Master of Science Thesis

Investigation and calibration of various detection systems which can be used for emergency internal contamination checks

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Dedicated to Athina
"Of suns and worlds I've nothing to be quoted;
How men torment themselves, is all I've noted.
The little god o' the world sticks to the same old way,
And is as whimsical as on Creation's day.
Life somewhat better might content him,
But for the gleam of heavenly light which Thou hast lent him:
He calls it Reason - thence his power's increased,
To be far beastlier than any beast."

Goethe
Abstract

In the case of a nuclear accident, the release of radioactive substances into the environment may pose a significant threat for the public health. One of the main concerns is radioactive iodine which tends to accumulate in the thyroid causing damage to the gland and increasing the cancer risk. As a result, a thyroid monitoring campaign on large groups of the population, should be an essential part of the emergency response should a nuclear accident ever occur.

For this reason, various gamma spectrometers and monitors were calibrated so that they can be part of such a campaign. Neck/thyroid phantoms and vials containing radioactive solutions, simulating contaminated thyroid glands of different age groups, were used in specific geometries in order to study the response of the detection systems and derive their peak efficiency. In addition, the sensitivity of detection was estimated and quality assurance charts for the energy resolution and decay corrected area of certain energy peaks were established. A separate chapter was dedicated to the uncertainties due to anatomical and postural variabilities. Based on the overall results of this study, a technical manual was prepared, including guidelines for the use of these detectors in a rapid monitoring campaign in order to derive the activity of radioiodine in the thyroid gland. Finally, a simple method for triage was presented, including charts of warning and action levels for the present thyroid activity according to critical levels for the committed effective dose.
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The main results of my work were based on I-131, a fast-decaying nuclide, not available at SCK•CEN, which I wouldn’t have obtained without the help of Peter Covens and Daniëlle Berus from the VUB hospital in Brussels. Getting just a concentrated radioactive solution is not enough; it was Leen Verheyen and Bart Vennekens whom I should thank for preparing my vials. These vials, simulating the lobes of contaminated thyroid glands were placed inside neck phantoms, designed with the help of Athina Venou and manufactured by Jurgen Verlinden.

I would also like to thank Reinhard Boons for manufacturing the detector holder I designed for quality assurance measurements and Johan Camps for letting me use the lanthanum bromide detector. Filip Vanhavere, Christian Mihailescu and Michel Bruggeman deserve special thanks for giving me deeper insight in the areas of uncertainty
analysis and gamma spectroscopy.

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Thank you all.
Aristotle Onassis

Aristotle Onassis, son of Socrates and Penelope, was born in Smyrna in 1906. In 1922 he arrived in Greece as a refugee, and shortly thereafter emigrated to Argentina. In 1932 he bought his first ship, which he named Calliroe after his sister.

In 1946 Aristotle Onassis married the daughter of the ship-owner Stavros Livanos, Athina with whom he had two children: Alexander Socrates Onassis and Christina. Aristotle Onassis, thanks to his genius for business, very rapidly rose to be one of the world’s biggest shipping magnates, owning mainly oil tankers. He became a legendary figure, not only in worldwide financial circles but also in the eyes of ordinary people. In 1956 he acquired the concession to operate an air transport company from the Greek State and founded Olympic Airways. The Company started to operate on the 6th of April 1957, with a standard of service for the passengers, which would be inconceivable nowadays, for cost reasons. Olympic Airways was soon flying to destinations all over the world, and won a name for itself as one of the safest airline companies. At the end of 1974, Onassis rescinded the contract with the Greek State and on the 4th August 1975, after his death, Olympic Airways was transferred to it.

On January 24, 1973, his son Alexander Socrates Onassis, then just 25 years old, was killed in an air-crash. His son’s sudden and untimely death dealt Onassis a shattering blow, from which he never recovered. He died two years later, on March 15, 1975, in Paris.
“Alexander S. Onassis” Public Benefit Foundation

The “Alexander S. Onassis” Public Benefit Foundation was established in December 1975 in accordance with Aristotle Onassis’ last wish to honor the memory of his son, Alexander. The “Alexander S. Onassis” Public Benefit Foundations headquarters are located in Vaduz, Liechtenstein, as was directed in Aristotle Onassis’ will.

Culture, education, the environment, health, and social solidarity come first on the agenda of the “Alexander S. Onassis” Public Benefit Foundation. All projects of the “Alexander S. Onassis” Public Benefit Foundation relate to Greece or Greek culture and civilization. In the sector of social solidarity the Foundation promotes significant public benefit projects, while according to both the Foundation’s regulations and the wishes of Aristotle Onassis, individual charity is not allowed.

All activities of the “Alexander S. Onassis” Public Benefit Foundation are funded exclusively by the profits of an autonomous and institutionally independent Business Foundation named “Alexander S. Onassis” Foundation, also based in Vaduz, Liechtenstein. The Business Foundation engages mainly in shipping, real estate and financial products investments.
List of Abbreviations

SCK•CEN  Studiecentrum voor Kernenergie - Centre d’Étude de l’énergie Nucléaire
KTH  Kungliga Tekniska Högskolan
kEV  kilo-electron Volt
ADC  Analog to Digital Converter
MCA  Multi Channel Analyzer
PMT  Photo-Multiplier Tube
HVPS  High Voltage Power Supply
FWHM  Full Width at Half Maximum
FANC  Federal Agency for Nuclear Control
IRE  Institute for Radio-Elements
QA  Quality Assurance
PMMA  Poly-Methyl-Meth-Acrylate
PA6  Poly-Amide-6
MDA  Minimum Detectable Activity
BEGe  Broad Energy Germanium detector
cps  counts per second
INES  International Nuclear Event Scale
ICRP  International Commission on Radiological Protection
ALU  Upper Action Level
ALL  Lower Action Level
ROI  Region Of Interest
OECD-NEA  Organisation for Economic Cooperation and Development - Nuclear Energy Agency
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Preface

In August 2008, the Belgian authority on nuclear safety and radiation protection, the Federal Agency for Nuclear Control (FANC), was notified by the Institute of Radionuclides (IRE) that there was a leakage of 45 GBq of radioactive iodine at its site in Fleurus, Belgium, where IRE produces radioisotopes for medical use.

On the 1st of September 2008, the Federal Service for Public Health and the municipality of Fleurus organized a monitoring campaign for the presence of radioactive iodine in the thyroid gland in the population. Approximately 930 people took part in this campaign, including 350 children. No contamination was found. The FANC rated this incident at level 3 on the INES scale [1].

After the accident in Fukushima Dai-ichi nuclear power plant in March 2011, another monitoring campaign took place in Brussels, Belgium, in order to check for internal contamination those who were repatriated from Japan, following the nuclear accident.

In both campaigns, the Belgian Nuclear Research Center SCK•CEN was asked to participate and contribute with radiation detection systems and personnel familiar with internal contamination monitoring procedures. For this reason, the Anthropogammametry Laboratory within the Radiation Protection Dosimetry and Calibration Group decided to announce the master thesis project with the title “Investigation and calibration of various detection systems which can be used for emergency internal contamination checks”. This way, the emergency response with respect to thyroid monitoring would be better prepared, should a nuclear accident occur in the future.

The purpose of this project is to give practical guidance on conducting large scale monitoring of internally contaminated people using readily available equipment and improvised techniques. This guidance should assist in the advance preparation of emergency response plans and in implementing procedures aimed at identifying rapidly those most at risk (who would benefit from early medical intervention in order to avoid serious deterministic health effects and limit the incidence of stochastic effects) or those whose lower levels of contamination justifies a recorded assessment of committed dose. In such cases, hundreds or thousands of people may need screening for internal contamination and the public health authorities should be ready to use equipment that can be diverted from its regular use without delay. The authorities should also formulate a plan for monitoring which makes the best use of resources in producing the required information as quickly as possible. Therefore, the results of this master thesis together with the technical manual prepared for the corresponding use of the related detectors and monitors
are intended for institutions engaged in emergency response planning and for personnel in charge of internal contamination monitoring.
Chapter 1

Introduction

The thyroid is a butterfly-shaped gland, located in the lower front of the neck, below the Adam’s apple, along the front of the windpipe. It has two side lobes, connected by a bridge in the middle, called isthmus. The thyroid gets its name from the Greek word for “shield” (θυρεός) due to the shape of the thyroid cartilage.

The thyroid gland produces several hormones, collectively called thyroid hormones, which regulate the rate of metabolism and affect the growth and rate of function of many other systems in the body. It is composed of spherical follicles that selectively absorb iodine from the blood for the production of the thyroid hormones but also for storage of iodine. Thirty percent of all the body’s iodide ions are concentrated in the thyroid gland.

The experience of dose assessments performed after the accident at the Chernobyl nuclear power plant in 1986 has shown that incorporated I-131, Cs-134 and Cs-137 were the main sources of internal contamination in the exposed population [2]. The radioactive isotope that is mainly considered in the present study is I-131, although a small part of this work has been dedicated to I-125, as well. I-131 is a major product of uranium and plutonium fission (it comprises nearly 3% of the total products of fission) and it has been a significant contributor to the health hazards from the atmospheric nuclear bomb tests, the Chernobyl nuclear accident and the Fukushima Dai-ichi nuclear accident. Since the thyroid absorbs available iodine from the bloodstream without being able to distinguish between stable and radioactive iodine, it will absorb whatever it can. The radioactive iodine taken up by the thyroid causes radiation damage and gradually destroys the cells of the gland. This may lead to an increased cancer risk as well as radiation-induced thyroid diseases such as benign thyroid nodules, hypothyroidism and autoimmune thyroiditis. It is worth mentioning that in babies and children, the thyroid gland is one of the most radiation sensitive parts of the body.

As a result, in the case of a nuclear accident, a monitoring campaign with respect to the radioactive iodine uptake by the thyroid gland should be part of the emergency response, since it will help identify those who have been internally contaminated and possibly need medical treatment. Rapid monitoring is important because many radionuclides which may be present are short lived and the accident severity will need to be
quickly assessed. In addition, the results can be used later for epidemiological studies over large groups of the affected population. The detectors included in such a campaign should be appropriately calibrated before they are used for monitoring a potentially contaminated person.

- Appropriate energy calibration is needed in order to locate the peak of interest in the acquired spectrum with certainty. This peak corresponds to a characteristic photon emitted by the nuclide of interest and should be located at a particular position in the spectrum. This is possible only when the correct energy vs. channel relationship is established.

- Appropriate peak width calibration is needed in order to distinguish the peak of interest with certainty when other peaks are very close in a complex gamma spectrum. The correct peak width calibration allows also the spectrum analysis software to perform correctly the gamma peak analysis.

- When the peak of interest is located correctly and its area is clearly identified (based on the correct energy and peak width calibration of the detector), the area under the peak can be used in order to estimate the activity of the source (radioactive iodine uptake by the thyroid). In order to derive the present activity of iodine in the thyroid gland from the detector’s counting rate, the efficiency of the detector (with respect to the particular geometry) is needed. That means that the detector should be appropriately efficiency-calibrated.

The response of the radiation detection systems should be consistent in time when the same measurements are carried out under the same conditions. This ensures that the efficiency calibration is valid and can be used in a future campaign to derive the thyroid activity. For this reason, quality assurance (QA) charts were established so that the detectors’ response can be checked before a future campaign. If the QA checks show that the efficiency or energy resolution do not lie within the established acceptable limits, then it will not be allowed to use the detector with the calibration factors reported in this thesis.

Most of the radiation detection systems that were studied allow for the extraction of the gamma spectrum in digital form and further, detailed processing by the related gamma analysis software. These detectors are called spectrometers. However, in extreme cases where the thyroid monitoring campaign should be carried out over large groups of the population, other, less accurate instruments and methods may be used, should the public health authorities allow it. For this reason, this particular study included also three monitors: a dose rate meter and two count rate meters whose response can be an indication of the radioactive iodine uptake by the thyroid. The fact that there are several more of those monitors available SCK–CEN means that the demands of a large campaign can be met more easily.

When the radiiodine uptake by the thyroid gland is estimated by following rapid monitoring procedures, dosimetric tables can be used in order to estimate the intake and the corresponding committed effective dose. Action levels directly related to this
committed effective dose will indicate whether the monitored person runs any health risk, needs further monitoring using more accurate methods or needs to be medically treated in case the iodine activity in the thyroid exceeds a critical level.
1.1 Biokinetic model for iodine

For adults, it is assumed that, of the iodine reaching the blood, 30% is transported to the thyroid gland and the rest 70% is excreted directly in urine via the urinary bladder. The biological half-life in blood is taken to be 6 h. Iodine incorporated into thyroid hormones leaves the gland with biological half-life of 80 d. Most iodine (80%) is subsequently released and is available in the circulation for uptake by the thyroid or direct urinary excretion; the remainder is excreted via the large intestine in the faeces. Because of the short physical half-life of I-131, this recycling is not important in terms of the committed effective dose. The biokinetic model for iodine metabolism according to ICRP recommendations [3] is shown in figure 1.1.0.1.

\[
\begin{align*}
T_a &= 0.25\,d \\
T_b &= 80\,d \\
T_c &= 12\,d
\end{align*}
\]

Figure 1.1.0.1: Biokinetic model for iodine metabolism.

1.2 Theory on Calibration

1.2.1 Energy calibration

Energy calibration of a detector means establishing the correct relationship between the amount of energy transferred to the detector and hence, the height of the electronic pulse resulting from it and the number of the channel in which this pulse is stored. First, a rough energy calibration is achieved by choosing appropriately the amplification gain of the amplifier and then the exact calibration coefficients are evaluated. For this purpose, a least-squares fit to two or more pairs of energy and channel number is used to calibrate the analog-to-digital conversion (ADC) range in energy level (keV). In general:

\[
E_{\gamma}[\text{keV}] = c_0 + c_1 \cdot \text{channel}
\]

\(c_1\) is the linear energy scale (slope in keV/channel) of the Multi-Channel Analyzer
\(c_0\) is the intercept (usually set as close as possible to zero)
1.2. Theory on Calibration

As an example, an MCA of 1024 channels with a linear energy scale of 2 keV/channel covers an energy range of around 2 MeV. This energy window covers practically all gamma energies that may be encountered in a monitoring campaign for internal contamination and allows the detection of the nuclides of interest following a nuclear accident. The smaller the slope of the energy calibration curve, the shorter the energy range covered. Therefore, the energy scale can be adjusted according to the gamma peaks (low or high energy) of interest.

Since it is not possible to derive the values of $c_1$ and $c_0$ accurately, on a theoretical basis, these coefficients should be calculated based on a set of measurements. An active sample emitting photons covering the desired energy range is counted by the detector to be calibrated. The true position (channel number) of every energy peak is determined and the energy of the photon is plotted against channel number. An example of a linear energy calibration curve is shown in figure 1.2.1.1.

This curve can be used to determine the energy of a photon that is responsible for an unknown peak in the spectrum. The software usually determines the values of $c_1$ and $c_0$ by fitting a linear function to all the available points. These values are stored and recalled whenever an unknown pulse height spectrum is to be analyzed (the MCA uses the results from the previous energy calibration). However, the electronic modules are not absolutely stable under all conditions and as a result, the values of $c_1$ and $c_0$ drift slightly with time. Therefore, the detector requires frequent energy calibration. The analyst must establish (through successive measurements in time) the rate of drift for every detector system and decide on an energy calibration frequency that would generate new calibration parameters before the expected error becomes too large.
1.2.2 Peak width calibration

If a single-photon nuclide is counted, all the pulses from the full energy events should theoretically have the same height. In practice, it is found that the height values are spread over a narrow band of channels of the MCA. The full width at half the maximum height (FWHM) of a peak in the pulse height spectrum is used as a measure of this energy “spread”. This is a quantitative indication of the expected energy resolution of a detector, i.e. its ability to distinguish between two peaks of equal size that are close together. It can be expressed as an absolute value (in keV) or as a relative value with respect to the corresponding energy.

The FWHM increases with the energy of the photon and depends on intrinsic properties of the detector, the type and setting of the electronic modules and the layout of the cables. The analyst needs to count a calibration sample emitting photons that cover the energy region of interest. These data are then used by the software to establish the mathematical relation between the FWHM and the photon energy. The equation used by Genie 2000 Gamma Spectroscopy Software from Canberra for the peak width calibration curve is:

\[ FWHM[keV] = F_0 + F_1 \cdot \sqrt{E[keV]} \]

An example of a peak width calibration curve is shown in figure 1.2.2.1.

This relation is then used by the system to calculate the expected FWHM at any photon energy of interest. Deviation from the expected peak width calibration may indicate a possible malfunction of the detector. For example, in the case of a germanium detector, it may be an indication of vacuum loss.

The correct peak width calibration allows the gamma spectroscopy software to deconvolute a multiplet of peaks into the components with good accuracy. This is essential especially for sodium iodide detectors which do not have good resolution and therefore,
1.2. THEORY ON CALIBRATION

give spectra often including multiplets where the peak of interest is hidden.

1.2.3 Efficiency calibration

The full-energy peak efficiency $\varepsilon$ is defined as the fraction of the photons of a particular energy emitted by a source, that contributes to the corresponding full energy peak observed in the pulse height spectrum, so that:

$$\textit{Counting rate} = (\textit{source activity}) \cdot (\textit{emission probability}) \cdot (\textit{efficiency}) \Rightarrow$$

$$\frac{N[\text{counts}]}{t[\text{seconds}]} = A[Bq] \cdot I_\gamma \cdot \varepsilon$$

The counting rate refers to the counts $N$ under the full-energy peak observed in the pulse height spectrum detected during the measurement live time $t$. The emission probability $I_\gamma$ (yield) refers to the fraction of disintegrations that result in the emission of a photon of the corresponding energy $\gamma$. The activity of the source $A$ is assumed to be constant during the measurement given the short counting times (minutes) compared with half-lives of the nuclides of interest (days or years), in this study.

The value of efficiency depends on the geometry of the sample, its size, density and distance from detector and of course, on the detector itself as well as environmental conditions, such as temperature. Therefore, each geometry requires a specific efficiency calibration and for this reason, a calibration sample, i.e. a reference source accompanied by a certificate stating its initial activity, uncertainty and assay date, is used. This sample includes multiple energies and for each of these known energies an efficiency calibration factor is calculated:

$$\varepsilon = \frac{N[\text{counts}]}{A[Bq] \cdot I_\gamma \cdot t[\text{seconds}]} \Rightarrow$$

$$\frac{\text{counts}}{\text{sec}} \cdot (\text{emission probability for photons of } \gamma \text{ keV}) \Rightarrow$$

$$\text{detector's counts per emitted photon of } \gamma \text{ keV}$$

The generated series of data pairs of efficiency vs. energy can be plotted and fitted, giving the efficiency calibration curve of the detector for the particular geometry. An example of an efficiency calibration curve is shown in figure 1.2.3.1 Thus, the software
can calculate efficiency at any energy in the calibrated energy range when analyzing an unknown spectrum.

Once the efficiency calibration factors (and the curve) are derived, they can be used in the inverse way: to find the unknown activity of a radioactive sample by using the same detector and geometry.

\[ A[Bq] = \frac{N[\text{counts}]}{\varepsilon \cdot I_\gamma \cdot t[\text{seconds}]} \]

The value of the counting efficiency is determined by the following factors:

- Attenuation of photons inside the source due to absorption in the sample material.
- Attenuation of photons in the material over the entrance face of the detector (cap). The magnitude of this effect depends on the thickness and composition of the entrance window as well as the energy of the photons.
- The fraction of the photons emitted by the source that hits the effective volume of the detector. This is determined by the form and dimensions of the sample and the detector and the effective distance between the two.
- The fraction of the photons hitting the detector that contributes to the full-energy peak. This is determined by the physical size of the detector and on the photon energy.

In practice, it is not possible to calculate the efficiency at different energy values for all the geometric arrangements that are used in the laboratory. It is therefore standard practice to prepare calibration samples and determine the efficiency of the detector through measurements. These calibration samples must meet the following requirements:
They must be similar to the field samples (that are to be analyzed) in every respect: matrix composition, physical form and dimensions.

They must contain a number of nuclides (or a nuclide emitting a large number of different energy photons) to cover the energy region of interest. The establishment of an efficiency calibration curve can also be done using several sources by measuring them successively and combining the results afterwards.

Their activity values must be known accurately according to a national standard.

They must be mechanically robust (to prevent contamination of a detector/phantom) and chemically stable (to eliminate segregation of the active component from the matrix).

Normally, it is not possible to purchase calibration standards that satisfy all these requirements so the analyst has to prepare them in the laboratory.
Chapter 2
Methodology

2.1 Calibration of detectors for thyroid screening

For the calibration of the detectors for thyroid screening, each detector was placed in front of an anthropomorphic neck/thyroid phantom at certain distances. Two phantoms were used: one for children and teenagers and another for adults. A material (PMMA/PA6) with photon attenuation properties similar to the human soft tissue was chosen for the phantoms and holes were made in order to accommodate pairs of cylindrical vials with radioactive solutions. Each pair represented the two lobes of a contaminated thyroid gland for a different case of thyroid according to the age or corpulence of the person that could be screened in a real campaign. The distance between the detector cap and the surface of the neck phantom for the calibration was chosen to be 1 cm. However, the 15 cm distance was also used in order to study the effect of larger neck-detector distances (NDD). The detectors were not shielded during the calibration in the lab.

The spectrometers offered the possibility of extraction of the pulse-height spectrum for further, detailed analysis with the Genie 2000 Gamma Spectroscopy Software from Canberra. The most prominent peak of each nuclide of interest was used in order to derive the peak efficiency calibration factor. The acquisition time was chosen large enough to ensure sufficiently low uncertainty with respect to the radiation counting statistics. The calibration factors were used for the creation of the corresponding calibration files for Genie 2000. That means that in a thyroid monitoring campaign, these files can be inserted in the spectrum obtained for each monitored person in order to derive the activity of radioactive iodine in the thyroid gland. It should be noted that the spectrometers were calibrated with respect to I-131 and Ba-133 and only the germanium detector was calibrated with respect to I-129.

Since the monitors give just an indication (a dose rate or a count rate) as a response to the incident gamma radiation without differentiating photon energies, the relationship between the thyroid activity and the dose or count rate response was derived. For this purpose, the phantom and vials that correspond to the reference case of an adult neck/thyroid were used. The fast decaying calibration sources of I-131 had different
2.2. DETECTION LIMITS

values of activity over a period of a few days, and for each day, the detectors’ response was recorded. A linear fitting was used to derive the calibration factor in kBq/(μSv per hour) or kBq/cps [4].

2.2 Detection limits

The minimum detectable activity (MDA) with respect to the peak of interest, at 95% confidence level, was calculated based on Currie’s formula [5].

According to the frequently quoted as “Currie’s equation”, the minimum number of counts \( N_D \) needed to ensure a false-negative rate no larger than 5% when the system is operated with a critical level that, in turn, ensures a false-positive rate no greater than 5% is:

\[
N_D = 4.653 \cdot \sigma_{N_B} + 2.706
\]

where \( \sigma_{N_B} \) is the standard deviation of the background. In order to convert \( N_D \) to minimum detectable activity (MDA), the detector’s efficiency, the measurement time and the emission probability (yield) for the photon energy of interest are needed:

\[
MDA = \frac{N_D}{\varepsilon \cdot I \cdot t} = \frac{4.653 \cdot \sigma_{N_B} + 2.706}{\varepsilon \cdot I \cdot t}
\]

The above formula indicates that the factors that result in a reduced MDA are:

- Smaller background uncertainty, which means smaller contribution of the background counts in the gross peak area of interest
- Higher detection efficiency
- Longer measurement time

All the background spectra used for the estimation of the MDA were acquired without shielding the detectors or placing them in a shielded room (bunker). However, a lead shield was available only for one of the detectors and it was used in order to study the effect of shielding on the MDA.

2.3 Quality control for spectrometers

Quality assurance charts were also established for the spectrometers in order to ensure the validity of their results in a future thyroid monitoring campaign. For this purpose, holders were manufactured in order to accommodate point-like sources of Eu-152 (∼100 kBq in total) at a fixed distance of 10 cm between the sources and the front window of the spectrometers. With an acquisition time of 10 minutes, successive measurements for a certain period of time were carried out and the FWHM as well as the decay corrected area for the peaks shown in table 2.3.0.1 were recorded. The decay corrected area is the
area (counts) under the peak of interest taking the decay of the radioactive sources into account according to the following equation:

$$Decay\ Corrected\ Area\ (counts) = N_{dc,i} = \frac{N_i}{e^{-\lambda t}}$$

<table>
<thead>
<tr>
<th>Energy</th>
<th>Emission probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>121.8 keV</td>
<td>28.4%</td>
</tr>
<tr>
<td>344.3 keV</td>
<td>26.6%</td>
</tr>
<tr>
<td>1408 keV</td>
<td>20.9%</td>
</tr>
</tbody>
</table>

Table 2.3.0.1: Gamma radiation emissions from Eu-152 [6] used for quality assurance of the spectrometers.

Once a sufficiently large set of measurements $K$ (over a sufficiently long period of time) is obtained, then the standard deviation of the set (FWHM or decay corrected area for each peak) is calculated using the formula:

$$\sigma_{FWHM} = \left[ \frac{1}{K-1} \sum_{i=1}^{K} (FWHM_i - \bar{FWHM})^2 \right]^{1/2}$$

$$\sigma_{dc} = \left[ \frac{1}{K-1} \sum_{i=1}^{K} (N_{dc,i} - \bar{N}_{dc})^2 \right]^{1/2}$$

The “window” formed by the lower and upper warning levels ($\pm 2\sigma$) corresponds to a 95.4% confidence interval and the “window” formed by the lower and upper action levels ($\pm 3\sigma$) corresponds to a 99.7% confidence interval. Each detector can be used as long as a future quality assurance check does not exceed two consecutive warning levels or an action level.

It is worth mentioning that the same spectrometers available anywhere in the world can use the efficiency calibration files of this study in a thyroid screening campaign as long as their QA checks are successful.
Chapter 3

Equipment

3.1 Radiation detection instruments

The list of the detectors (crystal material and dimensions) that were calibrated is presented in table 3.1.0.1 and includes six spectrometers and three monitors (a dose rate and two count rate meters).

<table>
<thead>
<tr>
<th>Type of detector</th>
<th>Crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectrometers</strong></td>
<td></td>
</tr>
<tr>
<td>Semiconductor detector</td>
<td>- High-purity, Broad Energy Germanium</td>
</tr>
<tr>
<td></td>
<td>60 x 21.5 mm</td>
</tr>
<tr>
<td>Inorganic scintillators</td>
<td>- NaI(Tl) 3x3-inch</td>
</tr>
<tr>
<td></td>
<td>- 3 x NaI(Tl) 2x2-inch</td>
</tr>
<tr>
<td></td>
<td>- LaBr₃(Ce) 1.5x1.5-inch</td>
</tr>
<tr>
<td><strong>Monitors</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- ZnS(Ag) thin film (count rate)</td>
</tr>
<tr>
<td></td>
<td>- NaI(Tl) 32 x 2.5 mm (count rate)</td>
</tr>
<tr>
<td>Organic scintillator</td>
<td>- Plastic scintillator 3x3-inch (dose rate)</td>
</tr>
</tbody>
</table>

Table 3.1.0.1: The types, crystals and dimensions of the calibrated detectors.

3.1.1 High-purity germanium detector

Germanium detectors (and semiconductor detectors, in general) have the ability to resolve effectively the energy of particles out of a polyenergetic spectrum. However, despite their good resolution capabilities, their efficiency is significantly lower compared to sodium iodide detectors (which is the other category of detectors that is widely used in gamma spectrometry).

External voltage is applied to the semiconductor crystal establishing an electric field but there should be no current flow until radiation is deposited on the material. In this
In any case, energy is transferred to electrons of the valence band allowing them to overcome the forbidden energy gap. This way, electrons are brought to the conduction band, holes are left behind in the valence band (both electrons and holes are considered to be charge carriers) and conductivity increases. The electron-hole pairs that are produced are collected by the electric field producing a pulse. The higher the energy of the incident particle, the higher the number of generated charge carriers and the stronger the pulse that is produced.

The mechanism of charge carriers production is weak so an impurity is added to the crystal increasing the mobility of a certain type of carrier. If this impurity is a donor of electrons, then the electron of the donor that does not belong to a covalent bond in the crystal is loosely bounded and it belongs to an energy state that is closer to the conduction band. Therefore, when radiation impinges on the crystal, the majority of the charge carries are electrons. Such a crystal is an n-type semiconductor. On the other hand, if this impurity is an acceptor of electrons, then one electron of the germanium crystal may get attached to the acceptor in order to complete a covalent bond. This way, an energy state close to the valence band is created, an electron moves from the valence band to this energy state leaving a hole behind and the majority of the charge carriers are holes (mainly responsible for conductivity in this case). Such a crystal is a p-type semiconductor.

Figure 3.1.1.1: Broad Energy Germanium detector and Inspector 2000.
gap would be reduced so much that electrical conduction would be dominated by ther-
mally generated charge carriers and that would distort the signal of useful information
coming from charge carriers produced by the impinging radiation.

The broad energy germanium detector (BEGe) from Canberra that was calibrated has a
p-type crystal of 60 mm active diameter and 21.5 mm thickness. It was connected to the
Inspector 2000 Multi-Channel Analyzer also from Canberra. 8192 channels were chosen
in the MCA, covering an energy range of around 2200 keV (0.26 keV per channel). A
photo of this detector and the MCA is shown in figure 3.1.1.1. The spectrum acquisition
and analysis was directly done with Genie 2000.

3.1.2 Inorganic scintillators

Scintillators in general are materials (solid, liquid, gases) that produce sparks of visible
light (scintillations) when ionizing radiation passes through them.

The inorganic scintillators used in the present study, namely NaI(Tl), LaBr$_3$(Ce) and
ZnS(Ag) are solid crystals containing, in each case, an impurity (activator) that is men-
tioned inside the parentheses and is actually the main contributor to the luminescence of
the crystal. When ionizing radiation passes through the crystal, electrons are raised to
the conduction band while holes are created in the valence band and this way excitons
are formed. Most of the incident energy goes to the lattice of the crystal and activation
centers are raised to the excited states by absorbing electrons, holes and excitons. Their
de-excitation follows by the emission of photons of visible light which then impinge on
the photo-cathode of the photo-multiplier tube (PMT), resulting in a number of photo-
electrons. The generated photo-electrons are then successively accelerated by a series of
dynodes that are connected to a voltage divider establishing the necessary electric field.
When a wave of electrons impinges on each dynode, a secondary wave of a larger number
of electrons is produced, resulting in a pulse of electrons at the final dynode (anode) at
the end of the PMT.

The signal is then processed by the electronics of the counting system, i.e. the
preamplifier, the main amplifier, the analog-to-digital-converter (ADC) and the multi-
channel analyzer (MCA) and the pulse-height spectrum is acquired.

This is the case for all the spectrometers listed in table 3.1.0.1 that use an inorganic
scintillation crystal. However, the contamination monitors using inorganic scintillators
that operate as count rate meters respond to radiation indicating just a count rate in
counts per second (cps). These detectors are not connected to a computer for gamma
spectrum analysis.

The sodium iodide, thallium doped (NaI(Tl)) detector with a crystal of 3x3 inches from
Scionix Holand was coupled with the Inspector 2000 Multi-Channel Analyzer from Can-
berra. 1024 channels were chosen in the MCA, covering an energy range of around 2000
keV (2 keV per channel). A photo of this detector and MCA is shown in figure 3.1.2.1.
The spectrum acquisition and analysis was directly done with Genie 2000.

Three sodium iodide, thallium doped (NaI(Tl)) detectors with a crystal of 2x2 inches
were calibrated. What is different among them is the electronics and, in particular, the
MCA, namely the Inspector 1000, the NANOSPEC and the UNISPEC, respectively.

The NaI(Tl) 2x2 (Canberra), Inspector 1000 (Canberra) is a compact detector that
connects the probe with the multi-channel analyzer as shown in figure 3.1.2.2. It is a
completely autonomous device: it uses rechargeable batteries and has a processing unit
for acquisition and analysis of gamma spectra (with Genie 2000) which can also be
stored. Everything can be seen and controlled through a screen. Acquired spectra can
be transferred to a personal computer or calibration files can be loaded from a personal
computer with the use of the Inspector 1000 Maintenance V.1.2 software on Windows XP.
The analysis can be done afterwards with Genie 2000 on Windows 7. 512 channels
were chosen in the MCA, covering an energy range of around 1500 keV (3 keV per
channel).

The NaI(Tl) 2x2 NANOSPEC is a compact detector accommodating the crystal
and all the electronics, as shown in figure 3.1.2.3. The power supply is provided either
externally with batteries or internally with a cable connecting the detector with a plug
through a transformer. A cable is used to connect the detector with a personal computer
in order to acquire and save the spectrum with the winTMCA-32 software on Windows
XP. The analysis can be done afterwards with Genie 2000 on Windows 7. 1024 channels
were chosen in the MCA, covering an energy range of around 2100 keV (2 keV per
channel).

The NaI(Tl) 2x2 (Scionix Holand), UNISPEC (Canberra) is a compact detector
accommodating the crystal and all the electronics as shown in figure 3.1.2.4. Only a
cable is used to connect the detector with a personal computer in order to provide the
necessary high voltage power supply (HVPS) but also in order to acquire and analyze the
spectrum with Genie 2000. 1024 channels are used covering an energy range of around
2100 keV (2 keV per channel).

The LaBr$_3$(Ce) 1.5x1.5 (Berkeley Nucleonics Corp.), BNC Model, 940 Revealer
(Berkeley Nucleonics Corp.) is a compact detector that connects the probe with the
multi-channel analyzer as shown in figure 3.1.2.5. It uses rechargeable batteries and can
be used for acquisition and storage of gamma spectra as well as for nuclide identifica-
tion. However, the acquired gamma spectra cannot be directly analyzed which means
that they should be extracted (with the use of a memory card and stick) and their for-
mat should be converted (the Cambio File Converter software was used for this purpose)
before they can be analyzed with Genie 2000. The acquired spectrum can be seen on
the screen through which many acquisition parameters can be controlled as well. 512
channels were chosen in the MCA, covering an energy range of around 4500 keV (9 keV
per channel). It is worth mentioning that LaBr$_3$(Ce) is a relatively new scintillation ma-
terial used in detectors and provides comparable efficiency with sodium iodide detectors
but better energy resolution.

The count rate meter shown in figure 3.1.2.6 is a contamination monitor including an
alpha and beta contamination probe from Thermo Scientific coupled with the Thermo
Scientific Electra Survey Meter. The inorganic scintillation material that is used is
silver-activated, zinc sulfide (ZnS(Ag)), which is one of the oldest inorganic scintillators;
3.1. RADIATION DETECTION INSTRUMENTS

it was also used in the early experiments of Rutherford on alpha particle interactions and it has very high efficiency, comparable to that of NaI(Tl), but it is available only as poly-crystalline powder. As a result, its use is limited to thin screens for alpha particles or other heavy ions detection. [7]. If the particular count rate meter is switched to the beta channel, it gives a response to gamma radiation as well and a value of the count rate (in counts per second) appears on the digital screen.

The count rate meter shown in figure 3.1.2.7 is a contamination monitor including a probe with a sodium iodide crystal (32 x 2.5mm) from Thermo Scientific coupled with the 900 series mini monitor from the same company. Its response to gamma radiation is an analog signal of the count rate shown in logarithmic scale (needle).

Figure 3.1.2.1: NaI(Tl) 3x3-inch, Inspector 2000.

Figure 3.1.2.2: NaI(Tl) 2x2-inch, Inspector 1000.
CHAPTER 3. EQUIPMENT

Figure 3.1.2.3: NaI(Tl) 2x2-inch, NANOSPEC.

Figure 3.1.2.4: NaI(Tl) 2x2-inch, UNISPEC.

Figure 3.1.2.5: LaBr$_3$(Ce) 1.5x1.5-inch, BNC model, 940 SAM Revealer.
3.1. Radiation detection instruments

3.1.2.6: Thermo Scientific DP6 series scintillation alpha and beta contamination probe coupled with Thermo Scientific Electra Survey Meter.

3.1.3: Organic scintillator

The fluorescence in organics arises from transitions in the energy level structure of the molecules. The electron structure of the molecules has certain symmetry properties with characteristic energy levels. Energy can be absorbed by exciting the electron configuration into any one of a number of excited states. De-excitation follows by the emission of scintillation light (fluorescence).

The organic scintillator that was calibrated was the scintillator probe Automess 6150AD-b connected with the dose rate meter Automess AD6 (measuring unit), shown
in figure 3.1.3.1. This is a high sensitivity scintillator for X-ray and gamma radiation with a plastic crystal of 3x3 inches. The light generated in the scintillator by radiation is converted into a proportional current by a photo-multiplier and is fed through a current-frequency converter to the connected measuring unit. The probe electronics are equipped with a microprocessor and the probe is supplied with power from the battery of the connected measuring unit. The detector can be used over a photon energy range of 23 keV to 7 MeV and for dose rate measurements starting from as low as 5 nSv/h.

![Scintillator probe Automess 6150AD-b connected with the dose rate meter Automess AD6.](image)

3.2 Calibration sources

3.2.1 Vials of I-131 and Ba-133

Choice of vials

The shape and size of the thyroid gland varies significantly among different people and this “...extreme variation in the gross anatomy of the gland, is so much so that to speak of a “normal” thyroid gland is absurd” [8]. In general, it is butterfly-shaped with two, normally not symmetrical lobes whose shape and size depend on many parameters such as the gender, the age, the environmental conditions of the place where the person lives and the diet. Furthermore, in pathological cases, the dimensions of the gland may deviate significantly from the reported average values. As a result, when a phantom should be designed for calibration purposes in order to simulate the human neck and thyroid gland, it is a common practice to assume that the two thyroid lobes are identical, having a cylindrical shape and contain all of the thyroid iodine (hence, in the related geometry, the isthmus is neglected). However, the International Commission on Radiological Protection (ICRP), in an attempt to study in further detail the biokinetic models and
dosimetry, established different age groups and for each group, inter alia, average values for the thyroid mass were derived, based on extensive statistical studies [9]. The age grouping and average thyroid mass values recommended by ICRP are shown in Table 3.2.1.1. The last column includes the thyroid volume as derived by the thyroid mass using the specific gravity of 1.05 g/ml given by ICRP.

<table>
<thead>
<tr>
<th>Age group centroid</th>
<th>Range of age group</th>
<th>Thyroid mass male/female [g]</th>
<th>Thyroid volume male [ml]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1y</td>
<td>from 1y to 2y</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>5y</td>
<td>more than 2y to 7y</td>
<td>3.4</td>
<td>3.2</td>
</tr>
<tr>
<td>10y</td>
<td>more than 7y to 12y</td>
<td>7.9</td>
<td>7.5</td>
</tr>
<tr>
<td>15y</td>
<td>more than 12y to 17y</td>
<td>12</td>
<td>11.4</td>
</tr>
<tr>
<td>Adult</td>
<td>more than 17y</td>
<td>20/17</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 3.2.1.1: ICRP thyroid mass and volume for different age groups [9].

These values for the thyroid volume are a bit larger than the median values but still lie below the 97th percentile of the male thyroid volume among the Dutch schoolchildren [10]. Due to geographic proximity, it can be assumed that the statistics of the Belgian schoolchildren do not deviate substantially from the results of this study.

It should be mentioned that more anthropomorphic mock thyroid glands can be designed, based on the anatomy of a real person. In this case, the exact geometry can be obtained by using medical imaging techniques, such as ultrasound scanning. However, this process would be much more expensive and time-consuming and the mock thyroid gland would still correspond to a particular geometry (the anatomy of the particular person), i.e. it would not cover all thyroid cases. The assumption that the thyroid lobes are symmetrical and cylindrical, with a homogeneous radioactivity distribution, strictly contained within the thyroid volume is an oversimplification but the error that is introduced can be neglected for calibration purposes when it comes to rapid monitoring procedures.

The values for the thyroid volume derived from the ICRP recommendations and shown in Table 3.2.1.1, were used in order to choose the corresponding pairs of vials accordingly. In each pair, the volumes of the contained radioactive solutions simulated the two lobes of a contaminated thyroid gland. Water was used as matrix, having almost the same specific gravity as the thyroid gland. The choice of vials was made according to availability and in a way that the shape of each lobe was as realistic as possible (active height larger than the lobe diameter). The pairs of vials containing either I-131 or Ba-133 solutions that were used are shown in Figure 3.2.1.1. The total volume of the radioactive solution in each pair (active volume) had exactly the same value as the one recommended by ICRP (values shown in Table 3.2.1.1). The active height of each radioactive sample (mock thyroid gland) as well as the diameter of each vial are shown in Table 3.2.1.2.
Figure 3.2.1.1: Pairs of vials containing I-131 or Ba-133 solutions, simulating the two lobes of a contaminated thyroid gland. From left to right: adult, 15 years old, 10 years old, 5 years old, 1 years old.

<table>
<thead>
<tr>
<th>Age group</th>
<th>Active height centroid [mm]</th>
<th>Vial diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1y</td>
<td>12</td>
<td>9.4</td>
</tr>
<tr>
<td>5y</td>
<td>16</td>
<td>11.9</td>
</tr>
<tr>
<td>10y</td>
<td>33</td>
<td>12.5</td>
</tr>
<tr>
<td>15y</td>
<td>37</td>
<td>14.7</td>
</tr>
<tr>
<td>Adult</td>
<td>37</td>
<td>18.6</td>
</tr>
</tbody>
</table>

Table 3.2.1.2: Active height and diameter of vials for all thyroid cases.

### Iodine 131

I-131 decays into Xe-131 through beta decay with a half life of 8.03 days. The principal gamma radiation emissions from I-131 accompanied by the corresponding emission probabilities are shown in table 3.2.1.3.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Emission probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>284.3 keV</td>
<td>6.1%</td>
</tr>
<tr>
<td><strong>364.5 keV</strong></td>
<td><strong>81.5%</strong></td>
</tr>
<tr>
<td>637 keV</td>
<td>7.2%</td>
</tr>
</tbody>
</table>

Table 3.2.1.3: Principal gamma radiation emissions from I-131 accompanied by the corresponding emission probabilities [6].

The most distinctive gamma peak of the I-131 spectrum (spectra acquired by three different detectors are shown in figure 3.2.1.2) corresponds to the emission of 364.5 keV photons (emission probability 81.5%). As a matter of fact, the gamma photons mentioned in table 3.2.1.3 originate from the de-excitation of the daughter nucleus of
3.2. CALIBRATION SOURCES

Xe-131. However, the 364.5 keV peak is loosely attributed to I-131 since this is the particular radionuclide of interest.

![I-131 energy spectra from three different detectors.](image)

Figure 3.2.1.2: I-131 energy spectra from three different detectors.

Using a spectrum of I-131 in the geometry of interest, the efficiency for this energy (peak efficiency) can be derived:

\[ \varepsilon_{I_{131}} = \frac{N_{364.5\text{keV}}}{A_{I_{131}} \cdot I_{364.5\text{keV}} \cdot t} \]

Beta emissions from I-131 were not considered as they were completely absorbed in the solution, the vial and the phantom\(^1\).

**Barium 133**

The fact that I-131 has such a short half life makes it difficult to use it in the lab for calibration purposes because the measurements would have to be carried out in a short period of time and new sources would have to be produced when the radioactivity would become too weak. In addition, activity corrections are necessary because of the fast decay of I-131 during the period that the lab measurements are conducted. As a result, it is a common practice to use Ba-133 as a simulating source for calibration purposes instead of I-131 since it has peaks in the same region of the spectrum of I-131 and a

\(^1\)This was also true in the case of calibration of the detection systems with respect to the rest nuclides included in this study, namely Ba-133, I-129 and Eu-152.
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much longer half-life\(^2\).

Ba-133 decays into Cs-133 through electron capture with a half life of 10.52 years. Among the gamma photons emitted from Ba-133 (strictly speaking, from the de-excitation of the daughter Cs-133) shown in table 3.2.1.4, the 356 keV photons are sufficiently close to the characteristic energy of I-131 (364.5 keV) which means that the attenuation of gamma radiation, as well as the response and efficiency of the detector, is similar in these two cases. As a result, Ba-133 can be used as a simulating source of I-131 when it comes to \textit{peak efficiency} calibration based on the 364.5 keV gamma peak.

\[
\varepsilon_{\text{Ba-133}} = \frac{N_{356\text{keV}}}{A_{\text{Ba-133}} \cdot I_{356\text{keV}} \cdot t} \approx \varepsilon_{\text{I-131}}
\]

<table>
<thead>
<tr>
<th>Energy</th>
<th>Emission probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>81 keV</td>
<td>32.9%</td>
</tr>
<tr>
<td>276.4 keV</td>
<td>7.2%</td>
</tr>
<tr>
<td>302.9 keV</td>
<td>18.33%</td>
</tr>
<tr>
<td><strong>356 keV</strong></td>
<td><strong>62.1%</strong></td>
</tr>
<tr>
<td>383.9 keV</td>
<td>8.9%</td>
</tr>
</tbody>
</table>

Table 3.2.1.4: Principal gamma radiation emissions from Ba-133 accompanied by the corresponding emission probabilities [6].

An interesting remark as concerns the energy resolution of different types of detectors can be made based on figure 3.2.1.3 of Ba-133 spectra. Four of the characteristic gamma energies of the Ba-133 spectrum, namely 276.4 keV, 302.9 keV, 356 keV and 383.9 keV are so close that it is difficult for NaI(Tl) detectors to discriminate effectively. What appears in their spectrum instead is two peaks: one results from the convolution of the 276.4 keV and 302.9 keV peaks and the other from the convolution of the 356 keV and 383.9 keV. Fortunately, the gamma spectrum analysis software is able to deconvolute the overlapping peaks in order to study the 356 keV peak of interest separately. This is shown in figure 3.2.1.4 where a screenshot of the \textit{Interactive Peak Fit} step of \textit{Genie 2000} is presented. Next comes the lanthanum bromide detector which is able to distinguish these four peaks but there is still some overlapping. There are no such problems with the germanium detector which gives clear, sharp peaks for the gamma energies of interest.

It should be mentioned that the 437 keV peak of Ba-133 shown in the spectra acquired by sodium iodide detectors is the result of true coincidence summing of 356 keV and 81 keV photons (cascade summing). This peak cannot be used for quantitative analysis because of unknown coincidence probabilities. The losses of counting due to true coincidence summing are neglected in the present study (no correction method was applied).

\(^2\)That is the reason Ba-133 is often called "pseudo-iodine". As an example, it is used in nuclear medicine for the calibration of gamma cameras that are used for I-131 imaging.
3.2. **CALIBRATION SOURCES**

![Ba-133 spectra](Image)

**Figure 3.2.1.3:** Ba-133 energy spectra from four different detectors.

![Overlapping peaks](Image)

**Figure 3.2.1.4:** Overlapping peaks of Ba-133 spectrum obtained with NaI3x3inspector2000, resolved by *Genie 2000 - Interactive Peak Fit*.

Finally, it is noteworthy that instruments that measure counting rate or dose rate cannot differentiate among different particle energies which means that it would be a mistake to use a simulating source (like Ba-133) for this kind of calibration. For I-131, the Ba-133 simulation is generally not valid [11]. Although the main gamma energies are similar for I-131 and Ba-133, the latter has intense X-ray emissions which contribute
The simulation of I-131 by Ba-133 is valid only for thick sodium iodide crystals because the probability of detection of a photon impinging on the detector approaches 1 and is hence less dependent on its energy.

### 3.2.2 I-129 simulating I-125

Iodine 125 is also produced in nuclear reactors and can be a radiological hazard in case of an accident. It has a half life of 59.4 days and decays by electron capture. The principal gamma and X-rays emitted are shown in table 3.2.2.1.

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Energy (keV)</th>
<th>Emission probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>35.5</td>
<td>6.7%</td>
</tr>
<tr>
<td>X-rays</td>
<td>27.2</td>
<td>40.1%</td>
</tr>
<tr>
<td></td>
<td>27.5</td>
<td>74.7%</td>
</tr>
<tr>
<td></td>
<td>30.9</td>
<td>6.9%</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>13.3%</td>
</tr>
<tr>
<td></td>
<td>31.7</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>31.7</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

Table 3.2.2.1: Principal X-ray and gamma radiation emissions from I-125 accompanied by the corresponding emission probabilities [6].

The low energy peaks of I-125 (27-35 keV) cannot be resolved by the scintillator detectors that is why only the BEGe was calibrated for I-125 in order to get more accurate results. When the BEGe detector was used, the two most prominent peaks of I-125, i.e. 27.2 keV (40.1%) and 27.5 keV (74.7%) appeared as one with a total emission probability of 114.8%. If the efficiency for this combined peak of I-125 is known, the thyroid activity will be derived as:

\[
A_{I_{125}} = \frac{N_{27.2+27.5keV}}{\varepsilon_{I_{125}} \cdot I_{27.2+27.5keV} \cdot t}
\]

Since the fast decaying I-125 was not available in the lab, vials with I-129 were used instead. I-129 emits energies close to the energies of I-125 but it has a much larger half life (15.7 million years) so it is a common practice to use it as a calibration source instead of I-125. I-129 decays through beta minus decay to Xe-129 and the principal gamma and X-rays emitted are shown in table 3.2.2.2.
3.2. CALIBRATION SOURCES

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Energy</th>
<th>Emission probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>39.6 keV</td>
<td>7.5%</td>
</tr>
<tr>
<td>X-rays</td>
<td>29.5 keV</td>
<td>19.9%</td>
</tr>
<tr>
<td></td>
<td>29.8 keV</td>
<td>36.7%</td>
</tr>
<tr>
<td></td>
<td>33.6 keV</td>
<td>3.4%</td>
</tr>
<tr>
<td></td>
<td>33.6 keV</td>
<td>6.6%</td>
</tr>
<tr>
<td></td>
<td>34.4 keV</td>
<td>2%</td>
</tr>
</tbody>
</table>

Table 3.2.2.2: Principal gamma radiation emissions from I-129 accompanied by the corresponding emission probabilities [6].

When the BEGe was used, the two most prominent peaks of I-129 (29.5 keV (19.9%) and 29.8 keV (36.7%)) appeared as one with a total emission probability of 56.7%. This is clear in figure 3.2.2.1 where the spectrum of I-129 is shown. The combination of these two peaks is very close to the energy of interest (∼27.5 keV of I-125) hence, it was used in order to derive the corresponding peak efficiency:

$$\varepsilon_{I125} \approx \varepsilon_{I129} = \frac{N_{29.5+29.8\text{keV}}}{A_{I129}\cdot I_{29.5+29.8\text{keV}} \cdot t}$$

The vials containing I-129 solution that were used are shown in figure 3.2.2.2. These sources were already available (new I-129 vials were not manufactured) and their shape is significantly different from the vials containing I-131. The active volume in each vial was 10 ml (2×10 ml = 20 ml for the whole thyroid gland corresponding to the adult
case of thyroid). The active diameter of the solution in each vial was 23.8 mm and the active height 22.5 mm.

Figure 3.2.2.2: Pair of vials containing I-129 simulating the two lobes of a thyroid gland contaminated by I-125.

### 3.2.3 Eu-152

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Emission probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>121.8</td>
<td>28.7%</td>
</tr>
<tr>
<td>244.7</td>
<td>7.6%</td>
</tr>
<tr>
<td>344.3</td>
<td>26.6%</td>
</tr>
<tr>
<td>778.9</td>
<td>13%</td>
</tr>
<tr>
<td>964.1</td>
<td>14.7%</td>
</tr>
<tr>
<td>1085.9</td>
<td>10.2%</td>
</tr>
<tr>
<td>1112.1</td>
<td>13.7%</td>
</tr>
<tr>
<td>1408</td>
<td>21.1%</td>
</tr>
</tbody>
</table>

Table 3.2.3.1: Principal gamma radiation emissions from Eu-152 accompanied by the corresponding emission probabilities [6].

Eu-152 was used for establishing quality assurance charts for the spectrometers. It has a half life of 13.54 years and decays through beta plus, electron capture or beta minus decay. The major gamma radiation emissions from Eu-152 are shown in table 3.2.3.1. The Eu-152 spectra acquired by BEGe and NaI(Tl) 3x3-inch, Inspector 2000 are shown in figure 3.2.3.1.
Figure 3.2.3.1: Eu-152 gamma spectra acquired by BEGe and NaI(Tl) 3x3-inch, Inspector 2000.

The point-like sources of Eu-152 shown in figure 3.2.3.2 have been used to establish the quality assurance charts and should be available for future QA checks.

Figure 3.2.3.2: Eu-152 sources used for quality control.
3.3 Neck phantoms

The efficiency calibration of thyroid monitoring detection systems is usually performed using neck phantoms that simulate the human neck geometry and have photon attenuation properties similar to the human tissue.

The chosen material for the neck phantoms was PMMA/PA6 which has density $\varrho$ and photon attenuation coefficient $\mu$ similar to those of the soft tissue, as shown in table 3.3.0.2. The neck phantoms bore cylindrical holes to accommodate the pairs of vials that represented the different cases of thyroid gland. The thickness of the material between the holes and the surface of the phantom periphery was chosen according to age and corpulence in order to represent the overlying tissue layer in the human neck as realistically as possible.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varrho$ [g/cm$^3$]</th>
<th>$\mu/\varrho$ [cm$^2$/g]</th>
<th>$\mu$ [cm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (matrix)</td>
<td>1.00</td>
<td>0.1105</td>
<td>0.1105</td>
</tr>
<tr>
<td>PMMA/PA6 (phantom)</td>
<td>1.19</td>
<td>0.1073</td>
<td>0.1277</td>
</tr>
<tr>
<td>Soft tissue</td>
<td>1.06</td>
<td>0.1095</td>
<td>0.1161</td>
</tr>
</tbody>
</table>

Table 3.3.0.2: Density and mass attenuation coefficients for soft tissue and phantom material for 364.5 keV photons [12]

In practice, the large anatomical variability among different individuals, namely in the depth, size, shape and position of the thyroid gland, results in discrepancies between experimental calibration and real measurements, since typical phantoms feature average thyroid description. Moreover, whereas the calibration is performed in well-defined geometrical conditions, the real measurement might not reproduce the exact same conditions, since individual posture can substantially change the distance and alignment between the thyroid and the detector [13].

In general, the anatomic variability of the thyroid, as well as the differences in the detection geometry, can significantly influence the thyroid practical measurement, depending on the considered energy range [13].

3.3.1 Phantoms for calibration for I-131

The neck phantom for children and teenagers bore four pairs of holes (4 cases of thyroid for 1, 5, 10 and 15 years old) as shown in figure 3.3.1.1. The neck phantom for adults bore three identical pairs of holes, located at different depths as shown in figure 3.3.1.2. The dimensions of those phantoms that were used for calibration for I-131 are shown in table 3.3.1.1.
3.3. NECK PHANTOMS

Figure 3.3.1.1: Neck phantoms for children and teenagers for calibration for I-131.

Figure 3.3.1.2: Neck phantoms for adults for calibration for I-131.
In an attempt to represent the depth of the thyroid gland in a realistic way, the thickness of the overlying tissue layer was gradually increased from the case of the 1 year old child (8 mm) up to the case of adult1\(^3\) (15 mm). The second and third case of adult (adult2 and adult3) were exactly the same with the adult1 case with respect to the dimensions of the vials (the same vials were used) but a thicker tissue layer was chosen (19 mm and 23 mm, respectively) to account for more corpulent people. A cross section of a neck phantom including the radius \(R\) of each hole (thyroid lobe), the thickness of the overlying tissue layer \(T\) and their sum \((D=R+T)\) is depicted in figure 3.3.1.3. The corresponding values for all cases of thyroid are shown in figure 3.3.1.4.

Table 3.3.1.1: Cases of thyroid and dimensions of the neck phantoms used for calibration for I-131.

<table>
<thead>
<tr>
<th>Neck/thyroid phantom</th>
<th>Children and Teenagers</th>
<th>Adults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>10 cm</td>
<td>13 cm</td>
</tr>
<tr>
<td>Height</td>
<td>12 cm</td>
<td>14 cm</td>
</tr>
<tr>
<td>Cases of thyroid</td>
<td>1, 5, 10 and 15 yold</td>
<td>15, 19 and 23 mm depth</td>
</tr>
</tbody>
</table>

\(3\) Adult1 was taken as a reference case for the neck/thyroid geometry throughout this study.
3.3. NECK PHANTOMS

3.3.2 Phantom for calibration for I-125

The phantom that was used for calibration for I-125 is shown in figure 3.3.2.1. This phantom had a diameter of 13 cm, a height of 14 cm and bore two pairs of holes for adult thyroid glands at two different depths (15 mm and 23 mm). Distance from thyroid center-line to neck surface and the parts it consists of are shown in table 3.3.2.1.

<table>
<thead>
<tr>
<th></th>
<th>Radius [mm]</th>
<th>Tissue thickness [mm]</th>
<th>Total distance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>adult4</td>
<td>11.9</td>
<td>15</td>
<td>26.9</td>
</tr>
<tr>
<td>adult5</td>
<td>11.9</td>
<td>23</td>
<td>34.9</td>
</tr>
</tbody>
</table>

Table 3.3.2.1: Distance from thyroid center-line to neck surface for all cases of thyroid in the phantoms used for calibration for I-125.
3.4 Software

The software used for gamma spectrum acquisition, conversion and analysis as well as for calculations is listed in table 3.4.0.2.

<table>
<thead>
<tr>
<th>Software</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genie 2000 package, Canberra</td>
<td>Acquisition &amp; analysis of gamma spectra</td>
</tr>
<tr>
<td>WinTMCA-32</td>
<td>Acquisition of gamma spectra from NANOSPEC-pro detector</td>
</tr>
<tr>
<td>Inspector 1000 Maintenance, V.1.2</td>
<td>Transfer spectra and calibration files from/to NaI2x2, Inspector1000</td>
</tr>
<tr>
<td>Cambio File Converter (Nucleonica website)</td>
<td>Covert the N42 files (spectra) from the LaBr detector so that they can be processed by Genie 2000</td>
</tr>
<tr>
<td>Microsoft Office Excel 2013</td>
<td>Calculations &amp; derivation of charts</td>
</tr>
</tbody>
</table>

Table 3.4.0.2: Software used for the calibration of the detectors.
3.5 Holders for quality control

The purpose of designing and using a holder for the calibration sources and the spectrometers is to keep both at a certain distance and geometry. This way, identical measurements can be repeated over a large period of time in order to establish quality assurance charts. The variability of the FWHM and decay corrected area of certain energy peaks was recorded, setting criteria for consistent operation of the detectors in the future (QA checks). Figure 3.5.0.2 shows the holder for BEGe and figure 3.5.0.3 shows the holder used for the rest of the spectrometers.

![Figure 3.5.0.2: Holder for BEGe.](image1)

![Figure 3.5.0.3: Holder for all detectors apart from BEGe and the rate meters.](image2)
3.6 Lead shield

The available lead shield shown in figure 3.6.0.4 was suitable only for the case of the NaI(Tl) 2x2-inch, UNISPEC detector. It had a rectangular shape and bore a cylindrical hole to accommodate the detector. Its dimensions are shown in table 3.6.0.3. The effect of shielding on the minimum detectable activity was studied by using this detector with and without the shield, in order to acquire the background spectrum.

![Lead shield for the NaI(Tl) 2x2-inch, UNISPEC.](image)

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>27.5</td>
</tr>
<tr>
<td>Width</td>
<td>10</td>
</tr>
<tr>
<td>Height</td>
<td>10</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.6.0.3: Dimensions of the lead shield for the NaI(Tl) 2x2-inch, UNISPEC.
Chapter 4

Results and discussion

4.1 I-131

4.1.1 Peak efficiency of spectrometers

In figures 4.1.1.1 and 4.1.1.2, the efficiency calibration factors\(^1\) with respect to the 364.5 keV peak of I-131 for all spectrometers and thyroid cases at 1 cm and 15 cm neck-detector distance are plotted. The bars represent an uncertainty of around 5% for all cases of thyroid (confidence level of 95%) as explained in the following chapter.

![Efficiency for 364.5 keV at 1 cm distance](image)

Figure 4.1.1.1: Peak efficiency of the detectors for 364.5 keV photons for all thyroid cases at 1 cm neck-detector distance

\(^1\)The numerical values of all efficiency calibration factors for I-131 are shown in Appendix A
The efficiency at 15 cm neck-detector distance was one order of magnitude smaller compared to 1 cm neck-detector distance.

The sodium iodide 3x3-inch detector has the highest efficiency, followed by the three sodium iodide detectors with a smaller 2x2-inch crystal. The germanium detector has the smallest efficiency of all. The lanthanum bromide detector was not used for the 1 cm distance because its inconvenient shape would not allow to bring it so close to the neck of a person. Its efficiency is very low compared with the efficiency of the sodium iodide detectors because of the much smaller dimensions of the lanthanum bromide crystal.

Efficiency decreases for thyroid cases of older or more corpulent people because of the thicker overlying tissue layer but possibly also because of the more significant absorption of radiation by thyroid glands of larger volume (self-absorption). The lines connecting the data points in figures 4.1.1.1 and 4.1.1.2 were used just to show this trend.

It is common practice to use an adult neck/thyroid phantom to represent all cases of thyroid when it comes to the calibration of detectors for thyroid screening. Although it is true that the uncertainties due to anatomical variabilities are large enough to justify such an oversimplification, it is worth mentioning the effect on the derivation of the thyroid activity if only the efficiency for the reference case of adult1 is used. If the subscript \(i\) is used to denote any particular thyroid case, \(A_{\text{adult}1}\) to denote the thyroid activity of I-131 when using the efficiency for adult1 and \(A_i\) to denote the real thyroid activity of I-131 when using the actual efficiency \(\varepsilon_i\) of the particular thyroid case, then:

\[
A_i = \frac{N}{\varepsilon_i \cdot I \cdot t} = \frac{N}{\varepsilon_{\text{adult}1} \cdot I \cdot t} \cdot \frac{\varepsilon_{\text{adult}1}}{\varepsilon_i} \Rightarrow A_i = A_{\text{adult}1} \cdot \frac{\varepsilon_{\text{adult}1}}{\varepsilon_i}
\]
Figure 4.1.1.3: Activity multipliers for I-131 for all thyroid cases at 1 cm neck-detector distance taken the case of adult1 as a reference.

Figure 4.1.1.4: Activity multipliers for I-131 for all thyroid cases at 15 cm neck-detector distance taken the case of adult1 as a reference.
which means that in order to get the real value of thyroid activity activity $A_i$, the result $A_{\text{adult1}}$ should be multiplied (corrected) by a factor $\varepsilon_{\text{adult1}}/\varepsilon_i$ according to the case of thyroid. This activity multiplier is plotted in figures 4.1.1.3 and 4.1.1.4.

At 1 cm neck-detector distance, for the extreme case of 1 year old children, the activity multiplier is around 0.5. This means that, if the efficiency for adult1 $\varepsilon_{\text{adult1}}$ was used instead of the correct one $\varepsilon_{\text{1yold}}$, the estimated thyroid activity would have twice the value it should (+100% overestimate). At the other extreme, the thyroid activity of corpulent people would have been underestimated by approximately 25%. At 15 cm neck-detector distance, these deviations would become smaller (+40% and -15%, respectively) because in this case, the efficiency becomes less dependent on the geometrical characteristics of the phantom or the person’s neck/thyroid anatomy.

The spectrometers were calibrated with respect to the characteristic peaks of both I-131 and its simulating source Ba-133. The comparison between the two cases confirmed that Ba-133 gives valid results as well since the difference in efficiency was within the uncertainty limits for all detectors. This is shown in figures 4.1.1.5 and 4.1.1.6, which correspond to the reference case of adult1 at 1 cm and 15 cm neck-detector distance, respectively.

![Efficiency at 1 cm distance](image)

**Figure 4.1.1.5:** Comparison of peak efficiency of the detectors for 356 keV and 364.5 keV photons of Ba-133 and I-131 respectively, for the reference thyroid case of adult1, at 1 cm neck-detector distance
4.1.2 Detection limits of spectrometers

The minimum detectable activity of I-131 with respect to the 364.5 keV peak for all cases of thyroid when the various detectors are used for a counting time of 1000 seconds (16.7 minutes) is shown in figures 4.1.2.1 and 4.1.2.2 at 1 cm and 15 cm neck-detector distance, respectively. The MDA calculations were made by Genie 2000, based on the Currie’s formula described in section 2.2.
CHAPTER 4. RESULTS AND DISCUSSION

Figure 4.1.2.1: Minimum detectable activity for I-131 for all thyroid cases at 1 cm neck-detector distance and 1000 s acquisition time.

Figure 4.1.2.2: Minimum detectable activity for I-131 for all thyroid cases at 15 cm neck-detector distance.
4.1. I-131

Cases of older and more corpulent people result in higher MDA values because the efficiency is smaller. In addition, the values of MDA at 15 cm neck-detector distance were significantly larger (one order of magnitude) compared with the cases where the neck-detector distance was 1 cm, mainly because of the smaller efficiency but also because the neck itself functions as an additional shield for the detector (reduced background radiation levels).

The BEGe detector has lower detection limits compared with the rest of the spectrometers. This may be a sufficient reason for preferring it to sodium iodide detectors for low activity measurements, even though the scintillation detectors have greater efficiency. With good resolution, a peak with a few counts in it will concentrate those counts into only a few channels and those channels will stand out more distinctly above the background continuum. This enables more reliable detection and measurement especially when it comes to spectra containing small peaks on an uncertain background [15].

However, 1000 seconds acquisition time is large compared with the times normally chosen for rapid thyroid screening mainly because few detectors and personnel are available to cope with large groups of people. For this reason, the MDA was also calculated for 60 seconds acquisition time at 1 cm neck-detector distance. The results are shown in figure 4.1.2.3.

![Graph showing MDA of I-131 for 60 s measurement at 1 cm distance](image)

**Figure 4.1.2.3:** Minimum detectable activity for I-131 for all thyroid cases at 15 cm neck-detector distance and 60 s acquisition time.

The MDA values shown in figures 4.1.2.1, 4.1.2.2 and 4.1.2.3 were calculated without using any shield around the detectors or placing them inside a bunker (shielded room). However, the use of a shield around the detectors can substantially reduce the level of
background radiation which leads to lower detection limits and more reliable measurements. When a lead shield was used around the NaI2x2unispec, the MDA values were reduced by 60% for all thyroid cases, as shown in figure 4.1.2.4. For this reason, shielding the detectors during thyroid screening is strongly recommended.

![Graph showing the effect of lead shield on MDA](image)

Figure 4.1.2.4: Effect of lead shield around the NaI(Tl) 2x2-inch, UNISPEC detector on the MDA for all cases of thyroid at 1 cm neck-detector distance.

### 4.1.3 Monitors

**Dose rate probe Automess**

By using the fast decaying I-131 sources over a period of a few days and the reference thyroid case of adult1, the linear relationship between the dose rate and the corresponding thyroid activity was derived. This is shown in figure 4.1.3.1 for three neck-detector distances: 1 cm, 5 cm and 10 cm. For example, at 1 cm neck-detector distance, the simple formula (and the calibration factor) to derive the thyroid activity is:

\[
\text{Thyroid I} - 131 \ [kBq] = 0.08 \cdot [nSv/h] - 2.26
\]

\[
\text{Calibration Factor} = 0.08 \frac{kBq}{nSv/h}
\]

The vertical bars correspond to the uncertainty in the activity of the sources (95% confidence level) and the horizontal bars correspond to the range of the fluctuating indication of the dose rate in each measurement.
4.1. I-131

Figure 4.1.3.1: Relation between thyroid I-131 activity and dose rate for the dose rate probe Automess at various distances.

It should be noted that the calibration certificate of the detector is necessary in order to check if there is a systematic error in the measurement. If that is the case, the values of dose rate in figure 4.1.3.1 will have to be corrected accordingly. The calibration certificate is also necessary if the same detector, available anywhere in the world, is to use the calibration factors derived in this study for thyroid screening measurements.

**Thermo Scientific alpha and beta contamination probe**

By using the fast decaying I-131 sources over a period of a few days and the reference thyroid case of adult1, the linear relationship between the count rate and the corresponding thyroid activity was derived. This is shown in figure 4.1.3.2 for two neck-detector distances: 1 cm and 5 cm. For example, at 1 cm neck-detector distance, the simple formula (and the calibration factor) to derive the thyroid activity is:

\[
\text{Thyroid } I^{131} \text{ [kBq]} = 0.50 \cdot [\text{cps}] + 3.53
\]

\[
\text{Calibration Factor} = 0.5 \frac{\text{kBq}}{\text{cps}}
\]

The vertical bars correspond to the uncertainty in the activity of the sources (95% confidence level) and the horizontal bars correspond to the range of the fluctuating indication of the counting rate in each measurement.
CHAPTER 4. RESULTS AND DISCUSSION

The calibration certificate of the Thermo Scientific contamination probe refers only to alpha and beta radiation and thus no quantitative results can be drawn for the response to gamma radiation. The only thing that can and should be checked for the use of the detector is the consistency in the alpha and beta radiation response. If there is no systematic error in the future calibration certificate, it can be concluded that the response of the detector to gamma radiation is the same as during the period that it was calibrated. However, if there is a systematic error, the detector cannot be used because no correction can be applied in this case.

900 Series Mini Monitor

By using the fast decaying I-131 sources over a period of a few days and the reference thyroid case of adult1, the linear relationship between the count rate and the corresponding thyroid activity was derived. This is shown in figure 4.1.3.3 for three neck-detector distances: 1 cm, 5 cm and 10 cm. For example, at 1 cm neck-detector distance, the simple formula (and the calibration factor) to derive the thyroid activity is:

\[
\text{Thyroid I} - 131 \ [kBq] = 0.12 \cdot \text{[cps]} + 3.05
\]

\[
\text{Calibration Factor} = 0.12 \frac{kBq}{\text{cps}}
\]

The vertical bars correspond to the uncertainty in the activity of the sources (95%
confidence level) and the horizontal bars correspond to the range of the fluctuating indication of the dose rate in each measurement.

Figure 4.1.3.3: Relation between thyroid I-131 activity and counting rate for the 900 Series Mini Monitor.

It should be noted that the calibration certificate of the detector is necessary in order to check if there is a systematic error in the measurement. If that is the case, the values of dose rate in figure 4.1.3.3 will have to be corrected accordingly. The calibration certificate is also necessary if the same detector, available anywhere in the world, is to use the calibration factors derived in this study for thyroid screening measurements.

**Detection limits of monitors**

Typical contamination monitors used for screening have a minimum detectable activity of 2000 Bq for I-131 [4].

### 4.2 I-129 simulating I-125

The efficiency of the BEGe for the two most prominent peaks of I-129 (29.5 keV and 29.8 keV) which appear as one peak in the spectrum is shown in figure 4.2.0.4.

These values of efficiency were used in order to derive the minimum detectable activity of I-125 for 1000 s measurement time, shown in figure 4.2.0.5.

For 60 seconds measurement time at 1 cm distance, the MDA of I-125 was 19.8 Bq for adult4 and 31.9 Bq for adult5.
CHAPTER 4. RESULTS AND DISCUSSION

Figure 4.2.0.4: Peak efficiency of the BEGe for the ∼29 keV peak of I-129 for the thyroid cases of adult4 and adult5 at 1 cm and 15 cm neck-detector distance.

Figure 4.2.0.5: Minimum detectable activity of I-125 with respect to the ∼27 keV peak, when BEGe is used, for the thyroid cases adult4 and adult5 at 1 cm and 15 cm neck-detector distance. The measurement time is 1000 seconds.
4.3 Quality Assurance charts

Quality Assurance charts were established for all spectrometers with respect to the Full Width at Half Maximum and the decay corrected area of three prominent peaks of Eu-152: 121.8 keV, 344.3 keV and 1408 keV. Out of those 36 charts, two of them are presented below as examples. For the NaI(Tl) 3x3-inch (Inspector 2000) detector, the recorded values of the FWHM and the decay corrected area for the 344.3 keV peak are shown in figures 4.3.0.6 and 4.3.0.7, respectively. The QA charts include warning levels indicated by horizontal yellow lines and action levels indicated by horizontal red lines.

![Quality Assurance chart for the FWHM of the 344.3 keV peak of Eu-152](image)

**Figure 4.3.0.6**: NaI(Tl) 3x3-inch, Inspector 2000: Quality Assurance chart for the FWHM of the 344.3 keV peak of Eu-152.

---

\(^2\)The warning and action levels for the FWHM and the decay corrected area of three prominent peaks of Eu-152 for all spectrometers are shown in Appendix B
Figure 4.3.0.7: NaI(Tl) 3x3-inch, Inspector 2000: Quality Assurance chart for the decay corrected area of the 344.3 keV peak of Eu-152.
Chapter 5

Uncertainty Analysis for I-131

5.1 Efficiency calibration factors

Each efficiency calibration factor that is going to be used in a thyroid monitoring campaign was calculated according to a model of the real geometry and conditions:

$$\varepsilon_m = \frac{N_m}{A_m \cdot I \cdot t}$$

The combined relative standard uncertainty in the estimation of the efficiency calibration factor (all input quantities are uncorrelated) is given by the following equation, according to the ISO Guide to the Expression of Uncertainty in Measurement following equation [16]:

$$u_{\varepsilon_m} = \sqrt{u_{N_m}^2 + u_{A_m}^2 + u_I^2 + u_t^2}$$

The uncertainty in the area under the peak of interest $u_{N_m}$ is the result from the counting statistics that follow the Poisson probability distribution and it is directly given by the gamma spectrum analysis software (Type A evaluation of standard uncertainty). The acquisition time was chosen large enough so that the counts in the area under the peak were far more than 10000. Therefore, the corresponding relative standard uncertainty was less than 1% (in most cases between 0.1-0.5%).

The uncertainty in the activity of the calibration sources $u_{A_m}$ used in the lab model follows the normal probability distribution and it was stated in the certificate of the sources given by the manufacturer (Type B evaluation of uncertainty). For the I-131 sources, the relative uncertainty for each vial was 3-14% (coverage factor $k = 2$) and for the I-129 vials it was 2% (coverage factor $k = 2$). Since the thyroid activity in the lab model $A_m$ is the sum of the activities of the two vials simulating the two lobes, the corresponding relative uncertainty will be:

$$u_{A_m} = \sqrt{u_{A_{vial1}}^2 + u_{A_{vial2}}^2}$$
Normally, the relative standard uncertainty in the emission probability $u_I$ is relatively small and often neglected in these applications but especially for the 364.5 keV peak of I-131 which is the main nuclide of interest, it has a value of 0.76% [6]. This value is comparable with the other uncertainties so it was also taken into account.

The precision in the acquisition time was 0.01 seconds. Therefore, the related uncertainty was considered to be negligible and was not taken into account.

As a result, the combined relative standard uncertainty in the estimation of the efficiency calibration factor becomes:

$$u_{\varepsilon_m} \approx \sqrt{u_{N_m}^2 + u_{A_m}^2 + u_I^2}$$

This value was multiplied by 2 in order to get the combined uncertainty with a coverage factor of $k = 2$ and the bars in the plots of efficiency in figures 4.1.1.1 and 4.1.1.2 correspond to this combined uncertainty. As an example, the various uncertainties together with the combined uncertainty ($k = 2$) in the estimation of the peak efficiency of I-131 for the reference case of adult1 when the NaI(Tl) 3x3-inch, Inspector 2000 was used, are presented in figure 5.1.0.1.

![Figure 5.1.0.1: Total uncertainty of thyroid I-131 activity (coverage factor k=2) assuming no uncertainty due to position (lab measurements). NaI(Tl) 3x3-inch, Inspector 2000 was used and the case of adult1 was taken as a reference.](image)

As regards the I-131 measurements, in all cases of thyroid and detectors that were studied, the relative uncertainty in efficiency was less than 6% (coverage factor $k = 2$)
and the major contributor was the uncertainty in the activity of the sources.

It is important to mention that the uncertainty in efficiency due to the uncertainty in the relative position of the detector with respect to the neck phantom during the calibration measurements was neglected. This is because in the lab measurements, there was no physical movement as it would be the case with a real person being monitored and it was assumed that the neck-detector distance could be measured and controlled with sufficient accuracy and precision.

5.2 Activity of radioiodine in a contaminated thyroid

The activity of the contaminated thyroid of a person being monitored in a campaign will be calculated according to the formula:

\[ A = \frac{N}{\varepsilon \cdot I \cdot t} \]

where the efficiency \( \varepsilon \) refers to the real geometry, thyroid and conditions when a particular person is being monitored. The corresponding relative uncertainty in the estimation of the thyroid activity is (all input quantities are uncorrelated):

\[ u_A = \sqrt{u_N^2 + u_\varepsilon^2} \]

The uncertainties in the emission probability and measurement time were neglected because (as shown later) they are negligible compared with the other two terms of uncertainty.

However, it is not possible to know the real efficiency of each particular case hence, the efficiency calibration factor based on the lab model is used instead:

\[ \varepsilon \approx \varepsilon_m \]

\[ A = \frac{N}{\varepsilon \cdot I \cdot t} \Rightarrow A \approx \frac{N}{\varepsilon_m \cdot I \cdot t} \]

This approximation means that the lab measurement (in an attempt to imitate the real geometry and conditions) results in a calibration factor that is the best estimate of the real value of efficiency.

At this point, it would be useful to assume a correction factor to derive the real efficiency from the efficiency of the lab model:

\[ \varepsilon = e \cdot \varepsilon_m \]

The correction factor \( e \) can incorporate and account for all those variables (reasons, conditions and phenomena) that result in an estimate of efficiency \( \varepsilon_m \) that inevitably deviates from the real value \( \varepsilon \).

The major contributor to the difference between the real and the model efficiency is the difference in the geometry (other factors that may also affect the efficiency are
neglected in this study). Based on the assumption that $e \approx e_g$ where “g” stands for “geometry”:

$$A = \frac{N}{\varepsilon \cdot I \cdot t} \Rightarrow A = \frac{N}{e_g \cdot \varepsilon_m \cdot I \cdot t}$$

$$u_A = \sqrt{u_N^2 + u_e^2} \Rightarrow u_A = \sqrt{u_N^2 + u_{\varepsilon_m}^2 + u_{e_g}^2}$$

After a person has been monitored and the corresponding spectrum has been acquired, the gamma analysis software will calculate the relative uncertainty in the area under the peak of interest $u_N$. However, the relative uncertainty in the value of efficiency $u_e$ will be drawn by the calibration file that is loaded during the analysis of the gamma spectrum. This uncertainty combines the uncertainty of the efficiency calibration factor and the uncertainty in the model geometry, since it is an imitation of the real one:

$$u_e = \sqrt{u_{\varepsilon_m}^2 + u_{e_g}^2}$$

The way the relative uncertainty in the efficiency of the lab model $u_{\varepsilon_m}$ was derived was explained in the previous section.

As regards the uncertainty in the geometry used for calibration, the major factors that contribute to this uncertainty are:

- The volume and shape of the thyroid (anatomic variability).
- The thickness of the overlying tissue layer (anatomic variability).
- The relative position of the detector with respect to the neck of the person being monitored (postural variability).

This means that the geometry correction factor can be written as a product of the respective partial factors:

$$e_g = e_{\text{thyroid}} \cdot e_{\text{layer}} \cdot e_{\text{position}}$$

$$u_{e_g}^2 = u_{e_{\text{thyroid}}}^2 + u_{e_{\text{layer}}}^2 + u_{e_{\text{position}}}^2$$

### 5.2.1 The volume and shape of the thyroid

Although some statistical data may exist about the variation in the thyroid volume and shape, it is very difficult to estimate the uncertainty in the thyroid activity due to the uncertainty in the volume and shape of the gland. This is because of the irregular shape of the gland, the large variability in its volume and especially due to the complicated relationship between these two parameters and the efficiency of the corresponding geometry. That means that such an uncertainty analysis would require more elegant tools such as Monte Carlo simulations where realistic models of the thyroid gland could be...
used. The volume and shape of the gland could be changed in those models in order to study the effect on the related efficiency. Since Monte Carlo simulations were not included in the present study, this kind of uncertainty analysis was not carried out. However, the plots in figure 5.2.1.1 from ICRP and figure 5.2.1.2 from a survey in Dutch schoolchildren can give substantial information on the variation in the thyroid mass and volume.

![Figure 5.2.1.1: Mass of the thyroid gland as a function of the postnatal age [9].](image)

Figure 5.2.1.1: Mass of the thyroid gland as a function of the postnatal age [9]. The specific gravity of the thyroid gland is approximately 1.05 and can be used to derive the corresponding values of thyroid volume.

![Figure 5.2.1.2: Thyroid size determined by ultrasound scanning in Dutch schoolchildren (408 boys and 529 girls) according to age [10].](image)

Figure 5.2.1.2: Thyroid size determined by ultrasound scanning in Dutch schoolchildren (408 boys and 529 girls) according to age [10].

### 5.2.2 The thickness of the overlying tissue layer

In order to estimate the uncertainty in the thyroid activity due to the uncertainty in the thickness of the overlying tissue layer (this uncertainty is related to the corpulence of the monitored person), the case of adult1 was taken as a reference (thickness of tissue layer = 15 mm). An upper bound of 23 mm for the thickness of the tissue layer was
considered and the efficiency of the detectors for this extreme case was found. The uncertainty related to the thickness of the overlying tissue layer was estimated assuming a rectangular probability distribution with the case of adult1 as the midpoint. The results are shown in figure 5.2.2.1.

![Figure 5.2.2.1: Uncertainty in thyroid I-131 activity due to uncertainty in the thickness of the overlying tissue layer. The case of adult1 is taken as a reference.](image)

According to figure 5.2.2.1 the relative uncertainty in the thyroid activity due to the uncertainty in the thickness of the overlying tissue layer is around 15% when the neck-detector distance is 1 cm and around 8% when the neck-detector distance is 15 cm.

### 5.2.3 Relative positioning of the detector

During thyroid monitoring it is practically impossible for the person to remain absolutely still for 15 minutes. Even if the detector is positioned correctly at the beginning, there is going to be some physical movement due to breathing and when the person feels uncomfortable. The uncertainty due to the relative position is the combination of the uncertainties of the relative position with respect to the three dimensions in the cartesian coordinate system:

\[ e_g = e_x \cdot e_y \cdot e_z \]

\[ u_{\text{position}}^2 = u_x^2 + u_y^2 + u_z^2 \]
In an attempt to account for the position changes in the three dimensions in a realistic way, it was assumed that the error is bounded within the limits mentioned in the table 5.2.3.1 and shown in figure 5.2.3.1.

<table>
<thead>
<tr>
<th>Neck-detector distance</th>
<th>1 cm</th>
<th>15 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-axis</td>
<td>± 1 cm</td>
<td>± 2 cm</td>
</tr>
<tr>
<td>y-axis</td>
<td>± 1 cm</td>
<td>± 2 cm</td>
</tr>
<tr>
<td>z-axis</td>
<td>± 2 cm</td>
<td>± 3 cm</td>
</tr>
</tbody>
</table>

Table 5.2.3.1: Assumed boundaries for the relative position of the detector with respect to the neck.

It is worth mentioning that the values presented in table 5.2.3.1 are rather conservative and can significantly be reduced if precautions are taken for correct and fixed positioning during the measurements in a rapid thyroid screening campaign.

**When the neck-detector distance is 1 cm.**

The head of the monitored person can be positioned properly with the use of a head holder. If the head is not allowed to move backwards, then the only movement that is allowed in the y-axis is forward, bringing the person closer to the detector. As a result, a ±1 cm position uncertainty was assumed with regard to the y-axis.

Assuming that the trachea of the person (around which the thyroid is located) is always in parallel with the center-line of the neck, it is easy to position the detector with relatively small uncertainty with regard to the x-axis. As a result, a ±1 cm position uncertainty was assumed with regard to the x-axis.

However, the vertical position of the thyroid is very difficult to estimate. In addition, the thyroid moves vertically whenever the person swallows and in some reported cases, the gland may even be partially located behind the upper part of the sternum (giving a lower thyroid activity than the real value). In order to account for the above, a ±2 cm position uncertainty was assumed with regard to the z-axis.

**When the neck-detector distance is 15 cm.**

All the above position uncertainties (for the 1 cm neck-detector distance) with regard to the three dimensions in cartesian coordinates, were increased by 1 cm to account for the higher probability of wrong positioning of the detector when the monitoring is carried out at the much larger distance of 15 cm.

The above geometrical description is depicted in figure 5.2.3.1.
Figure 5.2.3.1: Assumed boundaries for the relative position of the detector with respect to the neck.

Figure 5.2.3.2: Uncertainty in thyroid activity of I-131 due to the uncertainty in the position of BEGe, Inspector 2000, with respect to the three axes: x, y, z. The case of adult1 was taken as a reference.
5.2. ACTIVITY OF RADIOIODINE IN A CONTAMINATED THYROID

Based on the above, the efficiency was calculated at the positions shown in figure 5.2.3.1 and the uncertainties due to positioning in the three dimensions were found. In order to show the relative contribution of these uncertainties, namely $u_x$, $u_y$ and $u_z$, to the total $u_{pos}$, the case of the BEGe, Inspector 2000 detector was used as an example and the results are shown in figure 5.2.3.2.

It is obvious that the main contributor to the activity uncertainty due to positioning is the uncertainty in the neck-detector distance (along the $y$ axis). If the uncertainties in all three directions are combined, the total uncertainty in efficiency due to the uncertainty in the detector’s position is derived. The results are shown in figure 5.2.3.3 for all detectors at 1 cm and 15 cm neck-detector distance.

![Uncertainty due to positioning](image)

Figure 5.2.3.3: Total uncertainty in thyroid I-131 activity due to uncertainty in the position for all detectors. The case of adult1 is taken as a reference.

It should be mentioned that the measurement geometry is symmetrical with respect to the $x$ and $z$ axes but not with respect to the $y$ axis. As concerns the $y$ axis, bringing the detector 1 cm closer to the neck would result in a larger relative increase in efficiency compared with the relative decrease if the detector is moved away from the neck by 1 cm. This can be theoretically explained as follows:

$$
\varepsilon \propto N \propto \frac{S}{4\pi r^2} \propto \frac{1}{r^2} \Rightarrow \left| \frac{\partial \varepsilon}{\partial r} \right| \propto \frac{1}{r}
$$

where $S$ is the surface of the detector crystal and $r$ is the neck-detector distance.

That means that the further away the detector is placed with respect to the neck, the less sensitive is the efficiency to changes in position.
5.2.4 Total uncertainty

If all partial factors are taken into account for the correction factor of the model efficiency, then:

\[ \varepsilon = e \cdot \varepsilon_m \Rightarrow \varepsilon = e_{\text{res}} \cdot e_{\text{thyroid}} \cdot e_{\text{layer}} \cdot e_{\text{position}} \cdot \varepsilon_m \]

The term \( e_{\text{res}} \) accounts for residual factors that affect the efficiency and which were not taken into account (e.g. environmental conditions). Since \( e_{\text{res}} \) and \( e_{\text{thyroid}} \) were not studied, the remaining factors result in the following total relative uncertainty:

\[ u_{\varepsilon} = \sqrt{u_{\varepsilon_m}^2 + u_{\text{layer}}^2 + u_{\text{position}}^2} \]

The total relative standard uncertainty (\( k = 1 \)) in the estimation of efficiency at 1 cm and 15 cm neck-detector distance is shown in table 5.2.4.1.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Neck-detector distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_{\varepsilon_m} )</td>
<td>( \sim 3% )</td>
</tr>
<tr>
<td>( u_{\text{layer}} )</td>
<td>13...16%</td>
</tr>
<tr>
<td>( u_{\text{position}} )</td>
<td>17...23%</td>
</tr>
<tr>
<td>( u_{\text{total,max}} )</td>
<td>( \sim 40% )</td>
</tr>
</tbody>
</table>

Table 5.2.4.1: Relative standard uncertainties in the estimation of efficiency.

The values of these total relative standard uncertainties (40\% and 30\%) are very conservative because in a real thyroid monitoring campaign, the position uncertainty (which is the major contributor) can be reduced significantly (compared with the values of table 5.2.4.1) if certain precautions are taken. However, in order to account for \( e_{\text{res}} \) and \( e_{\text{thyroid}} \) which were not studied, the values of 40\% (1 cm distance) and 30\% (15 cm distance) were chosen to be introduced in the efficiency calibration files to express the total uncertainty in efficiency.

There may be several other reasons, related to systematic errors, that can lead to larger uncertainties. For example, many people may have thyroids much bigger than it is assumed in the design of the phantoms used during the calibration procedures. Moreover, the thyroid gland can be placed behind the sternum (partially shielded) or even some part of the iodine can be distributed outside the thyroid gland, in malignant tissues. Some diseases can also block parts of the thyroid so that they cannot gather iodine. In addition, in cases of serious contamination, the dead time of the detector may become too long which means that counts are lost from the ROI. Finally, an error is introduced if there is a rotation angle in the relative position of the detector with respect to the person being monitored. It can be expected, that in such cases, the uncertainties in the detection efficiency can be substantially larger [17]. However, these extreme cases were
not taken into account in this study.

The major goal of the present study was the derivation of the efficiency calibration factors for different cases of thyroid (different age groups) and not a complete uncertainty and sensitivity analysis. For this purpose, the volume of the thyroid and the thickness of the corresponding overlying tissue layer was different in each group (increasing with age) in order to represent the neck/thyroid geometries in a realistic way. Therefore, these two variables were not studied separately, keeping one constant and changing the other.

It is worth mentioning that measurements performed with I-129, a low-energy gamma emitter, are generally more affected by geometrical changes, when compared with measurements of higher energy gamma from I-131 [18]. This is because the attenuation coefficient for photons through matter is much larger for low energies (e.g. the $29$ keV X-rays of I-129) compared with higher energies (e.g. the 364.5 keV $\gamma$-ray of I-131).

### 5.3 The effect of large neck-detector distance

When the detector is placed at larger distances from the phantom or the person being monitored, the detector’s efficiency becomes less sensitive to the geometrical characteristics of the phantom or the neck/thyroid geometry. The reason for this is that the related dimensions become smaller with respect to the neck-detector distance and therefore, the contaminated thyroid or the corresponding lab sources resemble more and more to a point source.

Beyond a certain distance, the difference between the calibration factor obtained using different phantoms can be reduced far below the total uncertainty of a typical in vivo measurement of high energy radionuclides [19]. Such uncertainty is estimated as a value around 20% [20] but even higher values up to 50% have been reported [11]. Therefore, different phantoms can be used as far as the calibration and the thyroid monitoring are performed at a sufficiently large distance. This way, the estimated thyroid activity can be independent of the phantom used for the calibration of the detection system [19]. Likewise, using the same calibration factor for different people (different neck/thyroid geometries) may introduce a negligible error, if the neck-detector distance was sufficiently large.

The larger the neck-detector distance, the more parallel are the tracks of the gamma rays that impinge on the detector window. Hence, the impinging photons travel distances of similar lengths within the volume of the crystal and they are attenuated to a similar extent. In this case, their probability of contributing to the full energy peak is higher and the detector’s response is more homogeneous within its crystal.

A problem when the detector is too close to the phantom during calibration (or too close to the neck of the individual during thyroid screening) while the calibration sources are very radioactive (or the thyroid is very contaminated), the dead time may increase significantly. This way, counts are lost from the peak of interest. In the case of calibration this results in a smaller value of efficiency and hence, in an overestimation of
the thyroid activity during a campaign. When a person is undergoing thyroid screening, losing counts from the peak of interest means that the thyroid activity is underestimated.

In addition, too high counting rates in cases of serious accidental intakes of radioactive iodine may result in too long dead time of the counter and the measurements will have to be performed at distances much larger than normally used during the calibration.

The disadvantage of having the detector at larger distances from the neck is that the sensitivity decreases with distance as a function of $\sim d^{-2}$, which may require a long counting time to reach the necessary detection limit for individual monitoring. In addition, at larger neck-detector distances, the effect of the background radiation is stronger because the neck, in front of the detector, functions as a shield, filtering some of the background radiation.

Choosing the neck-detector distance is the result of a compromise between the above advantages and disadvantages. A short neck-detector distance (e.g. 1 cm) is preferable in the case of rapid thyroid screening when the counting time is short, the detection limits are high and there is a need for detecting high thyroid activities as quickly as possible. However, if a person is found to be seriously contaminated, a larger neck-detector distance can be used afterwards in order to get a more accurate result.
Chapter 6
Thyroid Monitoring Campaign

The purpose of a campaign for rapid monitoring for internal contamination over large groups of people after a nuclear accident is triage, i.e. to sort people into groups based on their need for or likely benefit from immediate medical treatment. As concerns internal contamination with radioactive iodine, the first step is to determine the current activity in the thyroid gland. For reasons that have been presented in detail in the section of uncertainty analysis, the results from this kind of measurements are inevitably accompanied by large uncertainties (30-50%) which are considered to be acceptable for the purposes of a rapid monitoring campaign nevertheless [21].

The preparations and precautions that should be taken at the beginning and during a thyroid monitoring campaign are explicitly described in TMT Handbook [22] as simple and straightforward guidelines. Other sources such as the Direct Methods for Measuring Radionuclides in the Human Body (IAEA) [21], Rapid Monitoring of Large Groups of Internally Contaminated People Following A Radiation Accident (IAEA) [23] as well as the Guidance on Screening people for Internal Radioactive Contamination (HPA-CRCE) [24] can also provide very helpful information. There, the reader can find guidelines for the monitoring team, internal contamination report forms and information about methods for triage and monitoring.

All the detectors included in the present study are planned to be movable and easy to carry. During thyroid screening in a campaign, they are planned to be held in hand, although they can also be placed to a stand. Examples of the postural geometry and the position of the detector are shown in figure 6.0.0.1.

Efforts to position the detector correctly and keep the person still during the measurement will ensure lower uncertainty in the estimation of the thyroid activity. Although the uncertainties included in the calibration files are between 30-50% in order to account for this kind of errors, taking these precautions will minimize any systematic errors due to wrong positioning or movement. The use of a comfortable seat with a holder for the head of the individual to keep the movement bounded is strongly recommended.

In addition, the use of a shield for the detectors and the seat is strongly recommended in order to minimize the background radiation level and keep the MDA values as low as possible. Shielding is even more important when measurements have to be carried out
in an environment with higher background activity, for example close to the place where an accidental release took place.

Figure 6.0.0.1: Examples of the postural geometry of the person that will undergo thyroid screening and the detector.

If a person is seriously contaminated by radioactive iodine and no shield is used for the detector during the monitoring procedure, radioiodine in the bloodstream all over the body will affect the thyroid screening results. In this case, a measurement at the thigh location (external side of the thigh at the half of its length) would correspond to the contribution of extra-thyroidal photons and can be used for subtraction. The thigh location was chosen as it represents a large and fleshy muscular region where body tissue seeking nuclides may migrate [25]. Therefore, the shield is also used to minimize the contributions due to radiation from other regions of the body not only from internal contamination but also from external contamination. Experience has shown that when
an internal contamination occurs, hair and hands are also contaminated.

Based on the above, a supporting system can be set as shown in figure 6.0.0.2 which also allows an easy height adjustment of the detector in order to get a proper alignment with the thyroid, assuring the correct geometrical configuration and the comfort of the monitored person.

![Figure 6.0.0.2: Ideal position of the person being monitored and the detector, using a lead collimator for the detector and a shield for the person’s seat [26].](image)

The use of a head rest is also strongly recommended to reduce the person’s movements during the thyroid monitoring. This lack of stabilization can contribute significantly to an increase in the thyroid monitoring uncertainties [13].
6.1 Thyroid screening using spectrometers

When spectrometers are used, measurement times of up to 5 minutes are short enough to cope with large groups of people and large enough to give a reliable indication for triage. If a person is contaminated to a level close to the lower action level, the activity of radioactive iodine in the gland will be sufficient to indicate this. A more accurate estimation of the thyroid activity can be derived with longer measurement times (e.g. 1000 seconds).

Once the spectrum is acquired and saved, the corresponding calibration file can be loaded to Genie 2000. The calibration file will have a name in the form:

\[<\text{Detector}>._<\text{Nuclide}>._<\text{Neck-Detector Distance}>._<\text{Thyroid Case}>\]

(e.g. NaI3x3inspector2000_I131_1cm_12-17yold) and it should be chosen according to the age of the person, using the ICRP grouping shown in table 6.1.0.1.

<table>
<thead>
<tr>
<th>Age group centroid</th>
<th>Range of age group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year</td>
<td>from 1y to 2y</td>
</tr>
<tr>
<td>5 years</td>
<td>more than 2y to 7y</td>
</tr>
<tr>
<td>10 years</td>
<td>more than 7y to 12y</td>
</tr>
<tr>
<td>15 years</td>
<td>more than 12y to 17y</td>
</tr>
<tr>
<td>Adult</td>
<td>more than 17y</td>
</tr>
</tbody>
</table>

Table 6.1.0.1: ICRP grouping according to age [9].

Once the appropriate calibration file is loaded, the spectrum can be analyzed by Genie 2000 by executing an Analysis Sequence that includes the following steps:

- Peak area that provides a report for all the peaks and their net peak areas accompanied by their uncertainties.
6.1. THYROID SCREENING USING SPECTROMETERS

**Figure 6.1.0.3**: Example of a peak analysis report by *Genie 2000*

- *Interactive peak fit* that gives the user the possibility to improve the peak analysis for each peak separately
- *Area correction* for background subtraction
- *Efficiency correction* that takes into account the efficiency for the characteristic energy of the nuclide of interest that is included in the loaded calibration file
- *Nuclide identification* that looks only for the characteristic energy of the nuclide of interest and returns a report with the estimated activity according to this value of efficiency

---

**Table 6.1.0.3.1: Sample Title**

<table>
<thead>
<tr>
<th>No.</th>
<th>start</th>
<th>end</th>
<th>centroid (keV)</th>
<th>Energy (keV)</th>
<th>FWHM (keV)</th>
<th>Area (MBq)</th>
<th>Uncert. (MBq)</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF</td>
<td>1</td>
<td>303</td>
<td>310</td>
<td>306.95</td>
<td>80.36</td>
<td>0.5535</td>
<td>117192.37</td>
<td>372.38</td>
</tr>
<tr>
<td>F</td>
<td>2</td>
<td>1080</td>
<td>1093</td>
<td>1087.25</td>
<td>284.16</td>
<td>0.8154</td>
<td>93047.06</td>
<td>554.67</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>1386</td>
<td>1400</td>
<td>1393.79</td>
<td>364.21</td>
<td>0.8973</td>
<td>103010.38</td>
<td>987.71</td>
</tr>
<tr>
<td>F</td>
<td>4</td>
<td>2427</td>
<td>2445</td>
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<td>636.48</td>
<td>1.1532</td>
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<td>265.67</td>
</tr>
<tr>
<td>F</td>
<td>5</td>
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<td>2774</td>
<td>2764.93</td>
<td>722.31</td>
<td>1.2204</td>
<td>9767.65</td>
<td>98.11</td>
</tr>
</tbody>
</table>

M = First peak in a multiplet region
m = Other peak in a multiplet region
F = Fitted singlet
Errors quoted at 1.000 sigma
Chapter 6. Thyroid Monitoring Campaign

Figure 6.1.0.4: Example of a nuclide identification report by Genie 2000

- The Detection limits step that gives the minimum detectable activity for each case of monitored person

Figure 6.1.0.5: Example of an MDA report by Genie 2000
The internal contamination report forms included in the TMT Handbook [22] can be used to record the personal information of the monitored person as well as the results of the analysis of the derived spectrum.

It should be noted that the efficiency calibration curve included in the calibration file is just a horizontal straight line that corresponds to the detector’s peak efficiency with respect to the nuclide of interest. Applying the same efficiency for all photon energies will give a valid result (nuclide identification and estimation of thyroid activity) only with respect to this characteristic peak. As a result, the efficiency calibration files together with the analysis sequence files provide nuclide identification and estimation of thyroid activity only with respect to the nuclide of interest. If the Peak Analysis report indicates the presence of other radionuclides, calibration files for the suspected nuclides should be loaded and analysis sequence files including the appropriate Nuclide Library File (extension .NLB) should be executed. The measurement geometry will also have to change accordingly for other organ-specific or whole-body-distributed radionuclides.
6.2 Thyroid screening using monitors

When monitors are used, the screening time needs to be only a few seconds so that the dose rate or count rate stabilizes. The detector’s response is an indication of the thyroid activity, as shown in figures 4.1.3.1, 4.1.3.2 and 4.1.3.3. These plots can be used to derive the thyroid activity even for larger values of dose or count rates by extrapolation.

However, these detectors should not be the first choice in a thyroid monitoring campaign for the following reasons:

- They cannot differentiate radiation coming from different nuclides (contamination by I-131 or other radionuclides). Since they give a total response (dose or count rate) to any kind of radiation (particle type or energy) that impinges on the detector, they overestimate the activity of I-131 in the thyroid gland.

- The Thermo Scientific alpha and beta contamination probe is supposed to be used for alpha and beta radiation, giving just a response to gamma radiation when switched to the beta channel. Therefore, the calibration certificate (calibration only for alpha and beta radiation) does not provide information about the measurement uncertainty or the existence of a systematic error in the detection of gamma radiation.

- The calibration certificates of the Automess dose rate meter and the 900 series mini monitor were not available which means that there is not sufficient information about the measurement uncertainties and the possible existence of systematic errors.

Nevertheless, these three detectors give a quantitative response to gamma radiation and their indication (dose rate or count rate) should be significantly large in order to reach the lower action level of I-131 activity in the thyroid gland. That means that they may not be the ideal instruments for accurate quantification of the I-131 thyroid activity but they can still be used for triage since they can indicate exceedingly high thyroid activity in a few seconds.
6.3 Action levels and triage for I-131

Once the present activity of radioactive iodine in the thyroid is derived, the initial intake of radiiodine and the committed effective dose because of this intake can be estimated. These calculations are based on biokinetic models and dose coefficients established by ICRP which are accompanied by large uncertainties. Although the present study is focused on the determination of the thyroid activity of radiiodine, a short summary of these sources of uncertainty is noteworthy since they exceed significantly the uncertainties related to the estimation thyroid activity. The uncertainties related to the biokinetic and dosimetric model are:

1. Thyroid retention measurement uncertainties.
2. Biokinetic model parameter uncertainties: iodine transfer from blood to thyroid.
3. Dosimetric model parameter uncertainties: mass of the thyroid, fraction of ingested iodine absorbed by the thyroid, biological half-time of residence of iodine in the thyroid.

Since the present thyroid activity results in a committed effective dose, critical levels for the committed effective dose can be inversely translated into critical levels for the current thyroid activity and hence, for the indication given by the detector (net peak area, count rate or dose rate).

Although the dosimetric calculations and final triage will probably be conducted by (or according to) the public health authority, action and warning thyroid activity levels for adults and children with respect to two common ways of intake (ingestion and inhalation of type F) are presented. The purpose is to give a meaning to the thyroid activities found (and an idea of their critical values) as well as to offer a quick and simple method for triage.

The TMT Handbook [22] includes tables on the dose from an intake by ingestion or inhalation of I-131 (absorption type F) that corresponds to a measurement of 1 Bq in thyroid at specified times after a single intake by adults. By using the value of 200 mSv as an upper action level for the committed effective dose due to internal contamination (proposed by the TIARA project [27]), the upper action level for the measured thyroid activity at various times after intake can be derived. The triage is conducted according to the following guidelines:

- Values of thyroid activity beyond the upper action level ($AL_U$) shown in figures 6.3.0.6 and 6.3.0.7, indicate that the person is probably seriously contaminated and this should be verified urgently with primary (more accurate) monitoring methods.

- Reaching the $AL_U$ is an extreme case before which a warning level should be established. This is the lower action level $AL_L$ which is usually taken to be 10 times lower than the $AL_U$ and is shown in figures 6.3.0.6 and 6.3.0.7. A measurement that
exceeds the lower action levels but lies still below the upper action level indicates that the person is potentially contaminated to an extent that may require further treatment but primary monitoring methods are needed in order to determine the thyroid activity more accurately. In a more conservative approach, the $AL_U / AL_L$ ratio may be chosen to be higher than 10.

- When the measurement lies below the lower action level, the person does not run any significant risk but can still be considered for inclusion in a program of long-term follow up monitoring.

In order to derive the upper and lower action levels for children shown in figures 6.3.0.8 and 6.3.0.9, the corresponding values for adults are divided by a factor (usually 10). Based on the biokinetic and dosimetric models for children, I-131 is rapidly taken up by the thyroid gland and proceeds at a higher metabolic rate in a child. This, combined with the short half-life of I-131 (8.03 days) results in higher doses to children [25]. Hence, the corresponding action levels are significantly lower compared to adults to account for the sensitivity of young people to radiation effects. However, this factor of 10 can be increased further in a more conservative approach.

![Figure 6.3.0.6: Action levels for inhalation of I-131 (type F) for adults.](image-url)
6.3. ACTION LEVELS AND TRIAGE FOR I-131

Figure 6.3.0.7: Action levels for ingestion of I-131 for adults.

Figure 6.3.0.8: Action levels for inhalation of I-131 (type F) for children and teenagers.
Figure 6.3.0.9: Action levels for ingestion of I-131 for children and teenagers.
Chapter 7

Conclusions

In this study, several radiation detection systems were calibrated for rapid thyroid screening checks for internal contamination by radioactive iodine. The peak efficiency of the detectors was found to be of the order of a few percent at 1 cm neck-detector distance (1-6% for all thyroid cases) and one order of magnitude lower at 15 cm neck-detector distance. As concerns the lab measurements, the uncertainty from the counting statistics was far less than 1% whereas the uncertainty in the activity of the sources was of the order of a few percent.

As expected, the sodium iodide spectrometers had higher efficiency but the germanium detector had better resolution which resulted in much lower detection limits for the latter. For example, the FWHM of the 344.3 keV peak of Eu-152 for BEGe was approximately 30 times smaller compared with the corresponding value for the NaI(Tl) 3x3-inch detector. The superior resolution of the germanium detector reduces significantly the possibility of misinterpretation of spectral information. Increased energy resolution means that low intensity peaks can be more easily distinguished from the background continuum. It should also be noted that sensitivity is not a primary concern for a system designed specifically for emergency monitoring [26]. As a result, the Broad Energy Germanium detector could be used for more elaborate measurements and appeared to be a superior option compared with the other detection systems when it comes to thyroid monitoring. It should be noted though, that semiconductor detectors require crystal cooling which limits their portability.

By using different thyroid volumes and depths for different age groups, it was found that using only the efficiency calibration factors for adults in a thyroid monitoring campaign can lead to significant deviations from the actual thyroid activity. For example, at 1 cm neck-detector distance, the thyroid activity can be overestimated by 100% for small children or underestimated by 25% for more corpulent adults. As concerns the spectrometers, it was also shown that if Ba-133 have been used for the derivation of the I-131 efficiency calibration factors, the error that would have been introduced would have been within the uncertainty of the measurement and thus using Ba-133 as a mock-iodine source for calibration purposes gives valid results.

The minimum detectable activity of I-131 for all detectors was a few tens of Bq at
1 cm neck-detector distance for all thyroid cases and 1000 seconds measurement time. When the neck-detector distance was increased to 15 cm, the MDA increased by one order of magnitude. At 1 cm neck-detector distance and 60 seconds measurement time, the minimum detectable activity was between 50 and 400 Bq for all thyroid cases. All the above values for the MDA were far below 1 kBq whereas the lower action levels for the thyroid activity are of the order of tens or hundreds of kBq. As a result, the spectrometers present enough sensitivity to detect activity levels that correspond to minimum detectable effective doses of the order of $\sim 0.1$ mSv (when the monitoring campaign is conducted within the first three weeks after the intake).

Using a shield around a detector reduces significantly the level of background radiation and the interference from radiation coming from other regions of the body due to internal or external contamination. It was found in the lab measurements (not contaminated environment) that this way, the minimum detectable activity can be reduced by more than 50%. For this reason, the use of a shield for the detector as well as for the seat of the person being monitored during a thyroid monitoring campaign are strongly recommended.

Quality assurance charts were established including warning and action levels for the FWHM and the decay corrected area of certain peaks of Eu-152. QA checks before a campaign will indicate whether or not the detectors can be used for thyroid screening.

Furthermore, analysis sequence files were created in order to get a full report from the spectrum analysis by Genie 2000. Instead of carrying out the analysis step by step, a sequence file including all the analysis steps with the proper parameters and auxiliary files can facilitate and speed up the spectrum processing.

As concerns the measurements during a campaign, the thyroid activity uncertainty because of the uncertainty in the thickness of the overlying tissue layer is expected to be lower than $\sim 15\%$ and because of the uncertainty in the detector’s position is expected to be lower than $\sim 20\%$. Taking all sources of uncertainty into account, the total relative standard uncertainty in the thyroid activity is expected to be below 50% for neck-detector distances up to 15 cm. The major contributor to this uncertainty is the position of the detector (especially the uncertainty in the neck-detector distance). The uncertainties related to the anatomical variability can be reduced by increasing the neck-detector distance. However at larger distances, longer counting times may be necessary in order to meet the requirements for sufficiently low detection limits.

For rapid thyroid screening measurements, 1 cm neck-detector distance is recommended. This way, low thyroid contamination can be reliably quantified and cases of excessive thyroid contamination can be quickly identified. However, closer neck-detector distance means larger sensitivity to anatomical and postural variabilities which leads to larger uncertainties in the estimation of the thyroid activity. For this reason, a larger neck-detector distance (e.g. 15 cm) is recommended when it has been shown that the thyroid is highly contaminated and a more precise measurement is demanded.

Apart from six spectrometers, three monitors were also calibrated for thyroid screening. Linear plots were derived in order to relate the dose or count rate and the thyroid activity of I-131 so that the latter can be estimated by using a simple formula.
Finally, curves for the upper and lower action levels for the activity of I-131 in the thyroid gland were plotted. This curves can be used for triage according to the case of the person being monitored (child or adult), the time from intake (in days) and the type of intake (ingestion or inhalation).

The overall result of the present work was a technical manual for the use of the various detectors that have been studied. This manual describes the use of the detectors for rapid thyroid screening including, the initial parameters and quality assurance checks, the use of calibration and analysis sequence files and simple methods for triage.

Some recommendations in order to support more effectively a future thyroid monitoring campaign carried out by SCK•CEN can be the following:

- It is strongly recommended that the spectrum analysis software as well as the spectrometers should be installed on several portable computers. This would allow to monitor several people at the same time using all the spectrometers independently in order to reduce significantly the duration of the thyroid monitoring campaign.

- At the moment, there is only one frame that can accommodate one detector (the NaI(Tl) 2x2, UNISPEC). If more frames are designed and ordered, it would be possible not only to use all the detectors at the same time but also to reduce the uncertainty due to positioning.

- At the moment, only one lead shield is available for one particular detector (the NaI(Tl) 2x2, UNISPEC). It is strongly recommended that more shields should be manufactured since it was shown that this would reduce significantly the detection limits.

- It is crucial to ensure that in an emergency situation with risk of internal contamination, there will be people well informed about the use of these detection systems for thyroid screening so that they can be part of a monitoring team.

- The calibration Eu-152 sources as well as the holders that have been used for establishing the quality assurance charts should be readily available for future QA checks.

- A more complete uncertainty analysis can be done by using Monte Carlo simulations. In particular, these simulations can show the effect of different neck and thyroid geometries on efficiency which is very difficult to be done by using phantoms. Models of more realistic thyroid glands (of various shapes and sizes) and overlying tissue layers can be used for more realistic results. The simulation results can be validated against the results of the present study that has been based on real experiments using phantoms.
References


REFERENCES

[12] National Institute of Standards and Technology (NIST) Website: *Tables of X-ray mass attenuation coefficients*


Appendix A  
Efficiency calibration factors for I-131

<table>
<thead>
<tr>
<th>Efficiency [%]</th>
<th>NaI(Tl) 2x2, Inspector 1000</th>
<th>NaI(Tl) 2x2, NANOSPEC</th>
<th>NaI(Tl) 2x2, UNISPEC</th>
<th>Lanthanum Bromide</th>
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<td>Age group</td>
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<td>15 cm</td>
<td>Age group</td>
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Table A.1: Efficiency calibration factors for all detectors and cases of thyroid at 1 cm and 15 cm neck-detector distance.
## Appendix B

### Quality assurance warning & action levels

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<th>FWHM [keV]</th>
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</thead>
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<table>
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<tr>
<td>344.3 keV</td>
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<td>1408 keV</td>
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<td>344.3 keV</td>
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<table>
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<th>NaI(Tl) 2x2-inch, Inspector 1000</th>
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Table B.1: Warning and action levels for the FWHM of Eu-152 peaks.
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<th>NaI(Tl) 2x2-inch, UNISPEC</th>
<th>NaI(Tl) 2x2-inch, NANOSPEC</th>
<th>NaI(Tl) 2x2-inch, Inspector 1000</th>
<th>Lanthanum Bromide detector</th>
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<td>Warning Level</td>
<td>Upper</td>
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Table B.2: Warning and action levels for the decay corrected area of Eu-152 peaks.