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Assessment of accidental uptake of iodine-131 in emergency situations

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Abstract

The need for quantifying the uptake of radioiodine (^{131}I) in thyroids in emergency situations has repeatedly been demonstrated. With early stage measurements people who may have inhaled or ingested amounts of ^{131}I can be identified and the need for more extensive measurements and/or subsequent medical assessment can be evaluated. The report presents the outcome from the activity THYROID in which calibrations of thyroid monitoring equipment in the Nordic countries were harmonized. A total of 38 sites in Scandinavia were identified holding equipment usable for screening for thyroid ^{131}I contamination. Different instrument types can be used in an emergency situation as long as they are properly calibrated. The activity enabled to evaluate the regional preparedness regarding thyroid personal monitoring.

Key words

Thyroid dose, I-131, calibration, emergency preparedness

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Nordisk kärnsäkerhetsforskning
Nordic nuclear safety research

Assessment of accidental uptake of iodine-131 in emergency situations.

Report from the NKS-B THYROID (Contract: AFT/B(12)6)

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1. Background to the NKS activity THYROID

The need for quantifying the uptake of radioiodine (^{131}I) in thyroids in emergency situations has repeatedly been demonstrated in the wake of nuclear accidents. A striking example is the unexpected increase of thyroid cancers in children and young people in Ukraine, Belarussia and the southern parts of Russia following the Chernobyl accident (e.g. Zvonova and Balonov, 1993). Monitoring of individual children was implemented in Japan following the Fukushima accident. During the period of March 26th-30th, 2011, 1080 children of ages 0-15 years were monitored. However, no child had accumulated ^{131}I to the extent that the thyroid equivalent dose exceeded the decided screening level of 0.2 µSv/h (Povinec et al., 2013). In addition to releases from nuclear facilities, malevolent use of radiation and radioactive materials has become increasingly important to consider.

The aim of an early stage measurement is to identify people who may have inhaled or ingested amounts of ^{131}I that imply a need for more extensive measurements and subsequent medical assessment. Prompt screening of larger groups enables both the necessary early stage contamination control and the subsequent estimation of radiation doses. With proper calibration, many handheld instruments can be used for control measurements of internal contamination with ^{131}I (Rahola et al., 2006). Stationary gamma spectrometers specialized for thyroid monitoring are obviously useful as are other spectrometers that can be fitted to this measurement situation (e.g. mobile germanium detectors). Gamma cameras available in hospitals may also be an important resource in the context of ^{131}I measurements.

The NKS activity THYROID was conceived to evaluate and improve the status of thyroid measurement capabilities in the Nordic region. The activity enjoys a good participation from a number of labs. A similar project was previously conducted concerning whole-body counting facilities (del Risco Norrlid et al., 2012), which has established a regional network and facilitated the organization of, and recruitment to, the current project.

1.1 Scenarios for accidental release of ^{131}I

Iodine-131, ^{131}I, is a fission product with a physical half-life of 8.02 days. It is produced in large amounts in nuclear power plants and decays through negative beta decay with subsequent emission of gamma and X-ray radiation from the daughter ^{131}Xe. If ingested or inhaled, it is rapidly absorbed to blood from which 30% accumulates in the thyroid, where its biological half-life is around 90 days (ICRP, 1990). This gives an effective half-life of 7.4 days for ^{131}I in the thyroid.

Due to its high fission yield and high specific activity, the reactor inventory of ^{131}I is high – of the order of 10^{18} Bq. Despite being relatively short-lived, the isotope remains for long enough time to permit transfer in the food chain after a release to the environment, mainly via fallout

to grass, from grass to cows, and from cow milk to humans. Due to the high volatility of iodine it can escape from the reactor fuel even at relatively low temperatures. A well constrained release after a reactor accident with damaged fuel can constitute about 0.1% of the iodine and caesium inventories. If the reactor is breached, the release can be up to 10% of the inventory. It has been estimated that as much as 50% of the available iodine was released during the Chernobyl accident (UNSCEAR, 2000).

^{131}I is also widely used in medicine to diagnose and treat malfunction of the thyroid and thyroid cancer since it naturally concentrates in the thyroid. According to the national registry of isotope use in medicine administrated by the Swedish Radiation Safety Authority (www.ssm.se), 5106 doses of ^{131}I were delivered to patients during 2012 and the total activity is estimated to be 2.7 TBq. These figures represent hospitals all over Sweden and they suggest the activity that routinely must be transported across the country.

In summary, the scenarios for accidental release of ^{131}I are accidental releases from nuclear power plants, transport accidents and malicious use of stolen shipments of ^{131}I.

1.2 ^{131}I as internal contaminant

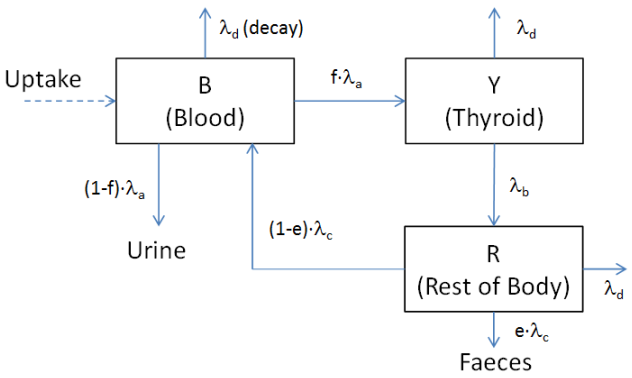
Intake of inorganic iodine, e.g. as potassium iodide from iodized salt, is vital for the human body and is used in the thyroid for building the thyroid hormones. The recommended dietary intake is in the range of 50-200 µg/d (WHO, 1996) and the main dietary source of it is sea food products and table-salt supplements. As much as one third of the world population are affected by inadequate iodine intake, while 70% of world households have access to iodized salt (WHO, 2007). Low dietary intake of iodine causes an up-regulation of the uptake mechanism and may cause enhanced thyroid accumulation upon exposure (Leggett, 2010). Nutrient status therefore affects the metabolism of iodine. Common chemical forms are iodide (I^-), iodate (IO_3^-) and elemental iodine (I_2), depending on the chemical environment.

Inorganic iodine is almost completely (99%) absorbed from ingested food within a few hours. The site of absorption is primarily the small intestine. Upon absorption, inorganic iodine is readily distributed in the blood and is actively taken up by follicular cells in the thyroid via an active membrane transport enzyme (Na-I symporter). Uptake from blood also takes place in the salivary glands and in the stomach lining (mucosa). The concentration of iodine at the sites of active uptake can become 20-40 times higher than in the blood. In the thyroid gland, iodine is oxidized and coupled to the amino acid tyrosine to form the thyroid hormones T3 and T4, which are released into the blood-stream. Upon distribution throughout the body, thyroid hormones are metabolized and inorganic iodine returned to the blood (Leggett 2010).

Upon inhalation of particles containing ^{131}I, only a fraction (30-40%) of the inhaled activity will eventually be transferred to the blood, depending on the size of particles and the rate of absorption (ICRP, 1994). Once the element has entered the blood, the distribution and

retention of iodine in the body can be described by a three-compartment model for calculating dose coefficients (see Figure 1) (ICRP, 1990).

The model allows for recycling of iodine to the thyroid, implying that organic iodine in the blood is metabolized in the tissues of the body and some inorganic iodide is returned to the blood to further accumulate in the thyroid gland. This recycling is, however, not so important for short-lived iodine isotopes like ^{131}I. Iodine that enters the blood, from e.g. the lungs or absorption in the gastro-intestinal (GI) tract, has a fractional uptake from blood to the thyroid of 30%. Depending on the amount of stable iodine in the diet, this fraction varies considerably between individuals and different countries. Furthermore, about 20% is excreted in organic form in faeces.



$\lambda_a = \ln(2)/T_a$	T_a = 0.25 d	Blood half-life	B(t=0) = 100%
$\lambda_b = \ln(2)/T_b$	T_b = 80 d	Thyroid half-life	Y(t=0) = 0%
$\lambda_c = \ln(2)/T_c$	T_c = 12 d	Rest of Body half-life	R(t=0) = 0%
$\lambda_d = \ln(2)/T_{½}$	$T_{½}$ (d)	Radioiodine half-life	
	f = 0.3	Thyroid uptake fraction	
	e = 0.2	Faecal excretion fraction	

$$dB/dt = (-\lambda_d - f \cdot \lambda_a - (1-f) \cdot \lambda_a) \cdot B(t) + (1-e) \cdot \lambda_c \cdot R(t)$$
$$dY/dt = (-\lambda_d - \lambda_b) \cdot Y(t) + f \cdot \lambda_a \cdot B(t)$$
$$dR/dt = (-\lambda_d - e \cdot \lambda_c - (1-e) \cdot \lambda_c) \cdot R(t) + \lambda_b \cdot Y(t)$$

Figure 1: Three-compartment model describing the retention and clearance of iodine to/from the thyroid (Modified from ICRP Publication 56; ICRP, 1990).

Calculations of the committed equivalent dose to the thyroid or the committed effective dose are facilitated by the publication of dose coefficients. These dose coefficients are given in units of committed equivalent dose to the thyroid per unit intake of ^{131}I (Sv/Bq). The amount of ^{131}I reaching the blood strongly depends on the route of intake, which must be determined. For inhalation, both the ICRP lung model and the GI-tract model are included but for ingestion only the GI-tract model is used.

In the case of inhalation, the chemical form of iodine, aerosol particle size and solubility must also be determined. Inhalation dose coefficients are given in ICRP Publication 71 (ICRP, 1995). For absorption type F (fast absorption in the lungs) and particles of Activity Median

Aerodynamic Diameter (AMAD) equal to 1 µm, the values of the dose coefficient is between $1.4 \cdot 10^{-6}$ for a 3-month child and $1.5 \cdot 10^{-7}$ for an adult. Figure 2 shows the retention of ^{131}I in the thyroid at different times after an intake of 1 Bq from inhalation and ingestion, respectively.

The dose coefficients for different intake routes and the problems related to the estimation of an intake are discussed in more detail in connection with the emergency scenario included in the THYROID activity; (see section 3.3 Thyroid and effective doses associated to an intake of ^{131}I).

In the event of a nuclear accident with expected release of ^{131}I, stable iodine is normally distributed to the population. Stable iodine prophylaxis works through saturation of the thyroid uptake mechanism and by competing with radioactive iodine. The recommended single-dose of iodine for prophylaxis ranges from 12.5 mg for infants to 100 mg for adults below 40 years of age (WHO 1999). Stable iodine has an apparent half-life of 91 days and in Figure 2 the thyroid retention functions for stable iodine (^{129}I) is also displayed.

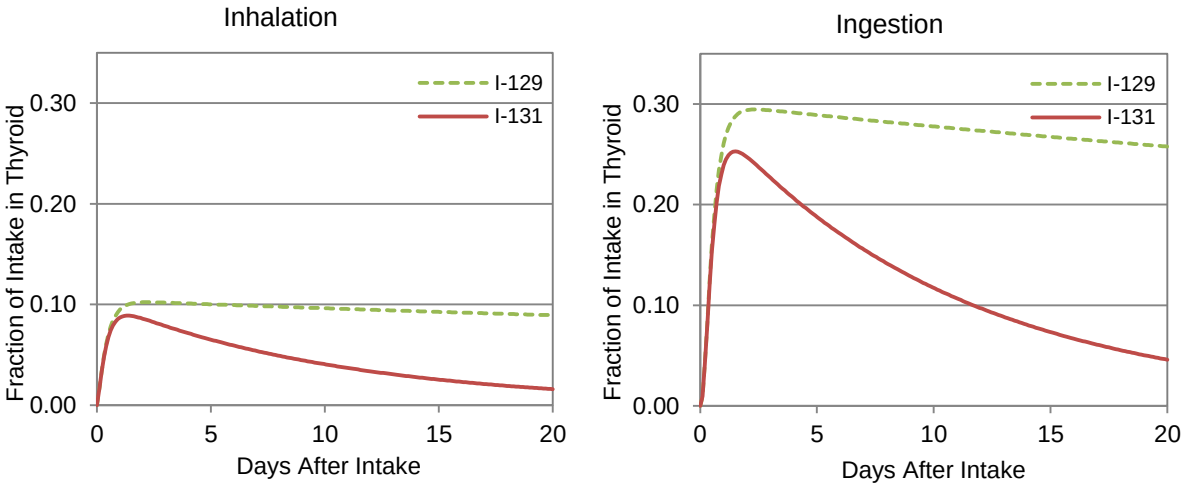


Figure 2: Retention functions for ^{131}I and ^{129}I (stable iodine) in adults after intake by inhalation or ingestion (Type F, AMAD 1 µm, Light Worker). Calculated in IMBA Professional (Bioassay) using ICRP respiratory and biokinetic models.

1.3 Goals of the NKS activity THYROID

- Harmonize calibrations of thyroid monitoring equipment in the Nordic countries
- Conduct an intercomparison exercise for determination of ^{131}I in thyroid
- Evaluate the regional preparedness regarding thyroid personal monitoring
- Evaluate the lowest limits of detection of ^{131}I with the present resources

2. Calibration

The aim of the calibrations was to allow participants to obtain calibration factors in order to enable measurements of ^{131}I in the thyroid gland. Neck phantoms of three sizes; adult, young and child were circulated. These contained certified sources of mock-iodine, here called "mock", of known and traceable activity. The mock, a mixture of ^{133}Ba and ^{137}Cs, is a practical simulator of ^{131}I due to its longer half-life and similarity of dominant gamma energy emissions.

By using the same set of sources for all calibrations, the performance of different instruments in terms of sensitivity and accuracy could be compared. The calibration factors were validated by measurements on also certified mock sources, which were circulated together with the calibration sources (see section 3, Verification Exercise). The activity of the pair of test-sources was unknown for the participants.

2.1 Calibration phantoms and mock iodine sources

A set of neck plastic phantoms (TF-04) representing a 6 year old child (CHILD), a 14 year old teenager (YOUNG) and an adult (ADULT) were purchased from STC Radek, Saint-Petersburg, Russia (http://radek.ru). Each phantom contained two ampules with homogenously distributed radioactivity positioned toward the front (anterior) to simulate emission from radioiodine accumulated in the thyroid gland (see Figure 3).

The sources consist of mock-iodine, a mixture of ^{133}Ba (≈90%) and ^{137}Cs (≈10%) in removable sealed ampoules. The mock's relative photon composition changes over time due to the 20 years difference in half-lives between Ba and Cs. In Table 1, the gammas and X-ray emissions over 30 keV and yield over 1% for ^{131}I (grey) and mock are presented for comparison. The gammas and X-ray below 30 keV are most likely stopped in the material of the neck phantom and never reach a detector.

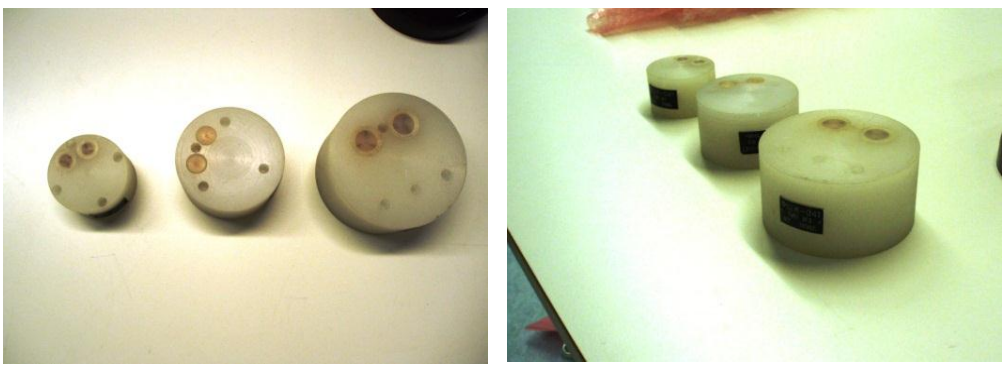


Figure 3: CHILD, YOUNG and ADULT neck phantoms containing pairs of ampoules in place of the thyroid gland.

The ampoule diameter varied with phantom type ensuring correct placement of sources. It was assumed that right-left interchange of sources has no effect on measurements since the activities of individual source of a pair are approximately equal. The activity of the sources was certified by the D.I. Mendeleyev Institute for Metrology (vniim.ru, Saint Petersburg, Russia). Table 2 contains the certified data for the calibration sources of mock with the statements on the expanded relative standard uncertainty (U_r) at the 95% confidence level.

Table 1: Gammas and X-ray for ^{131}I and the mock from 30 keV and up. The lines of high yield are bold.

^{131}I ($T_{1/2}$ = 8 days)		**Mock-iodine**			
		^{133}Ba ($T_{1/2}$ = 10.5 years)		**^{137}Cs ($T_{1/2}$ = 30 years)**	
E [keV]	y_i (%)	*E* [keV]	y_i (%)	E [keV]	y_i (%)
80.185	2.607	30.625	34	31.8174	1.95
284.305	6.06	**30.973**	62.8	32.1939	3.59
364.489	81.2	**35**	18.2	36.5	1.055
636.989	7.26	35.9	4.6	**661.657**	84.99
722.911	1.796	53.1622	2.14		
		79.6142	2.65		
		80.9979	32.9		
		276.3989	7.16		
		302.8508	18.34		
		356.0129	62.05		
		383.8485	8.94		

Table 2: Radek's certified data for mock sources used for the calibrations in THYROID.

Source, ID	Activity of ^{133}Ba, A_{ref}^{Ba133} [kBq] July 10, 2012	U_r (%) 2σ	Activity of ^{137}Cs, A_{ref}^{Cs137} [kBq] July 10, 2012	U_r (%) 2σ
CHILD a, 83.1.1	4.87	4	0.50	4
CHILD b, 83.1.2	4.86	4	0.51	4
YOUNG a, 83.2.1	7.63	4	1.05	4
YOUNG b, 83.2.2	7.62	4	1.06	4
ADULT a, 83.3.1	14.9	4	2.08	4
ADULT b, 83.3.2	14.7	4	2.08	4

2.2 Mock correction

The use of mock iodine sources for calibration is a way to circumvent the impractically short lifetime of ^{131}I. A mix of ^{133}Ba to ^{137}Cs can be balanced (about 10:1) to achieve a sum of gamma-yields that approximates that of ^{131}I, allowing the total activity of ^{133}Ba + ^{137}Cs to be regarded as an equivalent activity of ^{131}I (Marshall 1959). However, a degree of filtering through an absorbing material is required, as the X-ray and low-energy gammas from ^{133}Ba (81 keV) are more abundant than for ^{131}I (see Table 1). It was originally suggested to encapsulate the sources in 0.7 to 0.9 millimeters of cadmium, tin or Babbitt-metal.

The specifications of the mock iodine used in the current project do not indicate the presence of filtering material. We therefore assume that the low energy radiation is not attenuated as required. As consequence of this, the determination of ^{131}I based on mock calibrations can result either in underestimation or overestimation of the activity of ^{131}I.

If all photon energies are included in the calibration range of energies (ROI, Region Of Interest), and if assumed that detector efficiency is energy-independent, detectors calibrated with mock iodine will measure ^{131}I activities 2 to 3 times lower than the actual activity. As most detectors show higher efficiencies at lower energies, the deviation may be even greater (an example is shown in Figure 4).

Overestimation of ^{131}I activity may occur with spectrometers if the ROI covers only the major peaks of ^{133}Ba, 356 and 384 keV, while omitting the 303 keV peak. In this case the measured ^{131}I activity will become 20-25% too high. For spectrometers, this issue can anyhow be resolved by measuring all energies above 100 keV (e.g. ROI 100-1000 keV).

For integrating instruments (non-spectrometers), a correction factor must be introduced. This mock correction factor (F_{mock}) is calculated from the photon yields of ^{131}I, ^{133}Ba and ^{137}Cs, the actual source ratio of ^{133}Ba to ^{137}Cs, and the relative energy-response of the detector. It is meant to be multiplied with the obtained calibration factor (F_{cal}). An overview of calculated mock correction factors is presented in Appendix A.

The mock correction factor (F_{mock}) is given as:

$$F_{\text{mock}} = \frac{\sum_i e^{-\mu_i x} b_i R_i \gamma_{i,\text{mock}}}{\sum_j e^{-\mu_j x} b_j R_j \gamma_{j,\text{I131}}} \qquad (1)$$

where

- i, j are indeces over the discrete emitted photon energies for ^{131}I and mock iodine, respectively
- $e^{-\mu x}$ is the transmitted fraction of the photons passing through any material(s) between the sources and detector. It depends on material thickness (x) and material attenuation coefficient (μ) at the given photon energies (i, j)
- b is the build-up factor in the phantom material

R is the instrument specific relative detection efficiency for photons of the given energies (i, j)

γ is number of emitted photons of given energies (i, j) per decay (or the "yield") for ^{131}I (i) and mock iodine (j)

The ratio in Equation (1) is mostly determined by the ratio between gamma emission intensities and the instrument dependent relative detection efficiency. The linear attenuations and the contribution of photons emerging from Compton scattering within the solid angle of the detector (build-up) are of less importance in this case, where the thickness overlaying the calibration sources is as little as 1-2 cm. A precise determination of F_{mock} would have required a Monte Carlo calculation. In the current project, the correction factors were calculated from Equation (1).

The approximate relative detection efficiency for photons of given energies can be obtained from energy response curves found in manufacturers' instrument specifications or calculated from detector material interactions. Efficiency generally increases with lower photon energies as the probability of interaction increases (photoelectric or Compton). A low "cut-off" level below 50 keV represents the barrier of the detector entrance window or casing and the detector threshold (GM tube discharge, photomultiplier response). An example of energy response curve for a Geiger-Müller counter, $R(E)$, is presented in Figure 4.

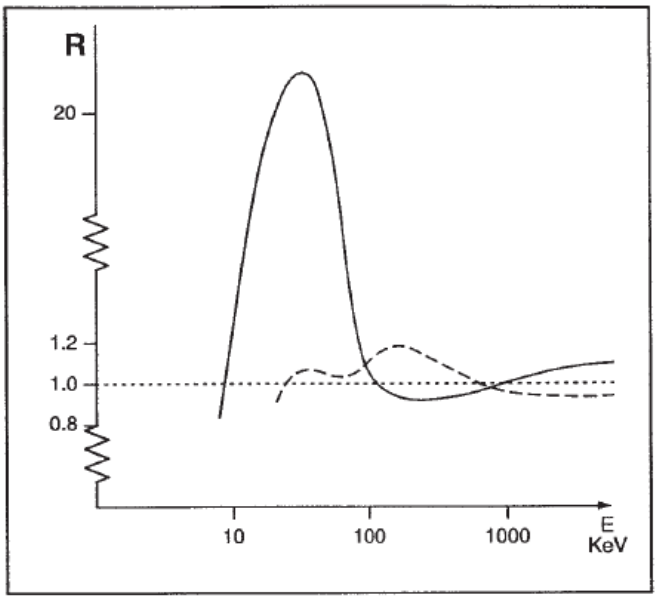


Figure 4: Geiger-Müller counter response curve. Non-compensated (solid) and energy-compensated (dashed).

Relative efficiency must be in the form of normalized (or absolute) count-rate per photon emission rate (constant photon fluence). For dose rate-meters, the energy response curves may be given as normalized count-rate per incident dose-rate (in air), which cannot be used

directly in the calculations but needs to be converted to relative efficiency dividing by the mass energy absorption coefficient for air (μ_{en}/ρ) (or Kerma) at different energies. The mass energy absorption coefficients can be retrieved from NIST database (NIST data Gateway, 2014).

In general, the information on energy response curves for integrating instruments was limited, and therefore the mock correction factor was only calculated for a small number of specific instruments. For guidance, the mock correction factor was also calculated for "generic" NaI crystals of different thicknesses and a plastic scintillator (vinyltoluene). Here, the relative detector efficiency was estimated from mass attenuation coefficients (μ/ρ) based on the absorption curves by NIST (NIST data Gateway, 2014). For GM tubes, only dose-response curves were available. Since these curves needed conversion to constant fluence, a default 30% uncertainty at two sigma level was applied to the mock correction. Mock corrections for different instruments together with the information collected on instrument's relative efficiency are presented in Appendix A.

In the case of high resolution spectrometers, the mock correction, F_{mock}, in the practical energy interval used, 300-700 keV, resolved individual peaks can be approximated to the ratio between emission rates of iodine at 364.5 keV and the sum of the emission rates of the peak(s) of the mock that is included in the ROI. Thus, having chosen a ROI covering the mock peak 356 keV results in a F_{mock}= 0.76. In the case a ROI covering both 356 and 384 keV is chosen, the F_{mock}= 0.87. The uncertainty associated to the mock correction for spectrometers was considered negligible since it is mostly based in the fluctuation on gamma emission data ("Flat" energy response assumed).

2.3 Measurement protocol for the calibrations

Participants were asked to perform measurements on the calibration phantoms at 0 cm and 10 cm distance from detector end-cap to phantom front, see Figure 5. The 0 cm geometry gives the highest sensitivity, while the 10 cm geometry allows for measurements through clothing or bandage, or in cases where near proximity of the instrument is uncomfortable for the subject.

For gamma cameras, the definition of phantom-detector distance varied as some participants did the calibrations with a collimator (plate) in front of the detector. In these cases, the phantom was positioned relative to the collimator's surface. Participants were encouraged to state a figure of uncertainty to account for the possible fluctuations in detector-phantom positioning/orientation (geometry uncertainty). Background measurements were performed with the phantom in place and unloaded, that is, with the source ampoules removed. This eliminates any shielding effect of the phantom on background count rate.

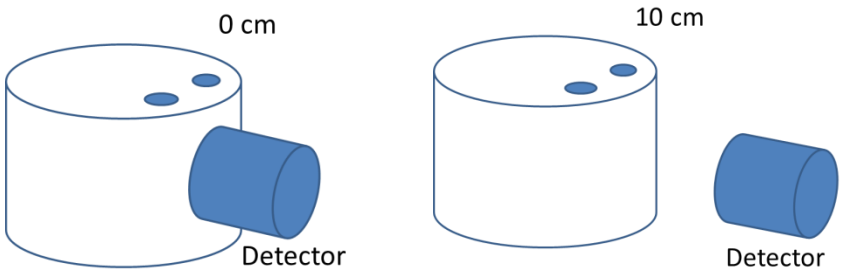


Figure 5: Illustration over the two measurement geometries used for the calibrations

2.4 Calibration factors for integrating instruments

For integrating instruments the calibration factors were calculated as the total activity of the calibration source set at the time of calibration divided by net count rate (background-subtracted).

$$F_{\text{cal}} = \frac{A^{\text{mock}}}{S_{\text{cal}}} \cdot F_{\text{mock}}, \qquad (2)$$

where:

F_{cal} is the calibration factor in units of Becquerel per counts per second or Becquerel per micro Sievert per hour $\left[\frac{\text{Bq}\cdot\text{s}}{\text{c}}\right]$, $\left[\frac{\text{Bq}\cdot\text{h}}{\mu\text{Sv}}\right]$.

A^{mock} is the mock total activity comprising of its components' activities $A^{\text{Ba133}} + A^{\text{Cs137}}$.

S_{cal} is the instrument's net count (dose) rate at calibration, $S_g - S_b$, gross minus background counts, in counts per second or micro Sievert per hour [c/s], [µSv/h], depending on the instrument (count or dose rate meter).

F_{mock} mock correction for integrating instruments, based on energy response curves.

The activities of the mock components $A^{\text{Ba133}}, A^{\text{Cs137}}$ are decay corrected, to account for the time elapsed (Δt) between the reference and the calibration date: $A_{\text{ref}} \cdot \exp(-\Delta t \cdot \ln 2/\text{T}_{1/2})$, $T_{1/2}$ being the half-lifes, 10.5 years for ^{133}Ba and 30 years for ^{137}Cs. A sum of the decay corrected activities for ^{133}Ba and ^{137}Cs is the calibration activity, A^{mock}, with relative uncertainty as:

$$u_r A^{\text{mock}} = \frac{\sqrt{\left(\frac{0.04 \cdot A^{\text{Ba133}}}{1.96}\right)^2 + \left(\frac{0.04 \cdot A^{\text{Cs137}}}{1.96}\right)^2}}{A^{\text{mock}}} \qquad (3)$$

The statements of activities in the certificate are made in the 95% confidence level (Table 2), which means that the evaluation to one sigma-level uncertainty requires dividing the certificates values by 1.96 considering a double-sided Gaussian distribution.

The relative uncertainty for the calibration factor is the square root of the sum of the squares of the relative uncertainties of the source activities, the net count rate and a "geometry" uncertainty (detector-phantom positioning/orientation).

$$u_r(F_{\text{cal}}) = \sqrt{u_r^2 S_{\text{cal}} + u_r^2 A + u_r^2 \text{Geom} + u_r^2 F_{\text{mock}}} \quad (4)$$

where

$u_r S_{\text{cal}}$ is the relative uncertainty for the instrument's net count rate at calibration

$u_r \text{Geom}$ is the relative uncertainty for the fluctuation in positioning and orienting the detector with respect to the phantom

$u_r F_{\text{mock}}$ is the relative uncertainty for the mock correction.

The relative uncertainty of the instrument's net count rate is determined as

$$u_r S = \frac{\sqrt{\frac{S_b}{t_b} + \frac{S_g}{t_g}}}{S} \quad (5)$$

where

S_b, S_g are the background and gross count rates

t_b, t_g are the measurement times for the background and the gross count, respectively

2.5 Calibration factors for spectrometers

For spectrometers the calibration factors were calculated as the activity of ^{133}Ba in the calibration source set at the time of calibration divided by net count rate in the selected region of interest (background-subtracted).

$$F_{\text{cal}} = \frac{A^{\text{Ba133}}}{S_{\text{cal}}^{\text{ROI}}} \cdot F_{\text{mock}} \quad (6)$$

where:

F_{cal} is the calibration factor in units of Becquerel per count per second $\left[\frac{\text{Bq}\cdot\text{s}}{\text{c}}\right]$

A^{Ba133} is the decay corrected ^{133}Ba activity, with relative uncertainty according to the certificate information, that is, 2% at one sigma level.

$S_{\text{cal}}^{\text{ROI}}$ is the spectrometer's net count rate in the selected region of interest - ROI in counts per second [c/s]

F_{mock} mock correction for spectrometers; equal to 0.76 for a ROI selection covering the mock peak 356 keV and to 0.87 for a ROI selection covering 356 and 384 keV.

Similarly to Equation (4), the relative uncertainty is calculated as the square root of the sum of the squares. For spectrometers, the contribution of $u_r MockF$ was considered negligible.

$$u_r(F_{\text{cal}}) = \sqrt{u_r^2 S_{\text{cal}}^{\text{ROI}} + u_r^2 A^{\text{Ba133}} + u_r^2 \text{Geom}} \quad (7)$$

3. Verification exercise

Several large nuclear accidents with significant releases of radioactive iodine have occurred in the last 60 years. Estimates of the released ^{131}I in these accidents are presented in Table 3.

Table 3: Estimated atmospheric releases of ^{131}I in nuclear accidents.

Accident	Estimated release of ^{131}I	Reference
Windscale (1957)	0.9–3.7 PBq	Garland and Wakeford (2007)
Three Mile Island (1979)	0.0005 PBq	Gudiksen and Dickerson (1990)
Chernobyl (1986)	1.2–1.7 PBq	UNSCEAR (2000a)
Fukushima (2011)	200 PBq	IRSN (2012)

Given the present-day high mobility of international travelers and workers, nuclear accidents abroad may result in a large number of exposed citizens returning from the affected area that needs to be screened for internal contamination of ^{131}I. In this context, a disaster in a foreign nuclear power plant in a faraway country was considered in an emergency scenario that served as prelude for the verification exercise.

Together with the calibration sources, the participating laboratories received one set of unknown mock sources to fit in the adult phantom containing ^{133}Ba. They were asked to report the activity of mock and to perform a dose assessment for potential ^{131}I intake. The results were to be reported within 72 hours. Reported activities were compared with the certified values. Participants' reports on thyroid dose associated to an intake of ^{131}I were compared to a best estimate. The emergency scenario circulated among participants can be found in Appendix B.

3.1 Mock activity, measurement uncertainty and minimum detectable activity

In the verification exercise the participants determined the activity of mock, as a total, or as the activity of the mock component ^{133}Ba in an adult neck. The known, traceable value for the unknown mock was ^{133}Ba activity of 35.8 ± 3.0 kBq (k=3), at the reference date, 1996-08-01.

The activity reports were all brought to the common date/time 2013-08-01 12:00:00 to allow for the comparison of reports from participants with the known traceable value of the mock activity. That is, 11.7 ± 1.0 kBq (k =3).

The determination of mock activity requires no mock correction as the photon emission from calibration and test sources are of similar composition ($F_{\mathrm{mock}} \equiv 1$).

The relative standard uncertainty associated to the determination of the mock activity (or its ^{133}Ba component) is the square root of the sum of the squares of the relative uncertainties of counting and the calibration factor.

The minimum detectable activity (MDA) in terms of mock activity is calculated as

$$\mathrm{MDA[Bq]} = F_{\mathrm{cal}} \cdot \left(\frac{k^2}{t_s} + 2k \sqrt{\frac{S_b}{t_b}\left(1 + \frac{t_b}{t_s}\right)} \right) \qquad (8)$$

where

k	is the confidence level 1.645 (one-sided Gaussian distribution) for 95%
S_b	is the count rate for the unloaded phantom (background)
t_s, t_b	are the counting times for loaded and unloaded phantom
F_{cal}	is the calibration factor with $F_{\mathrm{mock}} = 1$

It should be noted that for measurements on ^{131}I, the MDA must be multiplied with the mock correction factor as well.

3.2 Estimation of the activity of ^{131}I based on mock calibrations

The estimation of ^{131}I activity was not an assignment for the participants. To state the activity of ^{131}I based on mock calibrations the calibration factor should had been corrected. Otherwise the activity of ^{131}I can be underestimated down to a factor of 2 or more for integrating instruments, or overestimated up to 30% for high resolution spectrometers (see section 2.2, Mock correction).

The estimation of ^{131}I activity retained in the thyroid gland at the moment of the measurement based on mock calibrations is the registered count rate of the calibrated instrument multiplied with its mock-corrected calibration factor, as follows

$$A^{\mathrm{I131}} = (S_g - S_b) \cdot F_{\mathrm{cal}} \,, \qquad (9)$$

where:

$S_g - S_b$	is the instrument's net count (dose) rate, gross minus background counts, in counts per second or micro Sievert per hour [c/s], [µSv/h], depending on the instrument (count or dose rate meter).

The relative standard uncertainty associated to the determination of the activity of ^{131}I depends on the relative uncertainties (u_r) of net counting and the calibration factor,

$$u_r A^{\mathrm{I131}} = \sqrt{u_r^2 S + u_r^2 F_{\mathrm{cal}}} \qquad (10)$$

where:

$u_r S$ is the relative uncertainty of the instrument's net count rate as in Equation (5)

$u_r F_{\mathrm{cal}}$ is the relative uncertainty of the calibration factor, which depends of the instrument type and the statistical fluctuations during the calibration. See Equation (4) for count and dose rate instruments, Equation (7) for spectrometers.

The minimum detectable activity (MDA) of ^{131}I is calculated as in Equation (8), with the calibration factor, F_{cal} as in Equation (2) for count and dose rate instruments, and Equation (6) for spectrometers.

3.3 Thyroid and effective doses associated to an intake of ^{131}I

The participants were requested to use the measured mock activity as input for the evaluation of thyroid dose from a ^{131}I intake. Since the mock activity in the verification is a known and traceable value (11.7 ± 1.0 kBq (k=3)) it was possible to have a quite accurate best estimate for the thyroid dose assuming that this was the ^{131}I activity measured. The participant's reports on thyroid dose are compared to this best estimate. It was assumed in the scenario that the activity in the thyroid was measured three days after intake. Since the person left the site shortly after the release, it can be assumed that the route of intake was inhalation.

Table 4 shows the thyroid equivalent dose, H_{thyroid}, and the effective dose, E, calculated with the Integrated Modules for Bioassay Analysis – IMBA software (Birchall et al., 2003), using the ICRP-models for lungs (ICRP, 1994a), gastrointestinal tract and the biokinetics of iodine (ICRP, 1990). In the case of inhalation of iodine in the form of an aerosol, the doses will depend on the particle size of the aerosol, given by the activity median aerodynamic diameter (AMAD), as well as the absorption in the lungs, approximated by the three types fast (F), medium (M) and slow (S) absorption. The type V for vapour represents a very fast absorption.

The equivalent dose to the thyroid is approximately the same, regardless of the route of intake. In the case of inhalation, the intake is defined as the concentration of iodine in the ambient air times the breathing rate. In order to have a specified activity in the thyroid the intake will therefore depend strongly on the absorption in the lungs for further transport through blood to the thyroid. The effective dose, however, depends on the route of intake since the equivalent dose in other organs will be significant for some routes of intake. In the extreme case of inhalation of a particulate aerosol with AMAD 5 μm and absorption type S the lungs and colon will contribute 69% and 20% to the effective dose, respectively. For ingestion the thyroid contributes 100% to the effective dose.

For the given scenario, the best estimation of the equivalent dose to the thyroid is about 22 mSv since the most likely type of absorption is F (ICRP, 1995). The effective dose, under the

same assumptions, can be approximated to 1 mSv. Other ways to estimate the equivalent and effective dose are described below.

Table 4: Doses for intake by inhalation and ingestion calculated with IMBA.

Intake regime	Iodine form	AMAD [µm]	Absorption type	Intake [kBq]	$H_{Thyroid}$ [mSv]	E [mSv]
Inhalation	Particulate aerosol	1	F	148	22.4	1.13
Inhalation	Particulate aerosol	1	M	1092	24.6	2.63
Inhalation	Particulate aerosol	1	S	20 139	24.3	31.0
Inhalation	Particulate aerosol	5	F	107	22.4	1.12
Inhalation	Particulate aerosol	5	M	751	23.1	2.09
Inhalation	Particulate aerosol	5	S	11 486	22.9	17.5
Inhalation	Vapour, elemental iodine	N/A	F	57.3	22.4	1.13
Inhalation	Vapour, Methyl iodide	N/A	V	73.6	22.5	1.13
Ingestion	N/A	N/A	N/A	51.5	22.1	1.11

3.3.1 Biological half-life and ingestion dose coefficients

One approach is to use the biological and physical half-lives of ^{131}I to determine an effective half-life and calculate the thyroid activity at the time of intake (three days before measurement). The biological half-life for iodine can be approximated to 91 days, which is sometimes called an apparent half-life since the retention of iodine in the thyroid is modelled by a double exponential (ICRP, 1990). The second term in the retention function can be omitted for ^{131}I due to the short physical half-life of 8.01 days. Thus the effective half-life can be estimated to be 7.36 days.

Using the effective half-life and correcting for the fact that 30% of the activity in the blood is taken up by the thyroid, we find that the activity in the thyroid at the time of intake is 51.6 kBq. Next step is to apply the ICRP's dose coefficients to find the equivalent dose and the effective dose. The actual inhaled activity is still unknown; thus, applying the dose coefficients for inhalation (ICRP, 1995) will give a wrong result.

The ingestion dose coefficients for thyroid equivalent dose and effective dose per unit intake (ICRP, 1990) and (ICRP, 1994b) respectively will give a good approximation. The reason is that 100 % of the ingested iodine can be assumed to be transferred to the blood. The dose coefficients used are 0.44 mSv/kBq, for the thyroid equivalent dose and 0.022 mSv/kBq, for the effective dose. This method gives acceptable estimations of the doses: equivalent dose to the thyroid 23 mSv and effective dose 1 mSv.

3.3.2 ICRP 78 and inhalation dose coefficients

A second method is to use the data provided by ICRP in Publication 78 (ICRP, 1997). Table A.6.17 is this publication gives values of the fraction of inhaled activity retained in the thyroid at different times after intake. Three days after intake this fraction is 0.11, which gives an inhaled activity of 106 kBq. Using the inhalation dose coefficients (ICRP, 1995): 0.15 mSv/kBq for equivalent dose and 0.0074 mSv/kBq for effective dose (AMAD 1 μm and absorption type F), together with the calculated intake will slightly underestimate the correct doses. The calculation yields: equivalent dose to the thyroid 16 mSv and effective dose 0.8 mSv.

However, using the retention factor for AMAD 1 μm and absorption type F, which is 0.079, will yield 22 mSv and 1 mSv, respectively.

In this case it is also possible to use a conservative approach, using dose coefficients for elemental iodine, which are 0,39 mSv/kBq and 0,02 mSv/kBq, respectively (ICRP, 1995). The equivalent dose will then be 41 mSv and the effective dose 2 mSv.

3.3.3 Medical Internal Radiation Dose, MIRD S-values

An approximation of the thyroid equivalent dose can be found by applying the MIRD-formalism to calculate the mean absorbed dose to the thyroid from activity in the thyroid. With this method the S-value for the irradiation situation is multiplied by the total number of decays in the thyroid, which is found by integrating the single exponential using the effective half-life of ^{131}I.

The initial activity in the thyroid was calculated as described in section 3.3.1. However, when using the MIRD-approach we do not need to account for the 30% uptake in the thyroid and the initial activity will be 15.5 kBq. Integrating the decay function to infinity and using an S-value $S_{\text{thyroid}\leftarrow\text{thyroid}} = 1.57\cdot10^{-3}$ mGy MBq^{-1} s^{-1}, yields

$$\bar{D} = \tilde{A} \cdot S = \frac{A \cdot T_{½,\text{eff}}}{\ln 2} S = \frac{15.5 \cdot 10^{-3} \cdot 7.36 \cdot 24 \cdot 3600}{\ln 2} \cdot 1.57 \cdot 10^{-3} = 22 \text{ mGy} \qquad (11)$$

Since the radiation weighting factor, w_R, for beta-particles and photons equals 1, the equivalent dose is then equal to 22 mSv, in good agreement with the IMBA calculations.

4. Results of calibrations

A report template in an Excel spreadsheet was distributed, where all calculations were automatized. Apart from count-rates and times, participants had to enter the date of calibration for source decay correction and an estimate of the geometry uncertainty to account for the reproducibility of the phantom positioning and orientation. The mock activity was given as the sum of ^{133}Ba and ^{137}Cs activities at the date of calibration.

The participants reported calibration factors without correction for measurement of ^{131}I (F_{mock}= 1). The mock correction was applied afterwards based on the ROI used and information provided on the instrument's relative detection efficiency, see Appendix A. In Table 5, the calibration factors as reported by participants are presented. The reports from NRPA, though, were corrected and they can be used for directly determining the activity of ^{131}I based on mock calibrations.

Many of the gamma cameras were calibrated without removing the collimator, which means a longer distance source-detector and different attenuation conditions. In Table 5, this is specified with "collimator" in the column for instrument/measurement conditions.

The circulation order for the calibration phantom was Sweden, Denmark, Norway, Finland and Iceland.

Table 5: Reports of calibration factors F_{cal} without correction (that is for $F_{\mathrm{mock}} = 1$) for Child, Young and Adult, in units of $\left[\frac{\mathrm{Bq \cdot s}}{\mathrm{c}}\right]$ for spectrometers and count rate meters and in $\left[\frac{\mathrm{Bq \cdot h}}{\mu\mathrm{Sv}}\right]$ for dose rate meters. The distance is measured from detector or collimator front end, unless otherwise stated.

Site	Instrument/ measurement conditions	Instrument Type	Child 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Young 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Adult 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm
Nukleär medicin, Gävle sjukhus	Theo 10 (NaI 2x2) collimator, distances + 177 mm	portable spectrometer	537 1383	2.4 2.5	608 1487	2.5 2.3	750 1729	2.4 2.3
Bildmedicin Dalarna, Falulasarett	Atomlab 950 (NaI 2x2) collimator, distances +155 mm	portable spectrometer	486 1241	2.8 2.5	533 1231	2.3 3.2	677 1394	2.3 2.7
Radiofysiska laboratoriet, Norrlands universitets sjukhus, Umeå	HPGE	spectrometer	62 549	1.8 2.0	77 624	1.8 1.9	164 782	1.8 1.8
	SCA ratemeter (NaI)	portable count rate meter	- 1669	- 3.2	- 1770	- 2.7	- 2026	- 2.4
	Inspector 1000	portable count rate meter	21 345	2.2 5.1	31 419	2.1 4.5	55 435	2.1 3.5
	Berthold LB124	portable count rate meter	41 259	2.4 4.5	57 239	2.3 3.6	74 407	2.1 3.4
	Victoreen	portable count rate meter	20 259	2.1 4.5	28 305	2.1 3.9	55 407	2.1 3.4
Radiologisk fysik, Hallands sjukhus Halmstad	Theo 10 (NaI 2x2)	portable spectrometer	386 986	3.1 3.5	431 1127	2.9 3.3	512 1259	2.0 2.3
Lund University, SUS Malmö	Bicron 5H4Q (NaI Ø12.7 cm, h10.2 cm)	portable spectrometer	7 35	3.5 3.5	8 38.6	1.8 3.5	11 49	1.8 1.8
Medicinsk fysik Centrallasarettet, Växjö	Theo 10 (NaI 2x2)	stationary count rate meter	336 934	8.3 8.4	397 1037	8.2 8.3	487 1173	1.9 2.1
Radiofysik, IMH, Linköpings Universitetssjukhuset	Exploranium GR135	portable spectrometer	57 376	- -	82 313	- -	126 -	1.8 -
	Theo 10 (NaI 2x2)	portable spectrometer	539 1010	- -	1089 -		1210 -	1.8
	Infinia Hawkeye	gamma camera	- -	- -	65348 -	6 -	65348 -	6 -
Ringhals nuclear site, Väröbacka	Identifinder	portable dose rate meter *	15843 182349	- -	20622 188550	- -	35634 222892	- -
	LaBr 38S38/2/B380 Q665	stationary spectrometer	48 731	3.5 3.6	69 948	3.5 3.6	133 1048	1.8 1.9

* Calibration factors for dose rate meters are in units of $\left[\frac{\mathrm{Bq \cdot h}}{\mu\mathrm{Sv}}\right]$

(Continued)

Table 5 (continued): Calibration factors F_{cal} (for $F_{\mathrm{mock}} = 1$)

Site	Instrument/ measurement conditions	Instrument Type	Child 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Young 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Adult 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm
Medicinsk fysik, Sahlgrenska universitets sjukhuset, Göteborg	Captus 3000 S/N: CNV-536	stationary spectrometer	7 6	1.9 1.8	8 17	1.8 1.8	9 19	1.8 1.8
Radionuklid centralen, Lundssjukhus, Lund	Theo 10 (NaI 2x2)	portable spectrometer	474 1202	5.6 5.9	545 1416	5.5 5.7	234 1693	1.9 2.5
Universitetssjukhuset, Örebro	Ratemeter NaI-based	stationary count rate meter	130 320	2.0 2.2	143 325	1.9 2.1	130 296	1.8 1.9
Nukl. Med. Afd., Aalborg Univ. Hosp., Aalborg	Mini 900, GM ø 3.5 cm (dekontamineringskasse)	portable count rate meter	2607 101661	10.4 36.1	165 82249	10.2 10.2	8203 79980	10.4 12.9
	Mini 900, GM ø 5.5 cm (injektionsrum)	portable count rate meter	2118 25415	10.6 19.1	2136 32899	10.5 22.4	4705 26660	10.4 12.9
	Mini 900, GM ø 5.5 cm (sterillaboratorium)	portable count rate meter	1517 14523	10.6 15.0	2136 27416	10.5 18.0	4101 45703	10.4 15.0
	RDS-120 (afhentningsrum)	portable dose rate meter *	29046 -	30.9 -	37386 -	53.8 -	58167 -	46.4 -
	Mini 900, NaI ø 3.5 cm (injektionsrum)	portable dose rate meter *	9 145	5.4 6.0	15 164	5.3 5.8	29 195	5.3 5.6
	Mini 900, NaI ø 3.5 cm (analyselab)	portable count rate meter	6 120	5.4 7.6	9 157	5.4 7.1	19 1194	10.4 6.4
	MicroCont (Herfurth) large area gas detector (injektionsrum)	portable count rate meter	34 141	5.7 6.9	41 166	5.5 6.4	55 208	5.5 6.0
Nuclear Medicine & PET-Centre, Aarhus Univ. Hospital, Aarhus	Picker Axis, collimator	gamma camera	14686 28748	20.1 39.0	18642 25030	16.1 21.3	19065 24747	8.8 11.2
	Siemens Symbia T16, collimator	gamma camera	- 45823	- 36.0	- 37930	- 19.0	34999 48068	9.6 12.8
	Mediso TH-45, collimator	gamma camera	- 16561	- 18.8	- 24654	- 17.4	25988 34127	9.9 12.7
	Mini 900, 41	portable count rate meter	52 423	3.0 8.1	70 483	2.8 6.6	153 652	2.9 5.3
	Mini 900, 42B	portable count rate meter	37 462	2.7 7.8	55 514	2.6 6.3	124 680	2.7 5.2

* Calibration factors for dose rate meters are in units of $\left[\frac{\mathrm{Bq \cdot h}}{\mu\mathrm{Sv}}\right]$

(Continued)

Table 5 (continued): Calibration factors F_{cal} (for $F_{\mathrm{mock}} = 1$)

Site	Instrument/ measurement conditions	Instrument Type	Child 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Young 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Adult 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm
Bispebjerg Hosp. KFNM, rum 9. Bispebjerg, Copenhagen	Mini 900, 41	portable count rate meter	47 390	7.2 22.5	77 607	7.3 22.6	131 580	6.8 14.8
	RDS-120 (Rados)	portable dose rate meter *	23023 92092	30.5 76.1	34151 44305	29.0 33.9	69307 212541	29.8 60.9
	Bertholt LB 124 (without protection plate)	portable count rate meter	20 156	1.9 2.6	25 172	1.8 2.3	37 218	1.8 2.1
	PDS-100 G/ID (Mirion), CsI(Tl)	portable count rate meter	29 289	3.2 12.1	41 349	3.0 9.6	69 398	2.8 6.6
	Captus 2000	stationary spectrometer	691 1427	4.0 5.8	721 1518	3.3 4.8	855 1768	2.8 3.7
	Siemens Symbia T16	gamma camera	170 190	2.1 2.1	186 211	1.9 1.9	202 231	1.8 1.9
	Phillips Precedence, collimator LEGP	gamma camera	179 223	2.1 2.2	193 242	1.9 2.0	211 273	1.8 1.9
	Thyrus	gamma camera	1058 2280	3.3 5.5	1124 2577	2.7 4.2	1336 2869	2.3 3.0
Klinisk Fysiologisk & NM Afd., Glostrup	GE infinia	gamma camera	7 11	3.5 3.5	8 13	3.5 3.5	8 15	3.5 3.5
	GE Discovery	gamma camera	12 21	3.5 3.5	13 25	3.5 3.5	15 29	3.5 3.5
	Mediso	gamma camera	18 50	3.5 3.5	21 58	3.5 3.5	26 71	3.5 3.5
	CoMo 170	portable count rate meter	82 432	3.5 3.5	103 609	3.5 3.5	128 806	3.5 3.6
Dep. Clinical Physiology, Herlev **	Mediso TH-33, collimator LEGP	gamma camera	330 651	2.0 2.3	345 704	1.9 2.0	397 819	1.8 1.9
	Philips Skylight, collimator LEGP	gamma camera	260 -	2.2	- -	- -	275 -	1.8 -
	Philips Precedence (17), collimator HEGP	gamma camera	- 46237	- 86.8	42501 52755	49.5 61.3	40974 33048	24.8 20.1
	Philips Precedence (18), collimator HEGP	gamma camera	34448 12733	64.0 24.0	22110 -	25.7 -	25650 68955	15.6 40.9
Nuclear Medicine, Herning	Philips Brightview, collimator LEHR	gamma camera	67 64	33.7 33.7	61 76	33.6 33.6	61 77	33.6 33.6
Klinisk Fysiologisk og NM, Hillerød	Philips Brightview XCT	gamma camera	115 126	10.2 10.2	129 136	10.2 10.2	327 138	10.2 10.2

* Calibration factors for dose rate meters are in units of $\left[\frac{\mathrm{Bq \cdot h}}{\mu \mathrm{Sv}}\right]$

** Geometry uncertainty in Herlev site was set to zero

(Continued)

Table 5 (continued): Calibration factors F_{cal} (for $F_{\mathrm{mock}} = 1$)

Site	Instrument/ measurement conditions	Instrument Type	Child 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Young 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Adult 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm
Klin Fys Nukl. Med Afd, Køge	MicroCont II (Rados/Mirion) nr. 875	portable dose rate meter *	38 166	35.1 35.1	47 188	35.1 35.1	63 232	35.0 35.1
	MicroCont II (Rados/Mirion) nr. 435	portable dose rate meter *	35 142	35.1 35.1	42 169	35.1 35.1	56 218	35.0 35.1
	Bertholt LB 124	portable count rate meter	42 243	35.1 35.1	46 285	35.1 35.1	67 322	35.1 35.1
	Mediso TH33	gamma camera	- 481	- 49.5	254 538	35.1 35.1	300 670	35.0 35.1
	Siemens Spect CT Symbia	gamma camera	191 252	35.1 35.1	199 255	35.1 35.1	210 269	35.0 35.1
Nuklearmed. Afd.Næstved	Siemens Symbia S T16	gamma camera	15 29	5.3 5.3	17 35	5.3 5.3	18 36	5.3 5.3
	Siemens Symbia T16	gamma camera	16 32	5.3 5.3	18 35	5.3 5.3	20 38	5.3 5.3
	Siemens Symbia T16	gamma camera	16 31	5.3 5.3	18 35	5.3 5.3	19 36	5.3 5.3
NM/PET Rigshospitalet	Berthold LB 124	portable count rate meter	26 181	3.4 3.7	32 198	3.4 3.6	48 266	3.4 3.5
	Phillips Precedence rum 16, collimator LEGP	gamma camera	- -	- -	- -	- -	221.56 420.30	- 3.5
	Phillips Precedence rum 16, collimator high LEGP	gamma camera	- -	- -	- -	- -	886.15 2614.95	- 4.4
	DDD Solomobile, collimator LEHR	gamma camera	151 333	4.0 4.5	154 366	3.8 4.2	185 402	3.7 3.8
	Mediso TH45 collimator LEGP	gamma camera	217 385	3.8 4.1	244 427	3.7 3.7	271 495	3.5 3.7
	Philips Precedence rum 16, collimator main + high LEGP	gamma camera	162 284	3.6 3.8	171 307	3.6 3.7	197 362	3.4 3.5
	Mediso TH45	gamma camera	19 60	3.5 3.6	21 69	3.4 3.5	26 83	3.4 3.5
	Inspector 1000	portable dose rate meter *	29209 -	23.2 -	40269 -	21.3 -	72915 -	20.5 -
	RDS-200	portable dose rate meter *	27992 -	11.2 -	35454 -	9.8 -	51997 -	8.6 -
SIS, Knapholm Herlev	Thermo FHZ 502P NaI (sn 0842)	portable count rate meter	13 93	5.3 5.4	17 102	5.3 5.4	24 118	5.3 5.4
	Thermo FHZ 502P NaI (sn 0838)	portable count rate meter	14 91	5.3 5.4	17 101	5.3 5.4	24 113	5.3 5.4
	Thermo FHZ 502P NaI (sn 0837)	portable count rate meter	14 93	5.3 5.4	17 104	5.3 5.4	25 120	5.3 5.4

* Calibration factors for dose rate meters are in units of $\left[\frac{\mathrm{Bq \cdot h}}{\mu \mathrm{Sv}}\right]$

(Continued)

Table 5 (continued): Calibration factors F_{cal} (for $F_{\mathrm{mock}} = 1$)

Site	Instrument/ measurement conditions	Instrument Type	Child 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Young 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Adult 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm
SIS, Knapholm Herlev	RadEye B20 GM Open (sn 0367)	portable count rate meter	- -	- -	1656 22881	5.8 14.1	3320 23558	5.8 9.5
	Bicron Analyst, NaI Mini 5-44A (sn 1032)	portable count rate meter	9.1 141	6.8 7.6	15 166	6.8 21.3	30 221	6.8 13.1
Vejle	Mini 900, NaI	portable count rate meter	41 419	5.5 6.8	61 452	5.4 6.3	123 597	5.4 5.9
	CoMo 170	portable count rate meter	60 372	5.5 7.1	64 387	5.4 6.3	99 502	5.4 5.9
	MicroCont II RXE 260/10 (Rados/Mirion)	portable count rate meter	53 214	5.5 6.3	58 201	5.4 5.8	74 249	5.4 5.6
	Thermo Scientific, INTERCEPTOR™	portable count rate meter	82 913	5.5 9.3	106 1161	5.4 8.3	176 1265	5.5 6.8
	Philips Precedence, collimator	gamma camera	134 117	5.4 5.4	108 141	5.3 5.3	120 164	5.3 5.3
	Philips Skylight 21, collimator	gamma camera	106 139	5.4 5.4	120 163	5.3 5.3	133 183	5.3 5.3
	Philips Skylight 16, collimator	gamma camera	122 150	5.4 5.4	140 177	5.3 5.4	153 204	5.3 5.3
Klinisk Fyslogisk Afd; Regionshospitalet Viborg	Siemens Symbia T16, collimator MELP	gamma camera	7229 10517	11.7 13.1	7382 10856	11.0 11.6	8333 11661	10.5 10.7
	Siemens Symbia T2, collimator HE	gamma camera	17975 50904	15.8 35.1	29439 28833	16.2 15.9	30800 42087	12.5 14.0
	Thyrus ADAC, collimator LEHR	gamma camera	680 1331	10.2 10.4	738 1483	10.2 10.3	847 1668	10.2 10.2
	Siemens Symbia T16	gamma camera	17 73	10.2 10.2	20 85	10.2 10.2	27 100	10.2 10.2
	RDS-200	portable dose rate meter *	- -	- -	- -	- -	- 453943	- -
	CoMo170, GM, collimator	portable dose rate meter *	- 336532	- -	- 1633856	- -	- 1059197	- -
	CoMo170, NaI, collimator	portable dose rate meter §	- 109	- -	- 96	- -	- 101	- -
	CoMo170, NaI	portable dose rate meter §	- 57	- -	- 71	- -	- 81	- -
NRPA ***	Canberra Inspector 1000 NaI 3x3	stationary spectrometer	14 117	5.3 5.4	18 133	5.3 5.4	31 183	5.3 5.3
	Canberra Inspector 1000 LaBr 1,5x1,5	stationary spectrometer	73 702	5.4 5.5	107 779	5.4 5.5	183 1009	5.4 5.4
	HPGe Mobil lab. p-type, 35 % rel eff	stationary spectrometer	27 244	5.3 5.3	36 292	5.3 5.3	71 378	5.3 5.3

* Calibration factors for dose rate meters are in units of $\left[\frac{\mathrm{Bq \cdot h}}{\mu\mathrm{Sv}}\right]$

§ Calibration factors for dose rate meters are in units of $\left[\frac{\mathrm{Bq \cdot h}}{\mathrm{nSv}}\right]$

*** NRPA's calibration factors are corrected ($F_{\mathrm{mock}} \neq 1$)

(Continued)

Table 5 (continued): Calibration factors F_{cal} (for $F_{\mathrm{mock}} = 1$)

Site	Instrument/ measurement conditions	Instrument Type	Child 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Young 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm	Adult 0 cm 10 cm	U_r 1σ (%) 0 cm 10 cm
NRPA ***	Canberra uniSPEC NaI 3x3	stationary spectrometer	16 129	5.3 5.4	21 156	5.3 5.3	35 202	5.3 5.3
IFE Kjeller	6150 Automess AD-b	portable dose rate meter *	21824 -	5.4 -	27432 -	5.5 -	44681 -	5.4 -
	Ortec, digiBASE NaI 3x3	Stationary spectrometer	- 185	- 5.3	- 220	- 5.3	- 276	- 5.3
IFE Halden	"det02" NaI 3x3	spectrometer	22 423	2.1 2.3	26 521	2.0 2.2	43 554	2.0 2.1
STUK	HPGe mobile lab n-type 80% Ortec	stationary spectrometer	6.47 66.19	5.3 5.3	8.17 66.25	5.3 5.3	12.27 72.56	5.3 5.3
GR, Reykjavík	HPGe p-type 16% Ortec	portable spectrometer	73.70 759.92	1.9 2.2	100.63 896.63	1.8 2.0	179.35 1140.57	1.8 1.9
Landspitali, Isotope Dept. Reykjavík	Canberra Uptake counter	stationary count rate meter	- 685.67	- 6.4	- 714.18	- 6.0	- 894.68	- 5.8
Landspitali, Science Dept. Reykjavík	NaI diam 8.7 cm; 256 channels spectrum analyser	stationary spectrometer	7.25 33.55	4.4 4.4	8.45 36.39	4.4 4.4	10.85 49.40	1.8 1.8

* Calibration factors for dose rate meters are in units of $\left[\frac{\mathrm{Bq \cdot h}}{\mu \mathrm{Sv}}\right]$.

*** NRPA's calibration factors are corrected ($F_{\mathrm{mock}} \neq 1$)

5. Results of the verification exercise

5.1 Reported mock activity compared to certified value

The verification measurement could be performed with the phantom either 0 or 10 cm away from the detector. In any case, also for the instruments with collimators, the setup for verification measurement was reproducing the calibration setup.

Some calibrated instruments were not verified. The reason was that they were considered not sensitive enough for the purpose of thyroid screening. Some participants or instruments at the same site took part in the verification only. They used established calibrations in these cases. That is the case of Studsvik Nuclear AB in Sweden, one spectrometer at the whole body counter registered by Ringhals Nuclear in Sweden and one spectrometer at IFE Kjeller in Norway, for example.

Figure 6 and 7 contain the reports for mock activity measured with the phantom and detector in close contact, and with a distance of 10 cm between phantom and detector, respectively, and corrected to the common date 2013-08-01. Many of the measurements were performed only at the distance of 10 cm, that's why Figure 7 contains more instruments than Figure 6. The points without uncertainty bars correspond to values that were reported without uncertainty estimation. The range within 3 sigma of the certified value lies in the interval 11-13 kBq, which is marked with a grey band in Figures 6 and 7.

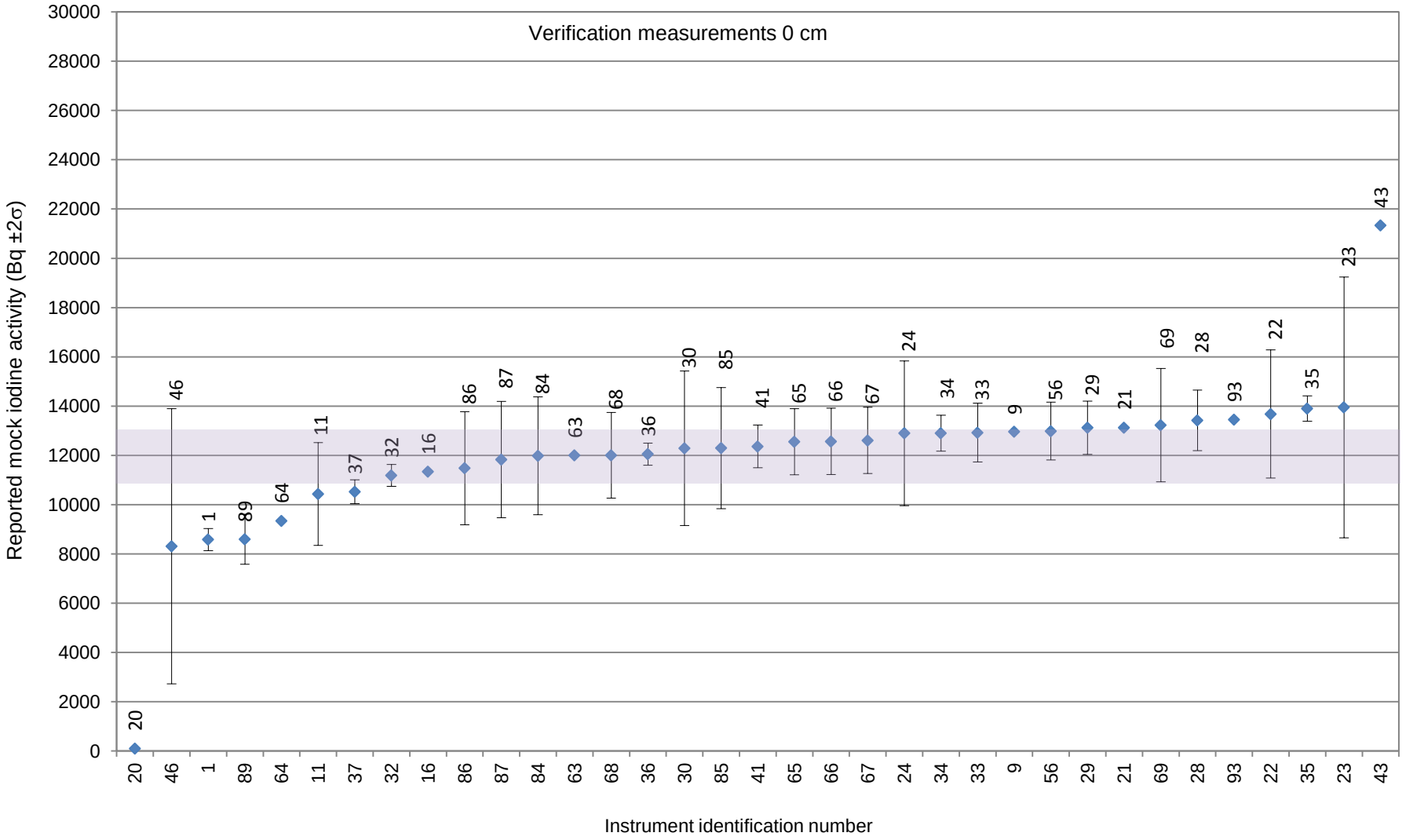


Figure 6: Mock activities reported for the verification measurement at close geometry (± 2σ). Shown activities are adjusted to certificate reference date. Acceptable values are in the range 11 000–13 000 Bq.

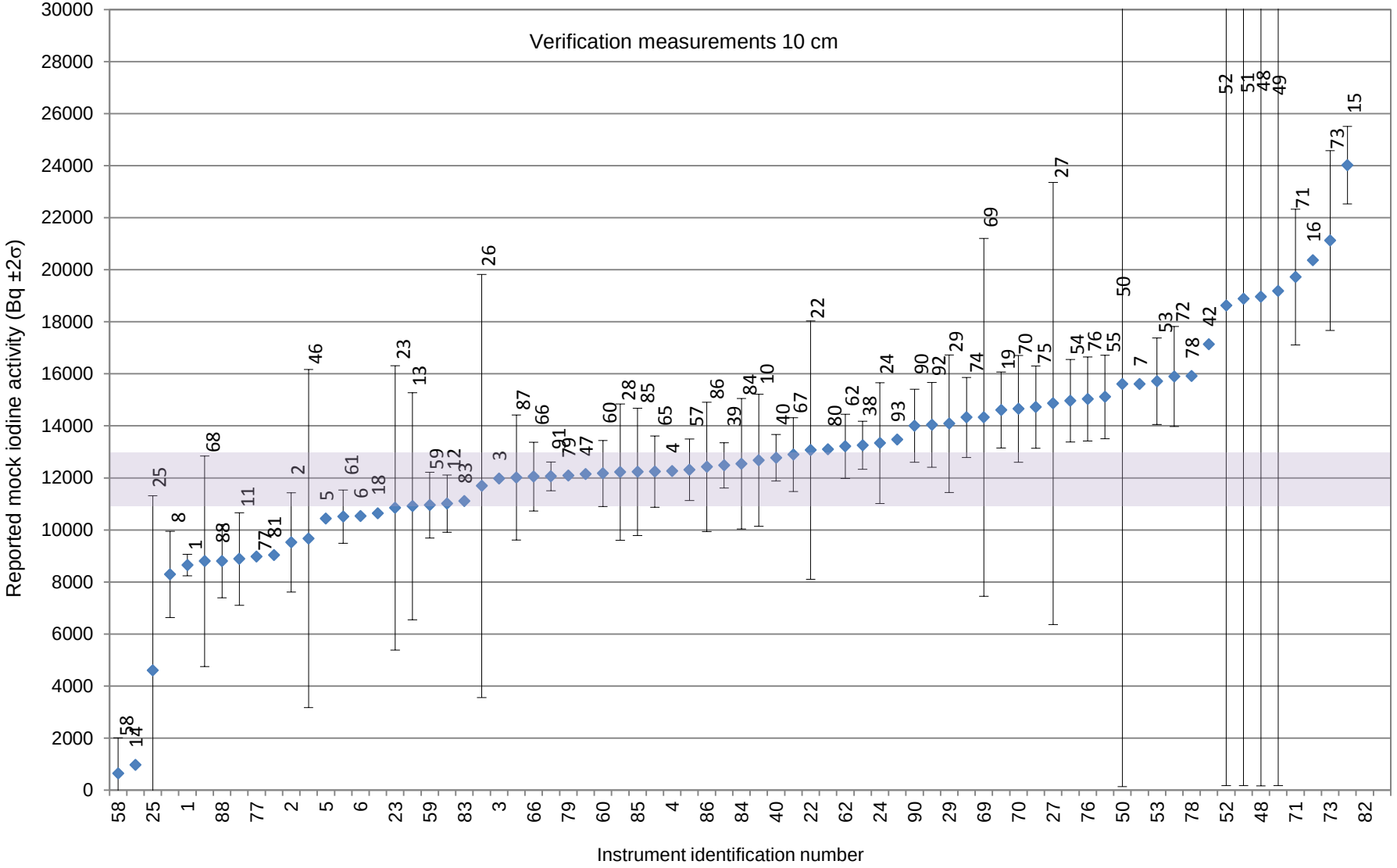


Figure 7 Mock activities reported for the verification measurement with the instrument at a distance of 10 cm from the phantom (± 2σ). Shown activities are adjusted to certificate reference date. Acceptable values are in the range 11 000–13 000 Bq.

5.2 MDAs at verification measurement

A summary view of the reports on minimum detectable activities is presented in Table 6 for the close geometry measurement. The MDAs are expressed in terms of mock activity. The entry for the table is the type of instrument with the list is sorted from the lowest to the highest MDA values, that is, with the most suitable instruments for an accurate quantification in the first rows and falling down to less suitable.

It should be kept in mind that the measured background level and counting-time directly affects the MDA. Therefore, the list in Table 6 does not represent a ranking of instruments sensitivity but rather the overall performance of the measurement setup. Instruments with MDA values above 1 kBq are, in general, not suitable for quantification but they can in emergency be used as screening tools for supporting triage of large groups.

Table 6: MDAs reports for the verification measurements at the close geometry

Instrument type	Instrument	MDA 0 cm
stationary spectrometer	NaI detectors 3" – 5", uniSPEC, Inspector, 5H4Q/5SS-X	2 – 7
spectrometer	HPGe detectors p-type 16 – 35 % rel.eff. , MCA	5 – 15
spectrometer in mobile lab	HPGE 80% n-type	14
gamma camera	Symbia T16 SPECT/CT without collimator	10 – 40
portable count rate meter	Berthold LB124 Ratemeter	14 – 50
portable spectrometer	Exploranium GR-135 (^{133}Ba)	58 – 70
portable count rate meter	Thermo FHZ 502P	58 – 70
stationary spectrometer	LaBr detector 1,5x1,5 Canberra	80
uptake meter (portable count rate meter/spectrometer)	Theo 10 NaI, 2x2"	87 – 120
uptake meter (portable count rate meter/spectrometer)	MED, CoMo 170	93 – 118
gamma camera	Philips Skylight 21 collimator	148 – 300
portable dose rate meter(*)	MicroCount RXE	182 – 230
gamma camera	Philips Brightview XCT or with collimator LEHR	196 – 220
portable count rate meter	Victoreen Ratemeter	220
gamma camera	Symbia T16 with collimators	234 – 280
gamma camera	Phillips Precedence collimator LEGP	190 – 265
gamma camera	Thyrus ADAC LEHR collimator	322 – 700
portable count rate meter	Mini Monitor Type 41, 42 and 42B	352 – 600
gamma camera	Mediso TH45 LEGP collimator	511 – 1040
stationary spectrometer	Captus 2000	532

portable count rate meter	PDS-100 G/ID	740
gamma camera	DDD Solomobile LEHR collimator	896
portable count rate meter	Mini Monitor series 900	1800 – 1850
gamma camera	Symbia T16 SPECT/CT MELP-collimator	1892 – 3000
portable dose rate meter	Rados 200	3000 – 4274
gamma camera	Picker Axis	8592
portable dose rate meter	Inspector 1000	8689
portable dose rate meter	Rados-RDS 120	19494

5.3 Reported thyroid doses compared to best estimate

The spread of reported thyroid equivalent doses is shown in Figure 8. The best estimate for the thyroid equivalent dose is 22 mSv as described in sections 3.3.1, 3.3.2 and 3.3.3. The results in between 18 – 24 mSv are therefore considered correct. The reports below 6 mSv and over 60 mSv are definitely outliers.

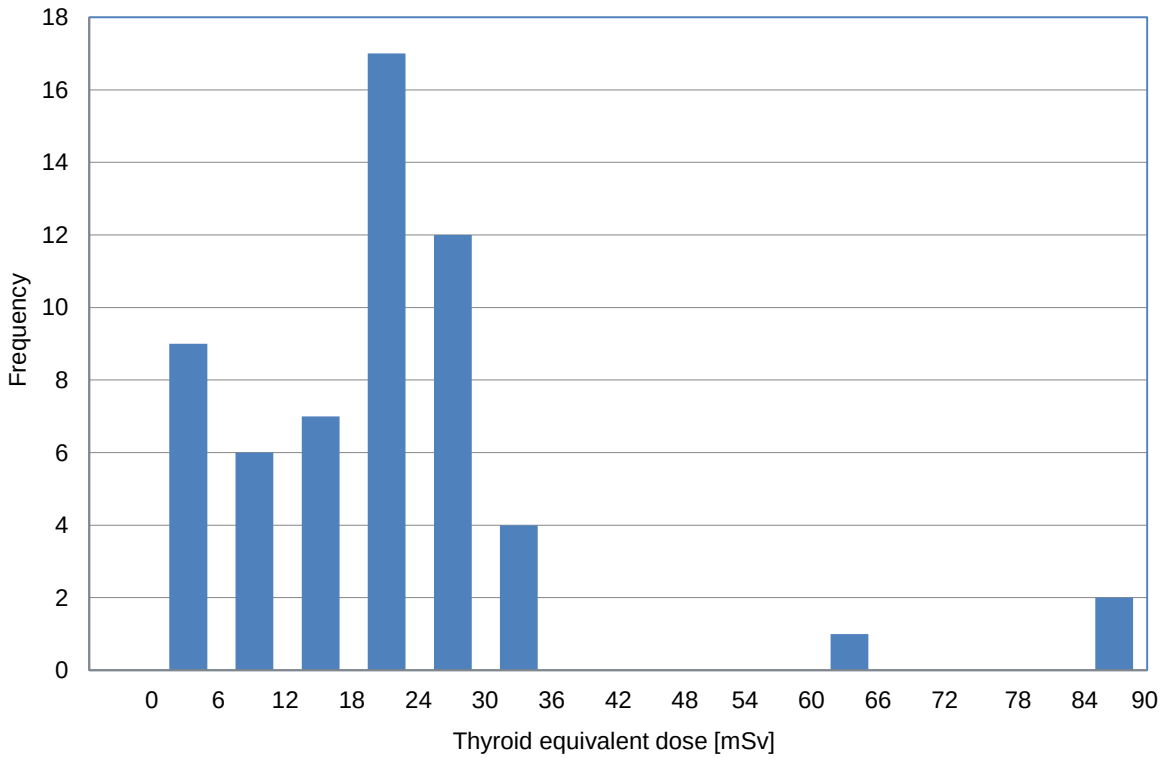


Figure 8 The values of thyroid equivalent dose reported are spread between 0.2 and 89 mSv with 17 reports out of 57 in the range 18 – 24 mSv.

5.4 Mock-corrected calibration factors for the determination of ^{131}I at close geometry for frequent instruments in Scandinavia

In Table 7 below, a selection of mock-corrected calibration factors is presented. These calibration factors may be readily used for determination of ^{131}I activity at close geometry (detector in contact with front of the neck), as shown in Figure 9.

The activity of ^{131}I is determined as $A^{I131} = (S_g - S_b) \cdot F_{\text{cal}}$, as in Equation (9). The gross count is the reading of the instrument when measuring at towards the thyroid glands (front of neck) while the background reading can be taken as a measurement towards the person's thigh; see Figure 9 (Rojas-Palma C. et al, 2009).

Figure 9: Illustration for thyroid and corresponding background measurement, as recommended in TMT handbook (Rojas-Palma et al., 2009)

Table 7: Calibration factors in units of $\left[\frac{\text{Bq}\cdot\text{s}}{\text{c}}\right]$ for estimating ^{131}I at "close" geometry (0 cm). $A^{\text{I}131} = (S_g - S_b) \cdot F_{cal}$.

Instrument type	Frequent models (Scandinavia 2013)	F_{cal}		
		Child	Young	Adult
stationary spectrometer	NaI 3x3 any electronic model	15 ± 1	18 ± 2	31 ± 2
spectrometer	HPGE 16 % any electronic model	64 ± 5	88 ± 6	156 ± 6
portable count rate meter	Berthold LB 124, Mini 900 NaI ø 3.5, MicroCont Herfurth, Victoreen, Inspector 1000, Thermo FHZ	25 ± 2	32 ± 3	48 ± 3
portable count rate meter	CoMo 170	82 ± 8	103 ± 8	128 ± 8
portable count rate meter	Mini 900, 41	140 ± 12	189 ± 15	413 ± 22
portable dose rate meter *	Inspector 1000	29209 ± 2200	40269 ± 2600	72915 ± 2600
gamma camera (no collimator)	GE Discovery, Siemens Symbia T16, Mediso, Mediso TH45	13 ± 1	18 ± 2	25 ± 2
gamma camera	DDD Solomobile, collimator LEHR	151 ± 12	154 ± 10	185 ± 10
gamma camera	Mediso TH45 collimator LEGP	217 ± 18	244 ± 18	271 ± 18
gamma camera	Phillips Precedence, collimator LEGP	161 ± 16	174 ± 15	190 ± 15
stationary count rate meter (uptake meter)	Theo 10 (NaI 2x2)	255 ± 16	302 ± 18	370 ± 20

* Calibration factors for dose rate meters are in units of $\left[\frac{\text{Bq}\cdot\text{h}}{\mu\text{Sv}}\right]$

6. Discussion

Calibrations were performed for most of the instruments initially registered in the project. The obtained calibration factors were validated through the verification exercise, which showed an overall satisfying performance (overlapping confidence intervals – 2σ of measured versus certified activity) of the majority of calibrations.

For the "close" (0 cm) geometry 27 out of 37 reported activities were satisfying while for the "far" (10 cm) geometry it was 46 out of 76 reported. Some reported measurements were considered non-satisfactory because no or zero uncertainty was stated. Other measurements on the other hand were reported with uncertainties exceeding 50 % (2σ), which renders these instruments less useful for screening purposes despite the interval overlap. Taking the variation in uncertainty into account, the overall picture favors measurements at 0 cm rather than 10 cm – the reason for this being unknown.

For the non-satisfying results, the uncertainty of the measurements must be expanded to achieve valid calibration factors and then reevaluated with regard to acceptable level of uncertainty (e.g. 50 %).

The estimation of thyroid dose was a challenge since at most of the sites this capability is not in use and/or continuously trained. Only 17 reports out of 57 were within the acceptable range, which highlights the need for a regional effort to raise competence in internal dose estimation.

Application of the mock-correction is relevant for integrating instruments where gamma energies are not discriminated (mostly handheld ratemeters). As shown in appendix A, the factors are typically in the range of 2-3, depending on the detector energy response. For NaI crystals larger than 1", plastic scintillators and some GM tubes, the detector response has little influence and a default mock correction factor of 3 can be used to assure overestimation rather than underestimation of ^{131}I activity. NaI crystals smaller than 1" require a progressively greater correction factor, with an increase to as much as 7-8 for a 2,5 mm thick crystal (e.g. Mini 900 – 44A). In general, spectrometers for which an energy-window (ROI) from 100-1000 keV was selected or centered around 365 keV (+/- 25%) don't need mock correction.

In the case of a nuclear emergency in the Nordic countries, a thyroid monitoring programme should be initiated if the air concentration of ^{131}I exceeds 1000 Bq/m^3 for more than two days (NEP, 2013). At this air concentration, 36 kBq would be inhaled per day with an assumed rate of inhalation of 10 liters per minute. Up to 6.2 kBq will be accumulated in the thyroid during a two-day exposure. Using the IMBA parameters inhalation, light worker, 1 µm AMAD (Birchall, 2003) gives an equivalent dose of 11 mSv and an effective dose of 0.55 mSv. Instruments to be used for this purpose must therefore be able to detect thyroid activities of approximately 1 kBq. Of the reported detection-limits (MDA), 60 out of 72 were below 1 kBq at 0 cm and 46 out of 68 at 10 cm. If the mock correction is applied (MDA multiplied by 3), it will be 47 out of 72 at 0 cm and 29 out of 68 at 10 cm.

7. Conclusions

The activity THYROID mobilized a considerable number of sites within the Nordic countries to take part of the calibration effort. A total of 38 sites were identified holding equipment usable for screening for thyroid ^{131}I contamination. Of those 34 sites received the calibration sources and delivered results for the activity. Because of time constrains four sites were left out of the circulation in Sweden and therefore are not listed in this report. The plans are to complete the circulation in Sweden outside the framework of the THYROID activity. Among those pending Swedish sites are FOI Umeå, Oskarshamn NPP, SSM and Sundsvall County Hospital

In total, 93 instruments were calibrated. The harmonized calibration effort provides a common Nordic traceability chain, which will facilitate to evaluate the impact of exposure on

large groups and subsequent risk analysis. Up to 50 instruments in the Nordic countries have been calibrated and verified during the project. The results of this activity show that another ca. 50 instruments are available but need verification or review of their calibration. The optimal measuring geometry is the “close” setup (0 cm).

Different instrument types can be used in an emergency situation as long as they are properly calibrated. The need for dose assessment training has been identified. The activity THYROID has identified the instruments “ready” to be used in prompt thyroid monitoring and provided the calibration factors to be used for some frequent instruments.

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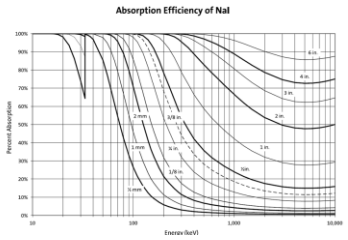
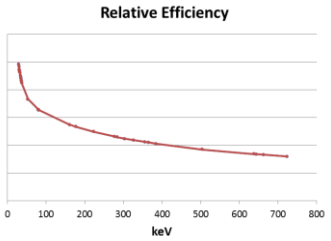
Appendix A. Mock corrections and energy responses for different detector types

Instrument	Energy response	ROI [keV]	Mock Correction Factors			U_r (% 2σ)
			Child	Young	Adult	
"Ideal" detector, generic	"Flat"	(all)	2.27	2.22	2.22	6
		50-1000	1.30	1.29	1.29	6
		100-1000	0.99	0.99	0.99	6
		350-360 [a]	0.69	0.67	0.67	6
		365 ± 15%	0.79	0.76	0.76	6
		365 ± 20%	0.99	0.96	0.96	6
		365 ± 25%	1.00	0.96	0.96	6
	+ 0.05 cm Al [b]	(all)	2.15	2.11	2.11	6
	+ 2 cm PE [b]	(all)	2.00	1.97	1.97	6
NaI scintillator, generic 	NaI, ½" μ/ρ	(all)	3.6	3.5	3.5	10
		50-1000	1.7	1.7	1.7	11
		100-1000	1.0	1.0	1.0	12
	NaI, 1" μ/ρ	(all)	2.8	2.7	2.7	10
		50-1000	1.5	1.4	1.4	11
		100-1000	1.0	1.0	1.0	12
	NaI, 2" μ/ρ	(all)	2.4	2.4	2.3	10
		50-1000	1.4	1.3	1.3	11
		100-1000	1.0	1.0	1.0	12
	NaI, 3" μ/ρ	(all)	2.3	2.3	2.3	10
		50-1000	1.3	1.3	1.3	11
		100-1000	1.0	1.0	1.0	12
Plastic scintillator, generic 	Vinyltoluene, 1 cm μ/ρ	0-1000	3.5	3.4	3.4	10
		50-1000	1.5	1.5	1.5	11
		100-1000	1.0	1.0	1.0	12

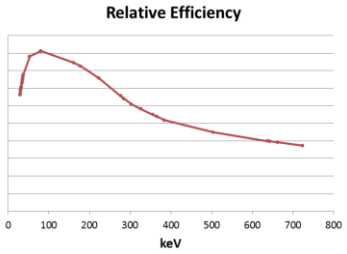
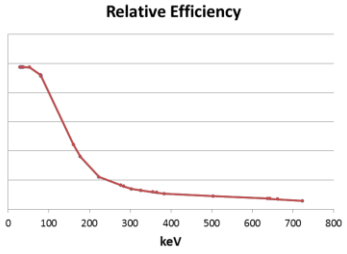
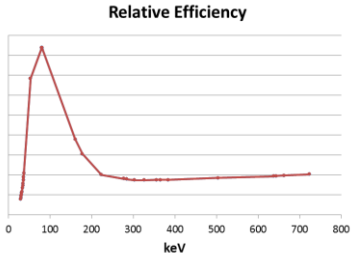
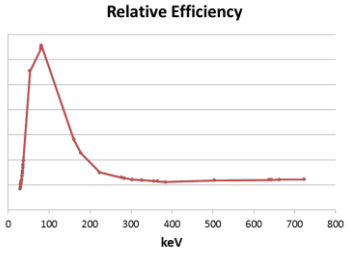
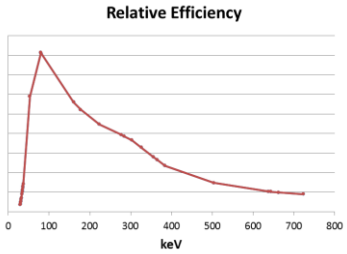
[a] Selection for ^{133}Ba 356 keV peak only.

[b] Absorber between source and detector. Attenuation only (build-up factor = 1).

μ/ρ Absorption calculated from linear mass attenuation coefficients (NIST).

continued

Appendix A (continued)

Instrument	Energy response	ROI [keV]	Mock Correction Factors			U_r (% 2σ)
			Child	Young	Adult	
Mini 900 - 41 	NaI, 19x25 mm	0-1000	2.8	2.7	2.7	11
Mini 900 - 44A 	NaI, 32x2.5 mm	0-1000	7.7	7.4	7.4	10
Mini 900 - LND7231 	GM, ø 26.8 mm	0-1000	§ 2.9	§ 2.8	§ 2.8	*30*
Mini 900 – LND7313 	GM, ø 44.5 mm	0-1000	§ 3.4	§ 3.3	§ 3.3	*30*
Thermo FHZ502 	NaI, 2”	0-1000	2.3	2.2	2.2	20

§ Converted from constant-dose energy response curve

Appendix B. Emergency scenario

The text below was sent out to the participating labs with the sources and phantoms.

A serious disaster, involving a sizeable release of radioactive materials including iodine isotopes, has occurred in a foreign nuclear power plant. The plant is in a faraway country and no significant contamination or health consequences are expected to reach your borders.

However, this country is a reasonably popular destination for travellers from your country. A large group of citizens from your country, who were staying in a city located in the trajectory of the radioactive plume have rushed to fill airplanes back home and will be arriving over the next few days.

Some of them have already arrived from the disaster area and are very concerned for themselves and their children regarding the contamination they have been exposed to by the inhalation of radioactive material. In response to this your government is asking your laboratory, among others, to perform thyroid measurements to these persons with the aim of assess their eventual contamination.

Three days after the disaster the first person to measure is already in your lab in the form of the set named "Adult neck phantom + test source", representing a 40 years old man, who landed earlier today.

Specifically on this first person, provide information on:

1. Activity and its measurement uncertainty (one sigma). Specify if you choose to answer based on measurement(s) done with an instrument (s) calibrated within this project and state which instrument (s). Otherwise, include details on the detector-system, measuring time, distance and applied calibration factor.

2. An assessment of the dose to thyroid if you have this capability.

3. Which dose assessment approach/tool is used?

4. Assuming that the value measured represents a mean value for the larger group of all travellers returning to your country, discuss the age-dependent risks attributable to the inhalation of radioactive ^{131}I.

5. Please add to your report all further comments or clarifications that you consider necessary to submit to your government.

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No. of references	22

Abstract

The need for quantifying the uptake of radioiodine (^{131}I) in thyroids in emergency situations has repeatedly been demonstrated. With early stage measurements people who may have inhaled or ingested amounts of ^{131}I can be identified and the need for more extensive measurements and/or subsequent medical assessment can be evaluated. The report presents the outcome from the activity THYROID in which calibrations of thyroid monitoring equipment in the Nordic countries were harmonized. A total of 38 sites in Scandinavia were identified holding equipment usable for screening for thyroid ^{131}I contamination. Different instrument types can be used in an emergency situation as long as they are properly calibrated. The activity enabled to evaluate the regional preparedness regarding thyroid personal monitoring.

Key words Thyroid dose, I-131, calibration, emergency preparedness

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