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REVIEW

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Review of methods to measure internal contamination in an emergency

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Abstract

In the event of a radiation emergency, people close to the site of the incident may be exposed to radiation by external exposure, or as a result of intakes of radioactive material. For these incidents it may be necessary to monitor members of the public both for external and internal contamination. This work reviews currently available equipment for the assessment of internal exposure following an emergency. It concentrates on incidents involving the spread of radioactive material and on contamination by radionuclides which emit penetrating radiation. It is essential that this monitoring is carried out as soon as possible so that people who have been exposed at a level which could have an effect on health can be identified and receive prompt medical assessment. Proposed action levels to identify people who need medical attention are reviewed to determine the required sensitivity of monitoring equipment. For releases containing gamma-ray emitting radionuclides the best means of measuring internal contamination is to use detectors placed close to the body (whole body or partial body monitoring). Laboratory based whole body monitors could be used but these may well be inconveniently located and so equipment which can be deployed to the site of an incident has been developed and these are described. The need for rapid selection and prioritisation of people for monitoring, methods to deal with potentially high numbers of contaminated people and the requirement for a means of rapidly interpreting monitoring information are also discussed.

It has been found that for many types of incidents and scenarios, systems based on unshielded high-resolution detectors and hand-held instruments do have the required sensitivity to identify people who require medical assessment.

Keywords: internal, contamination, emergencies, monitoring, screening, thyroid, whole body

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

1. Introduction

Plans to deal with radiological emergencies have in the past been focused on accidents at nuclear power plants. More recently the deliberate spreading of activity has been considered as a possible threat and so monitoring plans need to consider both of these possibilities. Radiation doses resulting from external contamination on the skin and clothing are important, as this can cause skin burns and there is the increased risk of internal contamination and contamination of other people. There could also be a requirement for rapid measurements of large groups of internally contaminated people. The main objective of these measurements is to ensure people who have received radionuclide intakes high enough to potentially cause deterministic health effects or tissue reactions are identified. A secondary objective is to quantify committed effective dose for people with lower levels of internal contamination. This information could be used to select people for decorporation therapy, inclusion in follow up monitoring and to inform the individual on their individual risk. Information on doses is also required by decision makers to gauge the severity of the incident and effectiveness of any countermeasures taken. In this paper, the term 'dose' refers to committed effective dose unless otherwise indicated.

After a release of radioactive material to the environment, it may be necessary to sort people into groups based on their actual or potential effects on their health. This procedure is known as triage and following a radiation incident would be used to identify people who have been exposed to radiation or radioactive material at a level that is likely to have an effect on their health. Before monitoring facilities are available, this triage can be done using information on clinical signs of exposure or location at the time of the incident. When monitoring is available, initial screening measurements can be used to rapidly identify those people who are likely to require care. This process of screening can be distinguished from monitoring which is aimed at determining an individual's dose and the resulting risk to health.

To determine levels of external and internal contamination, it may be necessary to set up a Radiation Monitoring Unit (RMU). Details of the procedures used at RMUs can be found elsewhere (Rojas-Palma *et al* 2009, Thompson *et al* 2011, CDC 2014a).

This paper presents an overview of whole body monitoring equipment developed for use following a radiation emergency affecting members of the public. If dose thresholds for serious deterministic effects are exceeded, there may be the need to identify affected people within 24–48 h of intake so there could be a need to monitor people as soon as possible after the incident. Early measurements are also required in order to be an effective tool for reassurance of the public. For these reasons only equipment which can be brought to the vicinity of the incident is discussed. The main aim is to show how recent advances have addressed the problems for a need for a rapid response and to deal with potentially large numbers of affected people.

When measurements have been carried out there needs to be a rapid means of deciding if more detailed individual assessments are required. This can best be achieved by comparing results of measurements with Action Levels. Action Levels need to be specified which if exceeded indicate that some actions are required. These actions could include medical assessment, additional (more accurate) measurements, provision of information to the individuals and inclusion in any programme of follow up monitoring. Action Levels need to be specified in terms of measured quantities so that direct comparison with measurement results can be made and appropriate actions taken. Before Action Levels can be determined, corresponding dose criteria must be set as the Action Level needs to reflect the likelihood of health effects. A summary of published dose criteria which correspond to Action Levels is presented in section 2.

2. Doses corresponding to action levels

Laboratory based whole body monitors are generally able to detect intakes corresponding to doses of much less than 1 mSv, for radionuclides which emit gamma-rays of energies above about 100 keV with high emission probabilities (e.g. Palmer *et al* (1991) and Smith *et al* (1994)). This level of sensitivity is often set as a requirement for routine monitoring of workers who may be occupationally exposed. However in an emergency the priority would be to screen people in order to identify people who could have levels of internal contamination high enough to require medical assessment or additional measurements and so less sensitive equipment could usefully be deployed.

A number of organisations, including ICRP, IAEA and NCRP, have provided relevant recommendations on Action Levels to be used following a radiation emergency, that correspond to doses where actions such as medical assessment should be considered.

ICRP (ICRP 2007) have made the judgment that no tissues are expected to express clinically relevant functional impairment at absorbed doses up to 100 mGy, with threshold doses for deterministic effects in most tissues of the order of 1 Gy or higher.

Reference levels based on RBE-weighted absorbed dose have been developed by IAEA (IAEA 2005). The RBE-weighted absorbed dose is the product of average absorbed dose in a tissue or organ and the relative biological effectiveness (RBE). The values set by IAEA are 2 Gy-Eq for dose to the red bone marrow (RBM) and 30 Gy-Eq for dose to the lung (lower values were set for intakes of actinides). The values for RBE used are 1 for photons and beta emitting radionuclides, 7 for alpha emitters which irradiate the lung and 2 for alpha emitters which irradiate the red bone marrow (RBM). If these reference levels are exceeded IAEA recommends actions including immediate medical attention, immediate decorporation (if available) and accurate calculation of organ specific doses.

NCRP Report 161 (NCRP 2008), contains values of Clinical Decision Guide (CDG) which is defined as the maximum once-in-a life-time intake which represents a stochastic risk that is within the range of risks associated with US guidance on dose limits for emergencies (DOE 2008) and also avoids deterministic effects. The CDG is intended for physicians to use when considering the need for medical treatment or as an indicator that more detailed investigation of absorbed doses is required. For avoidance of deterministic effects, NCRP have set criteria based on a RBE-weighted absorbed dose to RBM and lungs. The value for consideration of dose to RBM was set by NCRP to 0.25 Gy-Eq and 1 Gy-Eq for consideration of dose to the lung. RBE values of 2 and 7 were applied in deriving the RBE weighted absorbed dose values for RBM and lungs respectively.

The NCRP (NCRP 2008) stochastic risk criterion is set at a dose of 0.25 Sv (over 50 years for adults and to age 70 for children). Ménétrier *et al* (2005, 2007) proposed a dose action level of 200 mSv above which treatment to reduce doses should be considered and this is also the level adopted as the upper action level (AL_U) in the Triage, Monitoring and Treatment (TMT) Handbook (Rojas-Palma *et al* 2009). If the AL_U is exceeded the TMT Handbook specifies that the person should be referred for medical assessment.

The Radiation Emergency Medical Management web site (Sugarman *et al* 2010) recommends clinical treatment for intakes greater than 10 Annual Limit on Intakes (ALI) values. The ALI is the level of intake that would irradiate a person to the annual dose limit for occupational exposures and in this case the annual occupational dose limit is 50 mSv.

NCRP (NCRP 2008) note that except for a few specific radionuclides, and solubility types, intakes corresponding to CDGs are lower for stochastic risk criteria than deterministic risk criteria. Children as well as adults may be contaminated and so there is a need for Action Levels which are specific to children. UNSCEAR have said that risk estimates for children

might be a factor of two to three times higher than the estimate for a population exposed as adults (UNSCEAR 2006). NCRP have stated that action levels derived for adults should be divided by five for application to children and also pregnant women (NCRP 2008). The TMT Handbook takes a more cautious approach and proposes that Action Levels for children should be a factor of 10 lower than values derived for adults to provide an adequate degree of caution in the initial stages of the response to an incident. One problem for emergency responders is to select Action Levels for use for a particular event. However, the consensus is that adults who could receive committed effective doses greater than 200 mSv should be considered for medical treatment.

3. Prioritisation of people for measurements

Following an incident involving radiation, an urgent problem will be to differentiate those people needing care from the potentially large numbers who require only information and reassurance. Triage is the use of procedures for rapid sorting of people based on their degree of physical injury, and actual or potential effects on health. It is a fundamental part of the response to accidents and is designed to allocate medical treatment according to the urgency of the patients' needs. Similarly, triage based on radiological assessments should be used to sort people into groups depending on their individual radiation exposure. In the Triage Monitoring and Treatment Handbook, this process has been termed radiological triage (Rojas-Palma *et al* 2009).

The target group who should be identified for triage following an environmental contamination incident are those who have been closest to the source of the contamination, for example, those people evacuated from an inner cordon. Figure 1 shows a simplified version of the monitoring process which should be used at an radiation monitoring unit (RMU) for this target group. It illustrates how measurements of external and internal contamination are compared to action levels to enable people to be sorted into groups based on their level of exposure and appropriate actions are taken. In figure 1, M is the measurement which is compared with the upper action limit (AL_U) and the lower action limit (AL_L). More details on these action limits are contained in section 5. Screening for external contamination would always be required for a recent incident; the initial stage would be to identify people who need urgent decontamination and who are at risk of deterministic effects. The more detailed stage is to identify people who are not so contaminated but would still benefit from decontamination. After external contamination monitoring people should be monitored for internal contamination, and depending on the level found, appropriate action taken. Internal contamination monitoring is always needed as the presence of external contamination may not be a reliable indicator of internal contamination (if for example decontamination has already been carried out). For incidents involving radionuclides which do not emit penetrating radiation, screening for internal contamination will not be possible at the RMU. In this case screening based on urine sample analysis would be needed (Rojas-Palma *et al* 2009).

4. Internal contamination measurement systems

A large number of internal contamination measurement systems using detectors placed close to the person have been described which can be deployed to the site of an incident. The most common systems consist of one or more large well shielded detectors, although the use of unshielded detectors and hand-held monitors has also been described in the literature. These measurement systems are described below:

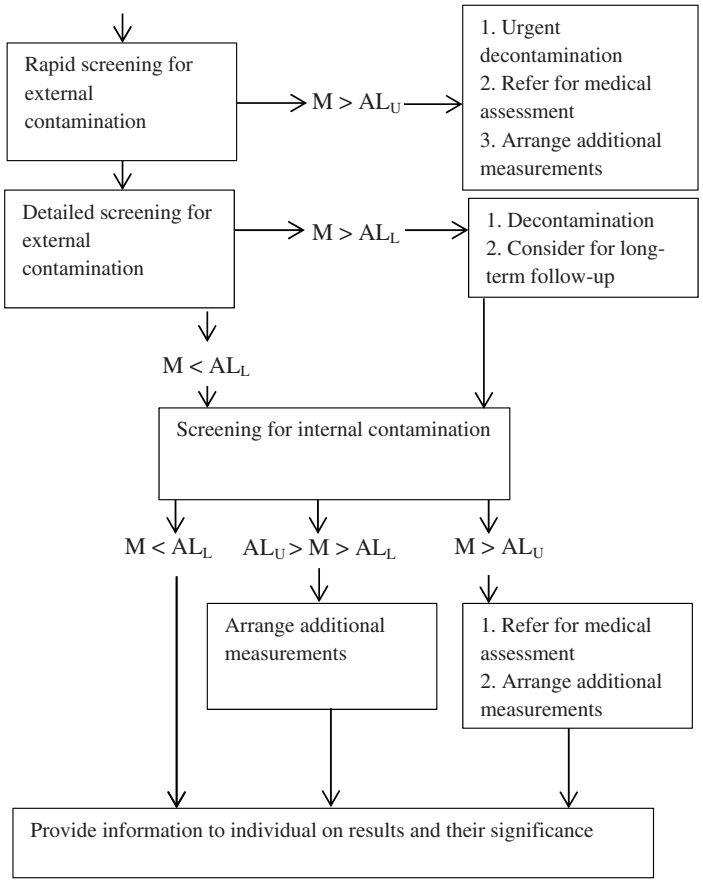

Figure 1. A simplified decision tree for monitoring and decontamination processes (modified from Thompson *et al* 2011).

4.1. Hand-held instruments

As previously stated, it is important that people who have received intakes high enough to require medical assessment are identified as soon as possible. The first responders arriving at the scene of a radiological accident are unlikely to be trained radiation specialists; it is more likely that they will be police, fire and medical services. Some of these first responders may be trained in the use of limited application radiation detectors (e.g. electronic personal dosemeters) but very few are trained to use more complex radiation detection equipment such as gamma-ray spectrometers. For this reason the use of simple portable monitoring equipment has recently been investigated as a means of screening people for internal contamination (Muikku and Rahola 2007, Youngman *et al* 2011, CDC 2014b). As well as being simple to operate, these instruments are readily portable and much cheaper than more sophisticated instruments. The main problem of using hand-held instruments is that most do not have a spectrometric capability and therefore the radionuclide must have been previously identified before radionuclide specific action levels can be used. Furthermore, it would not be possible to quantify the individual components in a mixture of radionuclides which for example would be released following a reactor accident.

The Radiation and Nuclear Safety Authority in Finland has calibrated field deployable gamma-ray spectrometry equipment based on NaI(Tl) crystals for iodine-131(^{131}I) in thyroid and radionuclides in whole body measurements under field conditions (Muikku and Rahola 2007). The authors propose that measurement times of a few minutes are used and for whole body measurements of caesium-137 (^{137}Cs) a Detection Limit (DL) of approximately 1 kBq is then achieved. This can be compared with the body content present one day after acute inhalation, corresponding to a dose of approximately 1 mSv, of 1×10^5 Bq. The DL is defined as the minimum activity which if present in the body would be detected on a stated proportion of measurements.

Hand-held instruments are routinely used for measurements of ^{131}I and iodine-125 (^{125}I) in the thyroid (Canadian Nuclear Safety Commission 2010, Youngman 2013). Calibrations have shown that a small NaI(Tl) crystal based instrument (Mini Instruments type 44A), which is commonly used for ^{131}I in thyroid measurements, has a detection limit of 140 kBq for measurement of ^{137}Cs in the body of an adult and is about half of this value for small children (Scott and Youngman 2008).

The US Centres for Disease Control and Prevention has published tables of net count rates corresponding to selected effective doses for monitoring of whole body activity (CDC 2014b). These factors were produced for four hand-held survey instruments and for adults. Four instruments were calibrated, three of these used NaI(Tl) detectors of dimensions 0.2×5 cm diameter, 2.5×2.5 cm diameter and 7.6×2.5 cm diameter and the fourth was a GM probe. Calibration factors are given for four different distances from person to probe, separately for males and females and for four positions of the probe; combinations of probe held in front or behind the person and either over the abdomen or chest. As well as the need to identify the radionuclide, responders must select the primary route of intake, particle size and the lung solubility class. Measured net count rates can then be compared with the values in tables which correspond to effective doses of 50, 250 and 500 mSv.

HPA (now part of PHE) has published guidance for rapid screening of people to identify people who require medical assessment following an incident where people may have inhaled or ingested radioactive material (Youngman *et al* 2011). In this report, the TMT Handbook (Rojas-Palma *et al* 2009) value of 200 mSv was used as the dose above which medical assessment is required. It was found that for five radionuclides (cobalt-60 (^{60}Co), selenium-75 (^{75}Se), caesium-137, iodine-131, and iridium-192 (^{192}Ir)) it would be possible to use hand-held instruments to identify those people who require medical assessment. Values of net counts per second data are presented for 3 age groups and for times between incident and measurement of up to 30 d, which correspond to doses where medical assessment is indicated. Deliberately cautious assumptions about the physical characteristics of the intake have been made in the calculation of the tabulated values. This approach ensures people who require medical assessment are not overlooked, but subsequent measurements and incident specific physical characteristics may well show that doses are much lower. A comparison of the count rate corresponding to an intake giving a dose of 200 mSv measured at 1 d after for intake for caesium-137 by an adult using a hand-held instrument can be made for a 0.2×5 cm diameter NaI(Tl), (CDC 2014b) detector and a 0.25×3.2 cm diameter NaI(Tl) detector (Youngman *et al* 2011). CDC (2014b) gives count rates for three intake scenarios, inhalation of Type F material with an AMAD of 1 micron, inhalation of Type F material with an AMAD of 5 microns and ingestion. The count rates do not vary greatly for the three intake scenarios, but the lowest count rate corresponding to 200 mSv is 1600 s^{-1}. This can be compared with a value of 70 s^{-1} for the smaller diameter detector (Youngman *et al* 2011). This difference can be partly explained because of a factor of two difference in detector volume and the more cautious assumptions about the physical characteristics of the intake made in the HPA study.

Table 1. Detection Limits for whole body (or ^{131}I in thyroid) measurement for the Detective™ based system and a shielded whole body monitoring system for a 5 min count.

Nuclide	Energy of principal emission (keV)	Detection limit[a], kBq			
		Detective™[b]		Transportable WBM[c]	
		Age 1 year	Adult	Age 1 year	Adult
^{60}Co	1332	3.2	4.4	0.16	0.38
^{75}Se	265	6.1	9.1	0.31	0.81
^{131}I	364	0.55	0.80	0.014	0.023
^{137}Cs	662	4.2	6.0	0.18	0.48
^{192}Ir	468	4.3	6.4	0.18	0.48
^{241}Am	60	33	66	3.8	12.2

[a] Detection Limits are for the 95% confidence level.
[b] Adapted from Youngman (2008).
[c] Adapted from Youngman (2001).

As hand-held instruments could be available in large numbers and can be used with minimal training, it would be possible to quickly screen large numbers of people. Although simple instruments can be useful for carrying out screening, they are unlikely to be sufficiently accurate to be used for the determination of individual dose for the most highly exposed individuals. Therefore laboratory based or more sophisticated systems need to be available for measurements of the most highly exposed individuals.

4.2. Systems based on unshielded detectors

The use of portable HPGe based radionuclide identifiers as field deployable whole body monitors was first described by Kramer *et al* (2005). These systems are based on a Detective™ (Advanced Measurement Technology) but other similar instruments are likely to be suitable. The addition of a portable computer running appropriate software allows the radionuclide identifier to operate as a standalone gamma-ray spectrometry system. Such systems are generally used without shielding. The key advantage over shielded systems is that they are easily transported and quickly set-up. Radionuclide identifiers using HPGe detectors are electrically cooled and can be operated from a battery which simplifies transport. Table 1 compares detection limits calculated for the PHE transportable WBM and a Detective™ based WBM (figure 2, Youngman 2008). Table 1 shows that the DL for the portable instrument is around a factor of 10 higher for whole body measurements of adults and a factor of 20 higher for measurements of young children. Assuming the intake took place 5 d earlier, a whole body content equivalent to the DL for an adult would correspond to a dose between 0.03 and 0.4 mSv for the selected radionuclides, with the exception of americium-241 where the dose is much higher (Youngman 2008).

A problem with whole body monitors without shielding is that they could not be used in areas where there is significant environmental contamination. The lack of shielding is not a problem in uncontaminated areas as the high resolution means that the contribution to background caused by naturally occurring radionuclides can be distinguished from the radionuclides of interest. For NaI(Tl) based systems the inferior resolution means that there is likely to be some interference between peaks from naturally occurring radionuclides and the radionuclides released during the incident. Radionuclide identifiers based on an HPGe detector are used by some first responder organisations and so could be available for use as whole body

Figure 2. Radionuclide identifier based field whole body monitors.

monitors soon after an incident. A disadvantage of the use of these instruments as whole body monitors is that the associated data acquisition and analysis software is complex and so training would be needed.

4.3. Shielded systems

Shielded systems were mostly developed as a direct result of the Chernobyl accident in 1986. These systems use thick lead shielding and typically a large sodium iodide (NaI(Tl)) based detectors and typically have a detection limit (DL) for caesium-137 (^{137}Cs) in the range 100 Bq–5000 Bq for a 10 min measurement period. Lahham and Fulop (1997) have described a heavily shielded system using ~5 cm thick lead, using a 12.5 cm diameter and 12.5 cm long NaI(Tl) detector. The DL for ^{137}Cs was determined to be 420 Bq for a 10 min count, and this was increased to 2420 Bq with a ground surface contamination of 1000 kBq m^{-2}. The French Defence Radiation Protection Service has two types of mobile whole body monitoring vehicles (Castagnet *et al* 2007). The first of these contains four person monitoring stages and uses a 5.1 × 5.1 cm NaI(Tl) detector for each station. The second vehicle is designed to be more sensitive and used a 7.6 × 12.7 × 40.6 cm NaI(Tl) detector with thick shielding. The DL for ^{137}Cs in whole body for the former system is 5000 Bq and 100 Bq for the latter for a 10 min count time. Details of other shielded NaI(Tl) detector based systems with similar characteristics to those described above have been published by Dantas *et al* (2010), Mizushita (1977) and Summering (1980).

The National Radiological Protection Board (now part of PHE) developed and built a transportable whole body monitoring system (Youngman 2001). This system is unusual as two hyper-pure Germanium (HPGe) detectors were used (figure 3). The larger detector is used for whole body measurements and the smaller detector for measurements of radioiodine in the thyroid. The use of high resolution HPGe detectors allows unambiguous identification of radionuclides and also allows individual radionuclides to be quantified in mixtures. This property is particularly useful for reactor accidents where complex mixtures of activation and fission products could be released, many with multiple gamma-ray emissions. This system uses lead shielding around the detector and in the base and back of the chair which gives background counts which approaches that normally only achieved in a purpose built laboratory facility (Scott 2014). As the background count rates are low, the system is very sensitive. The DL for ^{137}Cs for a 10 min count time is 200 Bq. Detection Limits for other radionuclides with gamma emissions above 100 keV and at least one gamma emission probability of over

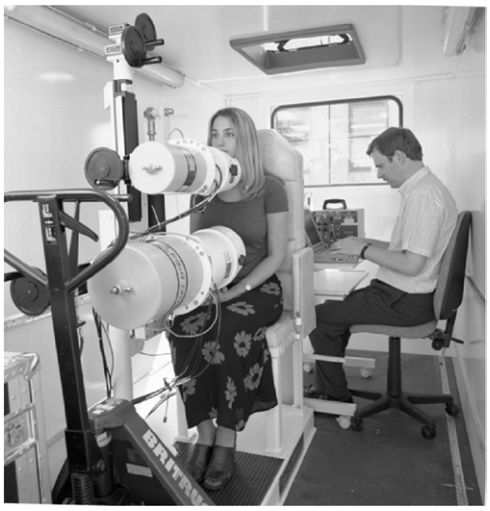

Figure 3. A transportable shielded whole body monitor (Youngman 2001).

10% correspond to effective doses of small fractions of a milli-Sievert (Youngman 2001). Other systems using HPGe detectors have also been described in the literature. The transportable system operated by the Radiation and Nuclear Safety Authority in Finland uses a single HPGe detector with a shielded chair (Rahola *et al* 2006) and the Institut de Radioprotection et de Sûreté Nucléaire in France has a lead shielded bed with two HPGe detectors which can be used for americium-241 in lung measurements and radioiodine in thyroid measurements as well as for whole body measurements (Castagnet *et al* 2007).

Although these well shielded NaI or HPGe detector based systems are very sensitive and could be used in areas of high environmental contamination, they do have some drawbacks for use in emergencies. The most important of these is that the detector supports and shielding are bulky and heavy and therefore difficult to transport which limits the response times. Particular disadvantages of HPGe detector based systems is that these are often cooled with hazardous liquid nitrogen which must either be transported or available locally and they are more delicate than other detector types. Most of these systems are permanently truck based so that they can be transported more easily but this adds significantly to initial and operational cost. Also this type of facility is rare and so the number of people measured per unit time would be low. This would not be a major issue for an accident at the majority of UK civil nuclear reactor sites where surrounding population densities are low, but is likely to be a serious problem for an incident in an area of high population density even if an effective triage system is used. A further disadvantage is that the complexity means they can only be operated by specialists in gamma-ray spectrometry. The main advantage of these shielded systems are that they are very similar in construction to laboratory based systems and when operated by trained staff are likely to be as accurate as laboratory systems. This accuracy means that they could be used to determine individual dose and to identify people for possible treatment to reduce dose.

4.4. Detection limits

The detection limits for caesium-137 in the body which can be attained with some whole body monitoring systems described previously, use are shown in table 2, together with DLs for three

Table 2. Reported detection limits for ^{137}Cs and effective dose corresponding to whole body activity at the level of the detection limit.

System	Detector type and size	Measurement time (mins)	DL[a], Bq	Approximate minimum detectable dose, mSv[b]	Reference
Well shielded laboratory based	5 NaI(Tl) detectors each 10 × 15 cm diam.	45	18	0.0003	Smith *et al* (1994)
Well shielded laboratory based	HPGe 10.6 × 7.5 cm diam.	45	30	0.0004	Smith *et al* (1994)
Well shielded laboratory based	4 × HPGe 8 × 6.8 cm diameter	20	33	0.0005	Palmer *et al* (1991)
Well shielded mobile	NaI(Tl) 5 × 5 cm diam.	10	5000	0.07	Castagnet *et al* (2007)
Well shielded mobile	NaI(Tl) 7.6 × 13 × 41 cm	10	100	0.001	Castagnet *et al* (2007)
Well shielded mobile	NaI(Tl) 12.5 × 12.5 cm	10	450	0.006	Lahham and Fulop (1997)
Well shielded mobile	HPGe 10.6 × 7.5 cm diam.	10	200	0.003	Youngman (2001)
Mobile gamma-ray spectrometer	NaI(Tl) 5.1 × 5.1 cm	1.7	1200	0.02	Muikku and Rahola (2007)
Mobile gamma-ray spectrometer	HPGe 3.0 × 5.0 cm diam.	5	500	0.007	Youngman (2008)
Hand-held instrument	NaI(Tl) 0.25 × 3.2 cm diam.	0.3[c]	120 000	2	Youngman *et al* (2011)

[a] For the 95% confidence level.
[b] Assumes whole body activity at the DL and intake by acute inhalation occurred 1 d before measurement. Dose calculated for adults, assuming Activity Median Aerodynamic Diameter of 5 μm, absorption Type F.
[c] Instantaneous count rate is indicated but the reading should be viewed for about 20 s to obtain an approximate average value.

laboratory based systems, to compare the performance of different types of measurement system. Table 2 presents DLs and the dose that these DLs correspond to for a measurement one day after acute intake. The doses shown in table 2 were calculated assuming that only ^{137}Cs was present in a release, intake was by inhalation and that there is no significant contribution to dose from other pathways, such as external irradiation.

Detection limits for other radionuclides which emit gamma-rays of energy greater than 200 keV and with high yield would be similar to the values presented in table 2. It can be seen that the DLs for ^{137}Cs for equipment designed for emergency use varies by a factor of over 1000 and the most sensitive have DLs for ^{137}Cs which approach laboratory based systems. It may be necessary to measure people at greater times between intake and measurement than 1 d. For ^{137}Cs, the approximate minimum detectable doses would increase by a factor of about 2.5 if measurements were made 100 d after intake. Table 2 also shows that the majority of systems are capable of detecting intakes which correspond to a small fraction of a millisievert, for measurements made up to 100 d after intake. The exception is for the hand-held

Table 3. Activities corresponding to action levels and clinical decision guides for selected radionuclides.[a]

Radionuclide	Solubility type	Method	AL_U,[b] kBq (200 mSv)	Retention indicative of an intake of 1 CDG[c], kBq	Approximate detection limit of hand-held instrument[d] (kBq)
^{60}Co	M	Whole body	12 000	17 000	70
	S		5000	7200	70
^{75}Se	F	Whole body	81 000	No value available	70
	M		65 000	No value available	70
^{131}I	F	Thyroid	2300	3000[e]	3
^{137}Cs	F	Whole body	18 000	33 000	120
^{192}Ir	F	Whole body	46 000	No value available	50
	M		21 000	28 000	50
	S		18 000	25 000	50
^{241}Am	M	Lung	0.45	0.5	1600

[a] Activities corresponding to the AL_U and CDG were calculated assuming measurement 24 h after intake by and adult, acute inhalation and Activity Median Aerodynamic Diameter (AMAD) is 5 μm.
[b] From Rojas-Palma *et al* (2009) annex 10.
[c] Adapted from NCRP (2008) table 11.1 and 11.2.
[d] For NaI(Tl) detector with diameter of 38 mm and 51 mm long (Youngman *et al* 2011).
[e] For adult >40 years.

instrument where the minimum detectable dose is approximately 5 mSv for a measurement made 100 d after intake; although this level of sensitivity is still good enough for screening purposes.

5. Capability of hand-held instruments for detecting people who require medical assessment

Table 2 presents data which shows the wide range of reported sensitivity of emergency whole body monitoring equipment. This section looks at the sensitivity required to meet the main aim of measurements i.e. to detect people who require medical assessment.

The activities in the body corresponding to the upper action level (AL_U), (Rojas-Palma *et al* 2009) and clinical decision guideline (CDG), (NCRP 2008) are compared with the detection limits achieved with a small hand-held NaI(Tl) detector (Youngman *et al* 2011) in table 3. The actions to follow if the AL_U or CDG are exceeded were discussed earlier.

The data in table 3 shows that activities in the body corresponding to the upper action level and CGDs are similar. Comparison of the Detection Limits for a typical hand-held NaI(Tl) based instrument with retention corresponding to doses equivalent to the CGD or AL_u (table 3) shows that except for ^{241}Am this type of instrument is capable of identifying individuals who need medical assessment assuming measurements were made one day after intake. For the intake scenario used in table 3, the activities corresponding to the CGD or AL_u would decrease by a factor of up to 10 for the radionuclides ^{60}Co, ^{75}Se, ^{137}Cs and ^{192}Ir if measurements were made 100 d after intake. Thus it would still be possible to use hand-held instruments to screen people to select those who require medical assessment for these radionuclides. The half-life of ^{131}I is relatively short, and for this radionuclides it would be possible to carry out screening to identify people who need medical assessment several weeks after intake. If the release contains significant amounts of radionuclides, such as actinides, which are not detectable in

Table 4. Summary of properties of types of monitoring equipment.

	Monitoring equipment type		
Property	Hand-held instruments	Unshielded HPGe detector	Shielded detectors
Complexity	Simple to operate	Specialist training required	Specialist training required
Relative cost	Low cost	Expensive	Potentially very expensive
Availability	May be readily available close to the incident	Limited. Used by some first responder organisations	Available to specialist radiological protection organisations only
Deployment	Simple	No special transportation needed	Special transport arrangements required
Power requirements	Battery operated	Battery operated but mains power required for longer-term operation	Main power required
Capable of spectrometry[a]?	No	Yes	Yes
Affected by environmental contamination?	Yes	Yes	Unlikely
Suitability for screening large numbers?	Yes	No	No
Suitability for more detailed assessment	No	Yes	Yes

[a] Some types of hand-held instrument have a spectrometry capability.

the body using hand-held instruments or external irradiation is a significant exposure pathway then it may well be necessary to use more sophisticated methods.

HPA (2010) have recommended upper and lower guidance levels for treatment of intakes of radiocaesium with Prussian Blue. At the lower guidance level, 30 mSv, the health benefit of treatment would be small but reassurance would be provided. At the upper guidance level, 300 mSv, the overall benefit of treatment would be expected to be significant. For the conditions used to calculate activities corresponding to AL_u and CDG in table 3, the activity of ^{137}Cs which corresponds to the lower guidance level is approximately 300 kBq. For the purposes of screening large numbers of people to prioritise them for measurements with more accurate systems, a screening level might be set at one tenth of the lower guidance level. Thus hand-held instruments could be used for times between intake and measurement of at least 100 d to prioritise people for accurate measurements.

If a release contains significant amounts of radionuclides which emit few gamma-rays per decay or only low energy gamma-rays (such as americium-241 (^{241}Am)) then it is likely that systems using large detectors which are well shielded will be needed to identify people who require medical assessment. The availability of equipment suitable for radionuclides such as ^{241}Am is very limited and so the most suitable method of screening large numbers of people is to use measurements of urine samples (Li *et al* 2010, Youngman *et al* 2011). The contribution of external irradiation to total dose may also need to be considered when designing a measurement strategy.

6. Conclusions

Following an incident involving spread of radioactive contamination to the environment there could be an urgent need to identify people who have received intakes high enough to require medical assessment. Laboratory based whole body monitoring systems could be used for incidents involving gamma-emitting radionuclides but these may be located far from the incident and have a limited throughput.

Transportable shielded measurement systems using large detectors have high sensitivity for measurements of activity in the body, but have disadvantages for deployment to an incident as they require special transport arrangements and highly trained staff. In addition they are expensive and as most countries only have one or two systems the number of people who can be monitored would be low. The key advantage of shielded systems is they are unlikely to be affected by environmental contamination.

Systems using high-resolution detectors which are unshielded are not affected by naturally occurring radionuclides in the environment as the gamma emissions from naturally occurring and anthropogenic radionuclides will not interfere in a gamma-ray spectrum. However, if used without shielding they would be affected by environmental contamination resulting from the incident. The advantages of this type of equipment are that it is easily portable, sensitive enough to identify people who require medical attention for most incidents where the radionuclide(s) released is gamma emitting and able to measure the individual components in a mixture of radionuclides.

For incidents where only one beta/gamma or gamma emitting radionuclide is released hand-held instruments may be sensitive enough to identify people who require medical assessment. Hand-held instruments have the advantage that they are likely to be available close to the incident and are simple to operate. Measurements of people found to be above the count rate corresponding to a dose Action Level can be prioritised for accurate measurements and receive prompt medical assessment. For emergency preparedness purposes it is recommended that if specialist mass internal contamination monitoring facilities are not available then arrangements should be made to calibrate hand-held instruments for initial internal contamination monitoring at the scene. The key advantage of using this type of equipment is the relatively low cost so that a large number of people can be monitored per unit time. There are important limitations on the use of these simple instruments, as methods are only applicable to radionuclides which emit gamma-rays above about 200 keV with a high emission probability. For incidents where mixtures of radionuclides are released hand-held instruments would still be useful in identifying people who have the highest levels of internal contamination. Simple instruments do not generally provide sufficient accuracy to be used for the determination of individual doses and so other laboratory based or more sophisticated systems need to be available to confirm measurements for the most highly exposed individuals. The properties of the various types of equipment available for emergency monitoring of internal contamination are summarised in table 4. For radionuclides which do not emit gamma-rays with high emission probability, and for incidents affecting large numbers of people, then it would be necessary to instigate a screening programme using analysis of urine samples.

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