all recognised as deterministic effects of radiation exposure that may occur months after exposure. However, there is very little information published on the threshold doses required for these effects after acute, as opposed to fractionated, radiation exposure. From radiotherapy experience 100 Gy is quoted as the tolerance dose for these effects to occur in 50% of those exposed within 5 yr. Muscle is quite resistant to radiation damage. Absorbed doses in excess of 500 Gy may be required for acute radiation necrosis, and such necrosis was seen in the Yanango case [21]. Weakness, atrophy and fibrosis are all recognised late effects of lower doses, although the extent to which these are seen may depend on the total volume of an individual muscle that is irradiated beyond a sufficient threshold.

It is clear that the exposure to the patient in this case can potentially lead to extremely high localised absorbed dose rates to the surrounding tissues, in the order of many hundreds or thousands of Grays per hour (see figures 10 and 11). While the dose clearly depends upon the activity of the fragment and the length of time that the fragment is present inside the patient, severe tissue damage and radiation necrosis of bone, muscle and other tissues is possible which may threaten the viability of the limb, although the effects can be delayed for days to weeks. For lower activities, or shorter exposure times, the likelihood of skin burns can be assessed but the impact on limb survivability is difficult to predict. The equivalent doses to other tissues (most notably red bone marrow) may also result in symptoms associated with ARS. However, the impact of this high equivalent dose to the bone marrow is somewhat difficult to interpret, especially if changes in casualty posture need to be considered. While the average dose to the bone marrow is high, this is driven by the very high localised doses to the parts of bone marrow close to the fragment. Bone marrow in other parts of the body will receive doses well below the calculated average equivalent dose. Thus, the bone marrow close to the fragment is likely to be destroyed by the very high radiation doses, while the bone marrow in other locations may survive.

5.2.2. Occupation dose to surgical team. Based on the dose rates shown in table 3, a surgeon standing 60 cm away from a 370 GBq source is likely to exceed the 20 mSv effective dose limits in under 5 min for the Co-60 source and under 10 min for the Ir-192 source. The hands of the surgeon, at 15 cm away from this source, are likely to exceed the 500 mSv equivalent dose limit in 5 min for the Co-60 source and 13 min for the Ir-192 source. This has significant implications for both damage control and primary surgery as both will require time greater than that permissible under IRR17.

The potential control measures for the surgical team follow the same radiological protection considerations of time, distance and shielding, as well as the potential substitution by another surgeon to reduce the personal dose burden.

Time—The reduction in the possible duration of a surgical procedure may inform the surgical planning, including the choice to attempt to remove the fragment and restore limb function or proceed to an amputation. The choice will also depend on the dose estimation and predicted damage to the limb (see next section).
Distance—The surgeon may be able to extend the distance from the patient, both body and hands, by posture, patient positioning and use of longer surgical instruments. However, this may increase the procedure time and risk surgical complications if there is a reduction in vision or surgical dexterity.

Shielding—The use of lead aprons has no significant impact on the absorbed dose. Lead aprons used for shielding from x-ray procedures have only a small effect on gamma radiation from Ir-192 or Co-60. To reduce the gamma dose rate from Ir-192 by a factor of 10 requires 12 mm of lead, or 46 mm of lead for Co-60. Lead aprons typically have a lead equivalence of 0.25–0.5 mm. Other shielding options may be possible. However, the planning and positioning of such shielding may add a significant delay to the surgery and increase the patient’s absorbed dose as well as interfere with the surgeon’s access to the patient.

For the lower activity source of 1 GBq, the surgeon will have several hours to work before exceeding these dose limits. This would allow for the appropriate surgical management of at least one patient. The ability to monitor dose rates is therefore vital for appropriate surgical decision making and reassurance to the surgical team. The management of multiple low activity patients may require the rotation of surgical teams or surgeons to prevent an accumulated dose exceeding the limits.

5.2.3. Implications for surgical management. Following a penetrating injury with a radioactive fragment with high enough dose rates to cause local necrosis and threaten limb viability, as well as a significant risk to the surgical team, amputation may be the only surgical option. The challenge in this scenario is sufficient dose estimation to inform the surgical decision in a timely manner.

The development of early wound infection is also a possibility, although broad spectrum antibiotics are given as part of the initial trauma care for any open wound. The potential impact of bone marrow suppression may also need to be considered in the case of a transient coagulopathy and immunosuppression. For this reason, a single surgical procedure before the bone marrow depression is also justifiable rather than repeater surgical ‘re-looks’ and further procedures. Concurrent cytokine stimulation therapy may also be appropriate to stimulate the growth of any spared bone marrow away from the site of injury.

Successful management of radiation doses within the surgical team would be reliant upon dose monitoring equipment, training and procedures that minimise time, maximise distance and make use of localised shielding. The amount of information and calculations highlights the importance of access to rapid specialist advice and decision support tools to support dose estimation and clinical effect prediction.

The management of a patient with a fragmentation injury to the torso was outside the scope of the initial study. However, the impact of a high-activity fragment close to organs with high radio-sensitivity (e.g. bowel) raises the ethical consideration of a significant occupational dose to the surgeon (and assistant), the risk of a fatal local exposure, futility despite surgery and potential palliative care.

Irrespective of which scenario, if the patient is conscious and has capacity, the decision-making process must include the patient as part of the informed consent process. Early recognition, dose rate assessment and planning with health physics support would be vital to make an informed decision.
6. Conclusion

This work has shown that DR detectors responded to the presence of a high-activity radioactive fragment in ways which were not anticipated. The way in which it responds, particularly the ‘bloom’ effect, is likely to depend on the specific imaging system and software used. Further work is planned to investigate whether there is a threshold gamma dose below which these effects will not be observed.

This work has also shown that the patient will receive extremely large radiation doses in the event of a high-activity fragment becoming embedded in a limb. The dose modelling within this report, for exposure to high-activity sources (370 GBq), showed the clear potential for limb-threatening radiation necrosis to occur. Moreover, the potential doses to the surgical team are sufficiently large that consideration would need to be given to management of their occupational doses. This may lead to challenging ethical and surgical decisions, including the necessity for amputation of an initially otherwise viable limb. However, the study shows that at high dose rates sufficient to cause local necrosis and threaten limb viability the decision is clearer.

From these initial findings, there are still many aspects that would benefit from further investigation. Future work may explore the relationship between the imaging effect and incident gamma dose rate, as well as the effect of exposure time and gamma energy on the size and appearance of the ‘bloom’. Further study will also be needed to determine the behaviour of imaging plates from other manufacturers and the appearance of such fragments under CT examination. Development of a decision support tool for the surgical team, based on a dose rate measurement at a set distance and appropriate control measures, is also needed. The implications of a high-activity radioactive fragment embedded in the torso also justify further study.

Although the study identifies significant challenges for the management of individual patients with high-activity radioactive fragments, the early recognition of an RDD and the radiation hazard by radiation monitoring is also of great importance. This will alert responders early to the presence of the radiation hazard. Effective monitoring and external decontamination will thereby allow for optimal patient management and, in most cases, the management of the trauma will take precedence and this study can reassure healthcare personnel that the radiation hazard is both quantifiable and can be adequately mitigated.

To close the loop of the medical exercise observation and lesson learned process, further medical training and exercise is recommended to inform and validate any guideline development.

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References

[1] North Atlantic Treaty Organisation 2018 Allied Medical Publication Amepd-7.1: The Medical Management of Chemical, Biological, Radiological and Nuclear Casualties 1st edn (Brussels: NATO Standardization Office)

[2] Ministry of Defence 2019 Joint Service Publication JSP 950 - Chapter 11: Clinical Guidelines for Operations (London: MOD)

[3] Ören Ü, Hansson M, Mattsson S and Räaf C L 2014 Detection of radioactive fragments in patients after radiological or nuclear emergencies using computed tomography and digital radiography J. Radiol. Prot. 34 231–47

[4] Majewski M, Nestler K, Veit D A, Dickmeyer B, Weldeck S, Port M and Becker B V 2020 Detection of embedded low-level radioactive shrapnel after the explosion of a radiological dispersal device in radiological emergency imaging Health Phys. 111 95–100

[5] Williams G and O’Malley M 2010 Surgical considerations in the management of combined radiation blast injury casualties caused by a radiological dirty bomb Injury Int. J. Care Injured 41 943–7

[6] HMSO 2017 The Ionising Radiations Regulations 2017 SI 1075 (London: HMSO)

[7] HMSO 2017 The Ionising Radiations Regulations Northern Ireland 2017 No 229 (London: HMSO)

[8] Harper F T, Musolino S V and Wente W B 2007 Realistic radiological dispersal device hazard boundaries and ramifications for early consequence management decisions Health Phys. 93 1–16

[9] Musolino S V, Harper F T, Buddemeier B, Brown M and Schlueck R 2013 Updated emergency response guidance for the first 48 h after the outdoor detonation of an explosive radiological dispersal device Health Phys. 105 65–73

[10] Smith J M, Ansari A and Harper F T 2005 Hospital management of mass radiological casualties: reassessing exposures from contaminated victims of an exploded radiological dispersal device Health Phys. 89 513–20

[11] IAEA 2005 IAEA Safety Standards, Categorization of Radioactive Sources, Safety Guide No. RS-G-1.9 (Vienna: IAEA)

[12] Pelowitz D B 2011 MCNPX Users Manual Version 2.7.0 LA-CP-11-00438I (Los Alamos: Los Alamos National Laboratory)

[13] Dimbylow P J 1996 The development of realistic voxel phantoms for electromagnetic field dosimetry Proc. Int. Workshop on Voxel Phantom Development; National Radiological Protection Board Report pp 1–7

[14] Delacroix D, Guerre J P, Leblanc P and Hickman C 2002 Radionuclide and radiation protection data handbook 2002 Radiat. Prot. Dosim. 98 1–168

[15] ICRP 2007 The 2007 recommendations of the International Commission on Radiological Protection Ann. ICRP 37 1–332

[16] Emami B 1991 Tolerance of normal tissue to therapeutic irradiation Int. J. Radiat. Oncol. Biol. Phys. 21 109–22

[17] Marks L B, Ten Haken K R and Martel M K 2010 Guest editor’s introduction to QUANTEC: a users guide Int. J. Radiat. Oncol. Biol. Phys. 76 S1–2

[18] Health Protection Agency 2009 High dose radiation effects and tissue injury. Report of the independent Advisory Group on Ionising Radiation Doc HPA vol RCE-10

[19] International Commission on Radiological Protection 2012 ICRP statement on tissue reactions and early and late effects of radiation in normal tissues and organs - threshold doses for tissue reactions in a radiation protection context Ann. ICRP 41 1–322

[20] Mettler F A and Upton A C 2008 Medical Effects of Ionizing Radiation 3rd edn (Philadelphia: Elsevier)

[21] IAEA 2000 The Radiological Accident in Yanango (Vienna: IAEA)

[22] IAEA 2002 The Radiological Accident in Gilan (Vienna: IAEA)