Measurement of Caesium -137 in the Human Body using a Whole Body Counter

By

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Abstract

Gamma radiation in the environment is mainly due to naturally occurring radionuclides. However, there is also a contribution from anthropogenic radionuclides such as ^{137}Cs which originate from nuclear fission processes. Since 1986, the accident at the Chernobyl power plant has been a significant source of artificial environmental radioactivity. In order to assess the radiological impact of these radionuclides, it is necessary to measure their activities in samples drawn from the environment and in plants and animals including human populations.

The whole body counter (WBC) at the University Hospital of Wales in Cardiff makes in vivo measurements of gamma emitting radionuclides using a scanning ring of six large-volume thallium-doped sodium iodide (NaI(Tl)) scintillation detectors. In this work the WBC was upgraded by the addition of two high purity germanium (HPGe) detectors. The performance and suitability of the detection systems were evaluated by comparing the detection limits for ^{137}Cs. Sensitivities were measured using sources of known activity in a water filled anthropomorphic phantom and theoretical minimum detectable count-rates were estimated from phantom background pulse height spectra. The theoretical minimum detectable activity was about 24 Bq for the combination of six NaI(Tl) detectors whereas for the individual HPGe detectors it was 64 Bq and 65 Bq, despite the much improved energy resolution

Activities of ^{137}Cs in the human body between 1993 and 2007 were estimated from the background NaI(Tl) spectra of 813 patients and compared with recent measurements in 14 volunteers. The body burden of ^{137}Cs in Cardiff patients increased from an average of about 60 Bq in the early and mid 1990s to a maximum of about 100 Bq in 2000. By 2007 it had decreased to about 40 Bq. This latter value was similar to that of Cardiff residents at the time of the Chernobyl accident and to that of the volunteers measured in 2007 (51 Bq). However, it was less than the mean activity of Cardiff residents in 1988 (130 Bq) indicating an overall decrease over a period of about 20 years.

The variation in the in vivo activity is probably due to complex inter-relationships between a number of factors such as the removal of deposited ^{137}Cs into the sea by rainfall, individual dietary choices, the imposition and removal of restrictions on foodstuffs from Chernobyl-affected areas and travel to countries that suffered greater initial fall-out than the UK.

CHAPTER ONE

INTRODUCTION

1.1 Natural radioactivity

The human body is exposed to natural background radiation every day from the ground, building materials, air, food, the universe and even substances in the body itself. In the United Kingdom, the greatest contribution to background ionising radiation dose comes from radiation of natural origin, which cannot be controlled. The average person receives an annual effective dose of 2.7 mSv, of which about 2.2 mSv is due to natural radiation (Hughes, et al., 2005).

The two major natural radiation sources are outer space, the cosmic radiation from which continuously irradiates the earth, and the earth's biosphere, which includes radionuclides that are present in the earth's crust (IAEA, 1991).

Humans are therefore exposed both externally, through cosmic radiation and radiation from naturally occurring radioactive materials outside the body, and internally, through natural radionuclides biologically present in the body, inhaled air and ingested foodstuffs. Terrestrial radiation is the largest natural cause of exposure and contributes about 85% of the average annual dose (Mason, 2002).

1.1.1 Cosmic radiation

There are two types of cosmic radiation: primary and secondary. Primary cosmic radiation is made up of extremely high energy protons and alpha particles. It originates outside the solar system and is found throughout space. Some of this primary cosmic radiation penetrates the earth's surface, interacting with the atmosphere and producing secondary cosmic radiation. However, its intensity is reduced by attenuation in the atmosphere. Other lower energy radiations in the form of electrons, photons, neutrons, pions and muons are also produced (Knoll, 2000).

Many radionuclides are produced from nuclear interactions of cosmic radiation in the atmosphere and these increase human radiation exposure by inhalation or ingestion through the food chain. These radionuclides include tritium (^{3}H), beryllium-7 (^{7}Be), carbon-14 (^{14}C) and sodium-22 (^{22}Na).

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has divided cosmic radiation into directly ionising radiation and neutron radiation. The estimated average dose rate due to directly ionising radiation at sea level is about 280 μSv per year in latitudes between 50° and 60° (corresponding to the UK), and 90 μSv per year from cosmic neutrons (United Nations, 2000).

Thus the total dose to the population in the UK from outdoor exposure to cosmic radiation is around 370 μSv per year. For indoor exposure, the dose rate is reduced because of the shielding effect of building materials. UNSCEAR suggests an average reduction of 20% compared with outdoor exposure, and it is estimated that people

spend about 90% of their time inside buildings (United Nations, 2000). Additionally, an average dose of about 30 μSv can be received from air travel. Therefore the total average dose to the UK population from all cosmic radiation exposure at sea level is around 330 μSv per year (Hughes, et al., 2005).

1.1.2 Terrestrial radionuclides

Terrestrial radiation is present in the environment at a variety of dose rates depending on the activity concentration in soil, rocks, water, air, food and even the human body itself. However, radioactivity in rocks and soil is the main source of external exposure to people.

The most important terrestrial radionuclides are ^{40}K, ^{87}Rb and the decay products of the ^{238}U and ^{232}Th series.

Natural terrestrial radionuclides are found throughout nature. Many have very long half-lives or are derived from a very long-lived parent radionuclide. Some were produced in stellar processes before the creation of the earth and are still present in the earth's crust. Rocks and soil contain small amounts of the radioactive substances uranium and thorium with their daughter products and their concentrations vary depending on the type of rock formation.

The most important naturally occurring radionuclides are potassium-40 (^{40}K) and members of the uranium-238 (^{238}U) series: ^{222}Rn, ^{210}Pb and ^{210}Po. These radionuclides may emit alpha (α), beta (β) and gamma (γ) radiation during their

decay. The ingestion and inhalation of naturally occurring radionuclides gives an internal radiation dose. These radionuclides also contribute to the direct external exposure from rocks, soils and building materials (Hughes, et al., 2005).

Radon (^{222}Rn) gas emanates from the decay of radium (^{226}Ra) in the ground. Radon has a half-life of 3.8 days and decays into a number of short-lived radionuclides, which increase dose by inhalation. The decay chain of the thorium series gives rise to thoron (^{220}Rn) which is another isotope of radon. The average annual dose from radon is around 1.2 mSv.

1.1.3 Radiation inside the human body

The uranium and thorium series of radionuclides, which are present in food and drinking water, can cause internal exposure from ingestion.

Two important elements that make up the human body are potassium and carbon and they have radioactive isotopes that add considerably to background radiation dose. Potassium-40 (^{40}K) occurs naturally, has a half-life of 1.2 x10^9 years and contributes approximately 0.2 mSv per year. Carbon-14 (^{14}C), which has a half-life of 5568 years, is a radionuclide found in all living things; it is produced by the interaction of neutrons in cosmic radiation with nitrogen atoms in the upper atmosphere. ^{14}C combines with oxygen to produce carbon dioxide gas. Plants absorb this gas during photosynthesis and animals feed on those plants. Thus it enters the human food chain when the animals are consumed.

In addition to ^{40}K and ^{12}C, a significant contribution to the radioactivity in the body comes from the gaseous decay products of the uranium and thorium series, radon and thoron. These gases diffuse from rocks and soil and attach themselves to dust particles in the air; when these particles are inhaled they result in radiation exposure, particularly to the lung. Naturally occurring radioactivity is also absorbed by plants and animals, thereby entering human foodstuffs (Martin & Harbison, 2006).

1.1.3.1 Potassium-40 (^{40}K)

Potassium-40 is a naturally occurring nuclide that was produced during the creation of the earth together with the other elements. Due to its long half-life of 1.28×10^9 years, it is still present on the earth. ^{40}K is the only radioactive isotope of potassium and represents 0.012% of the natural element. Natural potassium consists of three isotopes: ^{39}K, ^{40}K and ^{41}K with mass percentages of 93.08, 0.012 and 6.91 respectively (United Nations, 1993). ^{40}K decays by β^- emission to stable calcium-40 with a disintegration probability of 89% and by β^+ emission or electron capture to stable argon-40 (emitting gamma rays) with a probability of 11% as illustrated in Equations 1-1 to 1-3 and Figure 1-1. ^{40}K activity is determined by detecting the gamma rays at an energy of 1.461 MeV; the body of a 70 kg person contains 140 g of potassium and thus an activity of about 4000 Bq of ^{40}K (Rahman, et al., 2008).

Due to its presence in almost all foods, this nuclide gives the largest contribution to radiation dose (Samat, et al., 1997; Davis, 1963).

$$^{40}K + e^{-} \rightarrow {}^{40}Ar\ (stable) + \nu \qquad \text{Equation 1-1}$$

$$^{40}K \rightarrow {}^{40}Ar\ (stable) + \beta^{+} + \nu \qquad \text{Equation 1-2}$$

$$^{40}K \rightarrow {}^{40}Ca(stable)\ + \beta^{-} + \tilde{\nu} \qquad \text{Equation 1-3}$$

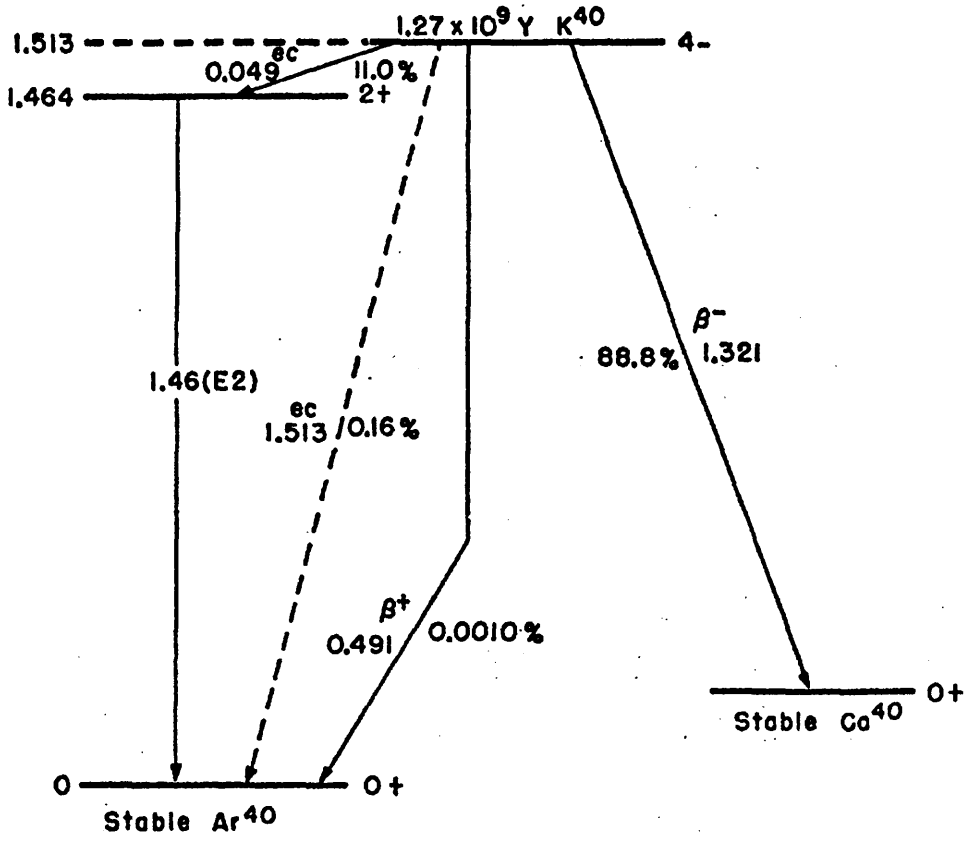


Figure 1-1: Decay scheme of ^{40}K (Lentz, et al., 1965)

The physiological relationship between caesium (Cs) and potassium (K) has been studied since the 1880s, when Sidney Ringer compared the effects of these elements on the contractions of an isolated frog heart. Caesium has been shown to compete with K although Cs is generally transported less readily than K.

In the 1950s, a new significance was attached to the investigation of the biological behaviour of Cs when increasing quantities of fission-produced ^{137}Cs were identified in the environment and in humans. The distribution and residence times of radiocaesium in the body were studied and an extensive literature was developed concerning the means of enhancing its excretion. A description of the accumulation and excretion of radiocaesium by the human body is often related to those of potassium due to the physical and chemical similarities of these two elements (Leggett, et al., 2003).

Radiocaesium body content is commonly expressed in terms of Becquerels per gram of potassium in the body and it is reasonable to relate the two elements as they have similar chemical and metabolic properties. Hence, the body distributions of potassium and caesium are similar (Fenwick, et al., 1992).

1.2 Artificial radioactivity

In addition to natural background radiation, people are also exposed to low and high energy radiation from man-made sources such as medical applications, consumer products, the atmospheric testing of nuclear weapons, the operation of nuclear power stations and nuclear accidents. The radiation dose to the public in the UK from human activity is generally small compared with the dose from naturally occurring radionuclides (Harrison & Phipps, 2002).

1.2.1 Medical applications

The early experiences of man-made sources of radiation involved a variety of applications of x-rays and radium. X-rays were discovered by Roentgen in Germany in 1895 and they have become useful for both diagnostic and therapeutic purposes in medicine. In 1896 radioactivity was discovered by Henry Becquerel in France and soon there were reports of its use in diagnosis and treatment. However, it has reported that 50 cases of tumours induced in radiologists from the histories of 94 cases in 1911. Such studies illustrated the early types of damage produced by x-rays and gave an indication of the longer-term effects such as skin cancer. It has been estimated that by 1922 more than 100 radiologists had died from occupationally produced cancer (Paterson, 1959).

Over 90% of the total exposure of the population from the medical uses of radiation comes from the diagnostic use of x-rays, with the total dose from therapeutic radiology being much less (Martin & Harbison, 1998).

Radionuclides have been used since 1934 in hospitals, laboratories and industries. The medical use of radioactive materials maybe classified into two categories: diagnostic and therapeutic administrations. Diagnostic applications of radioactive substances, such as these used in nuclear medicine, include the use of small amounts of radioactivity to image body organs. Therapeutic uses of radioactive materials include teletherapy and brachytherapy. In this case, the purpose of using radioactive substances is to kill cancerous tissue, reduce the tumour size or reduce pain.

Medical imaging technology has developed quickly, particularly over the last decades. Detailed three dimensional images of many parts of the body can be obtained in a few minutes and minimally invasive surgical procedures are conducted under fluoroscopic control. Patients receive considerable radiation doses from some of these procedures but they also receive many benefits, particularly when the procedures allow alternative and more hazardous diagnostic or therapeutic techniques to be avoided.

In nuclear medicine therapy, the radiation dose is delivered inside the body by the intravenous or oral administration of radiopharmaceuticals, rather than from an external radiation source. Ideally, the radiopharmaceuticals used emit ionising radiation that travels only a short distance, thus minimising unwanted side effects and damage to non-involved organs or nearby structures. The most widely used radiopharmaceuticals are ^{131}I sodium iodide for hyperthyroidism and thyroid cancer, ^{90}Y ibritumomab tiuxetan (Zevalin) and ^{131}I tositumomab (Bexxar) for refractory lymphoma, ^{131}I MIBG (metaiodobenzylguanidine) for neuroendocrine tumors and ^{153}Sm EDTMP or ^{89}Sr chloride for palliation of metastatic bone pain. Orally administered radiopharmaceuticals may take the form of capsules or liquid preparations. Another use of radionuclides is brachytherapy which is also known as internal radiotherapy. In brachytherapy, a solid radionuclide source is placed inside or close to the area requiring treatment. It may be used for cervical, prostate, breast and skin cancer, and to treat tumours in many other body sites. Brachytherapy represents an effective treatment option for many types of cancer (Stewart, 2007).

The most important feature of brachytherapy is that the irradiation only affects a very localised area around the radiation sources, whilst reducing the probability of

unnecessary damage to surrounding healthy tissues. Treatment can often be completed in less time than with other radiotherapy techniques. This can help reduce the chance of surviving cancer cells dividing and growing in the intervals between each radiotherapy dose (Stewart, 2007).

Investigational medical exposures should be justified and optimised on an individual patient basis by offsetting the very small radiation risk with the usually very significant benefits from improved diagnosis, leading to more effective treatment of the medical condition.

People in the UK are exposed to ionising radiation from natural and man made sources, but the main artificial source is medical radiology. The radiation dose is expressed as an effective dose usually given in units of millisieverts, mSv. The effective dose resulting from investigative nuclear medicine is influenced by the amount of radioactivity administered in megabecquerels (MBq). The average annual dose to the UK population due to medical exposures in 2005 was 410 μSv. This dose is due largely to the increased use of x-ray computed tomography, which gives advanced diagnostic information but also leads to a higher patient dose per investigation (Hughes, et al., 2005).

1.2.2 Consumer products

The use of radioactive elements in consumer products has been established for many years; the first applications involved the use of uranium compounds in the production of a variety of coloured glazed glassware. In the early part of the 19th century the

radioluminescent effects of radium were discovered and radioluminous paints were used in many consumer products. (Shaw, et al., 2007)

Some consumer products use the radioactive properties of a radionuclide e.g. amercium-241 in ionisation chamber smoke detectors. On the other hand, some products use other chemical or physical properties of the radionuclide e.g. luminescent gas lantern mantles that include thorium compounds.

In ionisation chamber smoke detectors, the air in the chamber is ionised by a radioactive source. When smoke enters the chamber, some ions will attach themselves to the heavier smoke particles causing a change in the resistance of the device; this change used to trigger an alarm. The most commonly used radionuclide in this device is americium-241 which gives rise to very low external dose rates.

Radionuclides have been used in the luminous paint industry for many years with radium-226 being the most widely used. This was also the first radionuclide to be used for luminising clocks, watches and other products but, in recent years, it has been replaced by tritium and promethium-147.

Some fluorescent lamps include small quantities of radioactive substances in order to provide initial ionisation. Many different radionuclides are used but the activities are generally very low. Also some electronic components (e.g. voltage regulators, current surge protectors, spark gap irradiators and indicator lights) contain small quantities of radioactive material, usually to cause ionisation and promote current flow (Shaw, et al., 2007).

Thorium compounds are sometimes added during the production of glass to change certain optical properties of lenses. They are also used in surface coatings to reduce glare. Uranium compounds are incorporated into the glass in the production of fluorescent and iridescent glass; it may also be added to the glaze used on the surface of tiles and tableware to produce a variety of colours.

In the early part of the 20th century, radium-226 was used for its supposed useful effects in many consumer products, such as radium blankets, radium corsets and radon emanators. These products were no longer used as the detrimental effects of radium became more fully understood (Shaw, et al., 2007).

1.2.3 Nuclear power stations

Members of the public in the UK are exposed to radionuclides which are routinely discharged from nuclear facilities and other establishments. There are nineteen nuclear power stations in the UK at fourteen locations: nine in England (Berkeley, Oldbury, Bradwell, Calder Hall, Dungeness, Hartlepool, Heysham, Hinkley Point and Sizewell), two in Wales (Trawsfyndd and Wylfa) and three in Scotland (Chapelcross, Hunterston and Torness). Figure 1- 2 shows the location of these nuclear stations on the UK map.

The main contributors to internal exposure from nuclear power stations are tritium (^{3}H), polonium-210 (^{210}Po), plutonium-239 (^{239}Pu) and cobalt-60 (^{60}Co). Other radionuclides from this source are caesium–137 (^{137}Cs), carbon-14 (^{14}C) and

strontium-90 (^{90}Sr). External exposure from direct radiation from British Energy stations is very low (Hughes, et al., 2005; British Energy, 2004).

In the UK, radioactivity in food and the environment from nuclear discharges is monitored by the Food Standards Agency (FSA) and the Scottish Environmental Protection Agency (SEPA) (Environment Agency, 2009). The highest radiation doses due to discharges were received by a group of people who consumed large amounts of fish and shellfish in Cumbria; their mean effective dose being 0.52 mSv in 2007.

Gaseous and liquid discharges from power stations are monitored by the Environmental Agency for England and Wales, and by Scottish Environment Protection Agency (SEPA). The doses were below the dose limit in 2007. In fact, total doses to the public from radiation around nuclear sites were below the annual national and European limit of 1 mSv in 2007 (Environment agency, 2009).

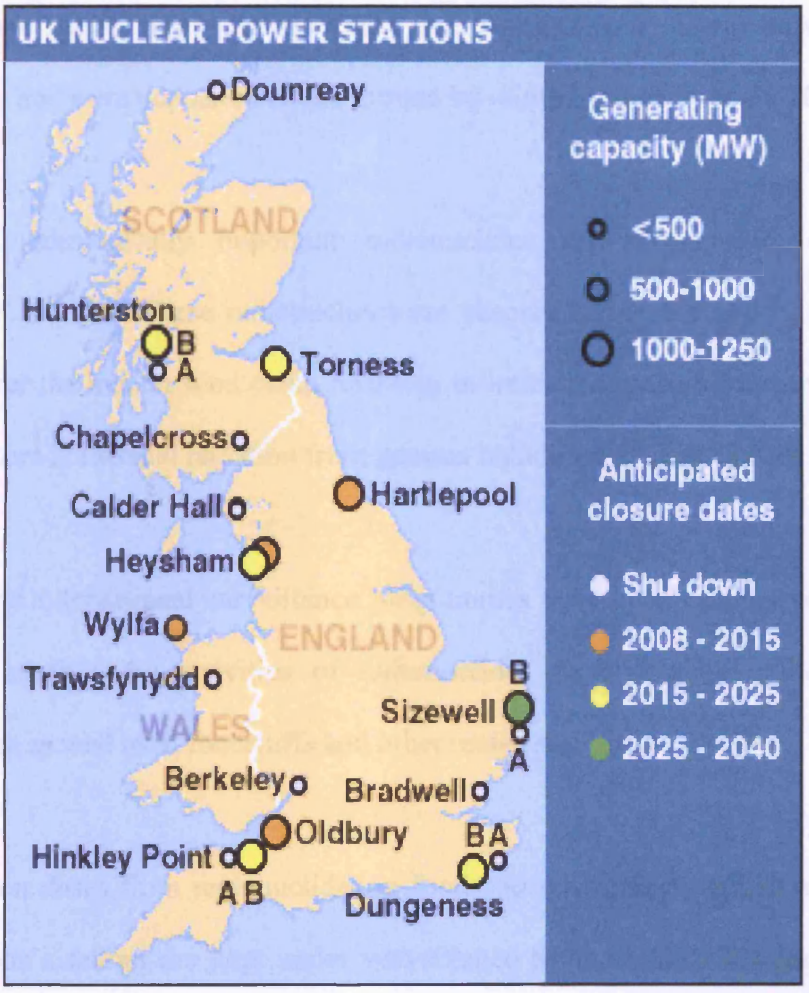


Figure 1-2: UK Nuclear Power Stations locations (British Energy, 2004).

1.2.4 Atomic weapons testing

Nuclear weapons testing began in the 1940s and the maximum fallout from this source was in the 1950s. The Partial Nuclear Test Ban Treaty in 1964 stopped the large scale testing of nuclear weapons in the atmosphere. However, these tests had already released radionuclides into the environment; some of these radionuclides were deposited around the test site while others were carried into the upper atmosphere.

After many years, these radionuclides were transferred downwards into the troposphere and were deposited on the ground by rainfall (Hughes, et al., 2005).

The most radiologically important radionuclides are strontium-90 (^{90}Sr) and caesium-137 (^{137}Cs). These radionuclides are absorbed from the soil by plants and thereby enter the human food chain resulting in internal exposure from ingestion; in addition, there is external radiation from gamma radiation which is emitted by ^{137}Cs.

National and international surveillance programmes have been established since the 1950s to monitor the activities of radionuclides from weapons fallout in the environment as well as in foodstuffs and other materials.

UK radiation doses from radionuclides in food and environment which are released from weapon's fallout are kept under surveillance by the United Kingdom Atomic Energy Authority (UKAEA), the Food Standards Agency and Scottish Environmental Protection Agency. The 2000 report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) showed that the average annual total dose from fallout in the northern hemisphere for 1999 was 5.9 μSv (United Nations, 2000).

Caesium isotopes (mainly ^{137}Cs) were the main contributors to doses due to fallout from atmospheric weapons testing. Caesium-137 delivered a whole body external beta/gamma dose of 3.2 μSv, while the main contributions to the ingestion dose of 2.7 μSv came from ^{90}Sr and ^{14}C. The average annual dose in the UK is about 6 μSv

(Hughes, et al., 2005) compared with peak values of more than 0.1 mSv in the 1960s (Hughes 1993, 1999).

The monitoring and surveillance programmes of radioactivity in air and rainwater in the UK have shown a slow decline in the activities of artificial radionuclides in the environment (Dale, 2002). Data from 10 consecutive survey years showed that the mean ^{137}Cs activity in air and rainwater for monitoring sites in the UK was very low and, in some cases, below the detection limit (Dale, 2002).

Measurements of fallout activity in foodstuffs have mainly been made in milk because of its feasibility for sampling and because it provides a good indication of the intake of radioactivity from the total amount of food consumed.

A milk monitoring programme carried out by the National Radiological Protection Board (NRPB) showed that for both ^{137}Cs and ^{90}Sr the activity concentrations were either close to or below detection limits (Hammond, 2003).

1.2.5 Nuclear accidents

The nuclear accidents that have most affected the UK were these at Windscale and at Chernobyl.

1.2.5.1 Windscale reactor accident

The former Windscale works of the United Kingdom Atomic Energy Authority at Sellafield on the Cumbria coast of north-west England was used for the production of plutonium and other materials for the UK nuclear weapons programme. The two reactors were built between 1947 and 1951 and first operated in 1950-1951.

These reactors were of the graphite-moderated type. They used natural and enriched uranium metal as fuel and were cooled by air; their design power was 180 MW. Polonium-210 and tritium (^{3}H) were also produced by irradiating bismuth oxide and a lithium alloy, respectively, and cobalt-60 (^{60}Co) was manufactured for industrial and medical use.

To reduce heat energy and to control its release, the graphite was annealed periodically by nuclear heating at low power with reduced airflow. This raised the temperature of the graphite until the stored energy was released.

In October 1957, during a normal discharge of energy, the reactor caught fire with the result that strongly radioactive smoke from the fire was released and spread over England, Wales and northern Europe. It took two days and five million litres of water to stop the fire. Caesium, iodine and polonium radionuclides were released into the environment. After the accident, a sampling programme was carried out on agricultural produce, milk and herbage from large areas of Britain to monitor and analyse their radionuclide content. As an example, the results showed the presence of caesium-137 (^{137}Cs) in dried milk samples (Garland, 2007).

1.2.5.2 Chernobyl accident

The Chernobyl nuclear power station is situated 100 km north-west of Kiev, Ukraine near to the border with Belarus. An accident occurred on 26th April 1986, resulting from the combination of a fault and an illegal operation in the form of an unauthorised experiment.

An explosion occurred in on of the reactors and this was followed by an influx of air into the reactor's graphite core. This started to burn resulting in the release of noble gases, fission fragments and uranium fuel into the atmosphere. Following this, a second explosion occurred following 10 days of fire. The main radionuclides in the release were ^{131}I, ^{134}Cs and ^{137}Cs.

On 26th April, at the time of the explosion, high atmospheric pressure was centred over north-west Russia and the wind carried the plume away towards the Baltic and Scandinavia. When the plume reached Scandinavia, it split into three parts: one moved towards Japan and China, a second crossed central Norway and the third part crossed central Europe.

On 2nd May, the radioactive plume reached the English Channel and spread into southern England. By late afternoon, the plume reached Cumbria and north Wales; heavy rain affected many parts of north Wales, the Pennines, Cumbria, the Isle of Man and south-west Scotland (Norman & Jeffery, 1988).

After the accident, radiocaesium was detected in sheep grazing in certain highland areas in the UK, which had been affected by heavy rainfall in the days following the accident. In order to prevent animals from entering the food chain with caesium above the recommended level of 1000 Bq per kg, a level based on the recommendations of an European Union Expert Committee in 1986, restrictions were made on the movement, sale and slaughter of sheep from the affected areas.

Monitoring programmes for sheep in the restricted areas of England and Scotland were carried out in summer 2008. Restrictions were removed where controls were no longer necessary (Environment Agency, 2009).

In 2008, a total of 373 farms (9 in England, 5 in Scotland and 359 in Wales) were subject to restrictions; there were around 200,000 sheep within these restricted areas. This represented a reduction of over 95% since 1986, when approximately 9,000 farms and over 4 millions sheep were placed under restriction across the UK (Environment Agency, 2009)

Table 1-1 gives the number of sheep and holdings under restrictions per country for 1986, 1990 and 2008 (Food Standards Agency, 2007).

		England	Wales	Scotland	N. Ireland	Total
June	**Farms**	1,670	5,100	2,144	-	8,914
1986	**Sheep**	867,000	2,000,000	1,358,000	-	4,225,000
August	**Farms**	150	420	69	122	761
1990	**Sheep**	170,000	300,000	124,000	53,000	647,000
May	**Farms**	9	359	19	0	387
2000	**sheep**	11,500	180,000	40,000	0	231,500
February	**Farms**	9	359	5	0	373
2008	**Sheep**	6,600	180,000	9,900	0	196,500

Table 1-1: Number of restricted farms and sheep between 1986 and 2008 (Food Standards Agency, 2007)

Measurements of activity in drinking water, milk, vegetables and meat were obtained in many parts of Europe, including the UK. In addition, samples of air, rain and foodstuffs were obtained by several organisations in the UK including nuclear power stations of the electricity boards, British Nuclear Fuel plc, the UK Atomic Energy Authority (UKAEA), the National Radiological Protection Board (NRBP) and the Ministry of Agriculture Fisheries and Food (MAFF). The estimated doses were less than 0.1 mSv (Norman & Jeffery, 1988).

All sources of ionising radiation exposure to the UK population are reviewed every few years, the most recent being in 2005 (Hughes, et al., 2005). From this review it is clear that sources of naturally occurring radiation and man-made radiation produced for medical use predominate. The average annual dose from naturally occurring

radiation was found to be 2.2 mSv with radon exposure indoors contributing about a half. The average annual dose from artificial radiation was 0.42 mSv and was mainly derived from medical procedures with x-rays. The overall average annual dose was 2.7 mSv. Exposures from non-medical, man-made sources were very low and radioactive waste discharges contributed less than 0.1 per cent of the total (Environment Agency, 2009).

1.3 Radioactivity in the environment and human body

Natural radionuclides include cosmogenic radionuclides (^{3}H, ^{14}C, ^{22}Na) and very long-lived primordial nuclides and their daughters (^{40}K and ^{238}U. ^{235}U, ^{232}Th chains). Anthropogenic radionuclides have been released into the environment from nuclear weapons production (mainly in the period 1940s-1950s), from nuclear weapons testing (mostly from 1950s-1960s) and from accidents.

Most chief radionuclides injected into the stratosphere were ^{131}I, ^{137}Cs. ^{90}Sr, ^{106}Ru, ^{144}Ce, ^{239}Pu; these were subsequently distributed all over the world.

Radionuclides move through the environment and into the human body through many different pathways; by inhalation, the consumption of food or drink and by absorption through the skin's surface.

1.4 Effects on human health

Understanding the health effects of low levels of ionising radiation is important because ionising radiation cannot be seen or felt, and so the fact that people are constantly exposed to radiation is not usually apparent. Such radiations can be detected by using devices such as Geiger counters and other detectors which are greatly improved since the days of Roentgen, Becquerel and the Curies; through such means, the location of the radiation and the amount of the radiation present can be determined (National Research Council, 2006).

Ionising radiation is radiation that has adequate energy to remove electrons from molecules and thus change their structure. This includes DNA within human body cells. Some of these changes are difficult for the body to repair correctly and can result in cancer or other illnesses. These biological effects begin with the ionisation of atoms, this being the mechanism by which radiation causes damage to human tissue. When ionising radiation interacts with cells, it can strike a critical part of the cell. This is often assumed to be the chromosomes since they contain the genetic information and instructions required for the cell to perform its function and to make copies of itself for reproduction purposes.

Some ionising radiation produces substances not normally found in the cell which can cause a breakdown of the cell structure and it components. Cells can repair the damage but sometimes they may be unable to reproduce themselves or will reproduce at an uncontrolled rate. Such cells can be the underlying cause of cancers. If a cell is

comprehensively damaged by radiation, or damaged in such a way that reproduction is affected, the cell may die (National Research Council, 2006).

The investigation of radiation effects started in 1911 when found tumour induced in x-ray radiologists and in occupationally exposed workers such as uranium miners, scientists and medical personnel (Martin & Harbison, 1996).

Observations were also carried out on patients exposed to radiation for diagnosis or treatments. Additional sources of information include people surviving the nuclear bombings in Japan and people exposed to nuclear accident fallout, such as that resulting from the Windscale accident in England in 1957 and the Chernobyl accident in Ukraine in 1986.

Radiation-induced changes at the cellular level can lead to two distinct types of injury: deterministic effects and stochastic effects. These two types of damage have quite different consequences.

1.4.1 Deterministic effects

Cell death or prevention of cell division results in depletion of the cell population within organs of the body. There is no observable effect on the body below a certain value of dose called the threshold. Above the threshold, effects begin to be observed and the severity of the effects will increase as the dose increases.

1.4.1.1 Acute radiation effects

Acute effects from large doses of ionising radiation appear in a short time after exposure to radiation. The effects are due to cell population depletion in many organs in the body as a result of cell killing and the prevention or delay of cell division.

An acute over exposure to radiation leads to reddening of the skin called erythema. Major effects include bone marrow, gastrointestinal or neuromuscular damage depending on the dose received. Doses above 1 Gy cause nausea and vomiting, this is called radiation sickness and it occurs a few hours after exposure. Exposure to absorbed doses above 2 Gy can lead to death in 10-15 days and for doses around 10 Gy, death will be due to secondary infections because of white blood cell depletion.

If the dose exceeds 10 Gy, the survival time drops abruptly to between 3 and 5 days. At even higher doses, survival times become shorter.

Doses to workers and members of the public received from the medical applications of radiation or from the nuclear industry are below the threshold for deterministic effects. However, such effects may occur from exposure to high doses from nuclear accidents or from low doses over long term (Martin & Harbison, 1996).

1.4.1.2 Late deterministic effects

Delayed effects can occur years after exposure; they include damage to the lens of the eye. This takes the form of observable opacities in the lens or visual impairment as a

result of a cataract. Studies on animals exposed to radiation indicate a slight reduction, in the life expectancy of individuals (Martin & Harbison, 1996).

1.4.2 Stochastic effects

In the 20th century, cancer became apparent in radiologists and their patients who were exposed to high doses of radiation, in people exposed to radiation from atomic bombs, in patients receiving radiation therapy and in occupationally exposed individuals such as uranium miners. This confirmed the ability of radiation to induce cancer. The development of cancer may take about 5 to 30 years or more between the time of the exposure and the appearance of the cancer.

The hereditary effects of radiation result from damage to the reproductive cells due to genetic mutations in the hereditary material of the cell. Ionising radiation can cause a rise in the mutation rate and the damage may be transmitted to later generations.

The risk of stochastic effects is proportional to radiation dose and there is no threshold (Martin & Harbison, 1996).

1.5 Caesium-137 (^{137}Cs)

^{137}Cs is a major fission product released from fission reactors, nuclear weapons testing and nuclear accidents as shown in Equations 1-4 and 1-5. This radionuclide was first detected in humans in 1956 by Miller and Marinelli using whole body

counting techniques. Subsequently, many laboratories all over the world investigated ^{137}Cs body burdens by whole body counting (Doerfel, 1981).

Caesium is found in Group 1of the periodic table and thus exhibits a valence of 1+. It belongs to the same group as potassium and will, therefore, behave in a similar manner. Potassium is an important nutrient for plants, animals, and humans and is relatively homogeneously distributed in the human body, mainly intracellularly in muscles and organs. Hence, after intake, caesium will have approximately the same distribution. Due to a relatively long half-life of 30.02 years, ^{137}Cs will contribute to additional radiation dose many years after an accident where anthropogenic radionuclides were released, whereas other shorter-lived nuclides contribute more to the overall dose during the first year. Caesium is a soluble element in body fluids. It is absorbed when ingested, distributed throughout the body and finally eliminated by the kidneys with an effective half-life in the body of 70 to 110 days in the adult (Boddy, 1975).

^{137}Cs decays by beta minus emission to a ^{137m}Ba metastable state which undergoes an isomeric transition to stable ^{137}Ba by the emission of a 661 keV photon as shown in Equations 1-6 and 1-7 and in Figure 1-3 (Miller, 1972).

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow {}^{137}_{53}I + {}^{95}_{39}Y + 4\,{}^{1}_{0}n \qquad \text{Equation 1-4}$$

$$^{137}I \xrightarrow{\beta^-} {}^{137}Xe \xrightarrow{\beta^-} {}^{137}Cs \qquad \text{Equation 1-5}$$

$$^{137}_{55}Cs \rightarrow {}^{137}_{56}{}^{m}Ba + \beta^{-}$$ Equation 1-6

$$^{137}_{56}{}^{m}Ba \rightarrow {}^{137}_{56}Ba\ (stable) + \gamma$$ Equation 1-7

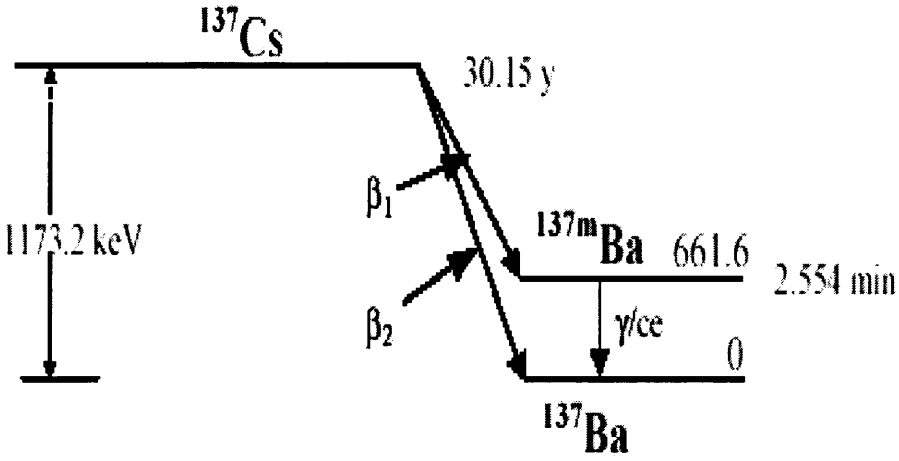


Figure 1-3: ^{137}Cs decay scheme (Miller, 1972).

^{137}Cs in the environment in the UK today mainly originates from atmospheric nuclear weapons tests and the Chernobyl accident. Nuclear facilities and other accidents contribute only a very small fraction of the total amount of ^{137}Cs.

1.5.1 Previous measurements of ^{137}Cs in humans

Since Miller and Marinelli first caesium-137 measurements in the human body in the United Kingdom in 1956 (Miller & Marinelli, 1956) by using whole body counting techniques many laboratories have investigated ^{137}Cs body burdens.

Subsequent measurements of body radioactivity made at the Atomic Energy Research Establishment in Harwell demonstrated the presence of radiocaesium in everyone, whether employed at Harwell or not i.e. radiocaesium was detected in those who had not had any occupational exposure to caesium-137 (Rundo, 1960).

The release of radionuclides due to the Windscale accident in October 1957 led to temporary increases in the radiocaesium content of milk over a wide area of England and Wales (Mayneord, et al., 1958) and (Booker, 1959) with the highest increases being closest to Windscale (Booker, 1959). Although no extensive study was made to estimate the activities in humans in this area, a few subjects were measured and the results were 2.5-3.0 times higher the pre-accident level. Between January and March 1958, as a result of the accident, the caesium-137/potassium-40 ratio increased about four-fold to a maximum, and then the level decreased to less than twice the pre-accident value towards the end of 1958 (Rundo, 1960). The average rainfall in West Cumbria is approximately double that in Oxfordshire (Fenwick, et al., 1992). Therefore the ^{137}Cs levels in the people of West Cumbria were about twice higher than those in Oxfordshire between 1962 and 1964 after the extensive atmospheric nuclear weapon testing in 1961 and 1962 the ^{137}Cs body content sharply increased and reached a maximum in 1964 (Doerfel, 1981).

In the Western Isles of Scotland the concentrations of ^{137}Cs in patients were higher than those in patients from the Scottish mainland (Williams, et al., 1981). Levels similar to those found in the Islanders were recorded in Harwell, Oxfordshire in 1964 after atmospheric weapons testing from 1961-1962 (Newton, et al., 1977) but values 100 times higher were found in Alaska and Finland in 1964 (United Nations, 1977).

There are three possible explanations for increased ^{137}Cs concentrations in Islanders. Firstly, higher rainfall over the islands may have produced greater fallout. Secondly, fallout was the same but the islanders' diet provided a greater than usual transfer of the radionuclide. The third possibility was that the excess ^{137}Cs came from waste discharged into the sea from Sellafield, which is the main source of ^{137}Cs in British coastal waters.

West Cumbrian coastal grasses, and sheep and cattle consuming these grasses, have higher ^{137}Cs concentrations because ^{137}Cs is discharged into the sea (Isles, et al., 1991).

Radiocaesium was also detected in sheep grazing in certain upland areas of the UK following the Chernobyl accident. These areas were subjected to heavy rainfall in the days after the accident. In fact, the areas of the UK most affected by ^{137}Cs deposition from the Chernobyl reactor accident were Cumbria, north Wales and southern Scotland. This activity was absorbed by the grass and entered the human food chain mainly via sheep meat.

The number of restricted farms and sheep has fallen every year since 1986, as the radiocaesium has become progressively less biologically available. However, in the UK, 373 upland farms were still affected by bans in 2008. About 190,000 sheep were affected within these restricted areas. The last farms will be derestricted by about 2016 (Environment Agency, 2009).

Radiocaesium levels in Edinburgh and Glasgow after Chernobyl had the highest concentration found in the UK. The highest levels of ^{137}Cs for Glasgow were approximately double the corresponding values for southern England.

In 1990–1991, the peak activity of ^{137}Cs in residents near the Dounreay nuclear establishment was 10 times higher than the average value for southern England at that time.

Most of the ^{137}Cs in humans before the Chernobyl accident in 1986 was assumed to be derived from the atmospheric testing of nuclear weapons; ^{137}Cs fallout is carried to earth in rain and then taken up by plants, thereby entering the human food chain. The main sources are milk and meat, which together account for 60 - 80% of the total intake (Agricultural Research Council radiobiological Laboratory, 1966).

Radiocaesium released during nuclear weapons testing in the 1950s and 1960s provided additional opportunities for research on the mechanisms of radiocaesium transfer to plants by foliar and root uptake pathways. This research topic received more attention following the accident at the Chernobyl nuclear power plant in April 1986, which resulted in wide scale deposition of radiocaesium over large areas of soil in Europe and the former Soviet Union (Zhu & Smolders, 2000).

Assessments of the effects of the radiation dose on the population of the European Community as a result of the Chernobyl reactor accident have been published. These assessments were based on early information about radionuclides measured in the environment and in foodstuffs, and standard assumptions about activity transfer and

intake by individuals. It was discovered that a substantial proportion of the doses arose from radiocaesium intake.

Dose assessments for the UK population have been determined separately for a number of regions that have been delineated according to meteorological conditions at the time of the passage of the contaminated air mass. For example, Cumbria suffered heavy rainfall and higher deposition of radionuclides than the rest of England. Therefore the maximum concentration of radionuclides in milk and meat produced in Cumbria were greater than in those produced in other parts of England.

Doses have been determined for all types of external exposure, inhalation and ingestion in the first year after the accident and for all the following years. In Cumbria, about 75% of the doses resulted from radiocaesium intake whereas in the rest of England the contribution from this source was about 50% (Fry & Britcher, 1987).

1.5.2 In vivo measurements of ^{137}Cs in Cardiff

In the immediate aftermath of the Chernobyl accident, in vivo measurements of ^{137}Cs activity were made in a small group of six volunteers using the whole body counter at the University Hospital of Wales, Cardiff (Burch & Owen, 1986). The mean activity increased continuously reaching a value of 107 Bq on 2nd July 1986. During the two month measurement period, the maximum activity in an individual volunteer was 294 Bq.

In June 1986, the average ^{137}Cs whole body content of Cardiff residents was similar to that measured in southern England. However, by July 1986 the levels were double those in southern England, and the levels in north Wales were double those in south Wales (Ham, 2003).

Subsequently, ^{137}Cs activity was measured in a larger group of volunteers as part of a UK-wide national survey of radioactivity in the general public (McKenzie, et al., 1989). Mean activity was 173 Bq with a range from less than 25 Bq to 423 Bq. These values were similar to those found at measurement sites in the south of England but less than those found in Bangor, Edinburgh, Glasgow and Seascale for example. In this survey, the maximum individual activity was 4194 Bq and this was found in a resident of north Wales.

These early Cardiff data have been compared with the in vivo measurements of ^{137}Cs described in this thesis.

1.6 Objectives

The ^{137}Cs activities measured in humans in Cardiff in the late 1980s were associated with the sudden release of a very large amount of this radionuclide into the environment at Chernobyl. Initially, the rate of intake through food and drink was greater than the rate of excretion, and so the in vivo activity increased. However, it is reasonable to suppose that over time, the rate of intake decreased as activity was removed by rainfall from the land to the sea. This would lead to a decrease in the body burden of ^{137}Cs since about 1990. Thus it is hypothesised that in vivo activity of

the radionuclide has decreased over the last 20 years and that current values are significantly lower than previously found in Cardiff.

The primary objective of this study was to test this hypothesis by calculating the in vivo activity of ^{137}Cs in (1) Cardiff whole body counter patients between 1993 and 2007 and (2) a group of volunteers. This was done by analysing their background gamma emission spectra.

Following a major refurbishment in the early 1990s, the Cardiff whole body counter has been fitted with two hyper-pure germanium HPGe semiconductor detectors in addition to the ring of six thallium-doped sodium iodide NaI(Tl) scintillation detectors. Because of their much better energy resolution, the HPGe detectors have a much lower background count-rate and much narrower spectral peaks than NaI(Tl) detectors. Their disadvantage is a much lower sensitivity (expressed as count-rate per unit activity). It is hypothesised that the minimum detectable activity of ^{137}Cs is lower for a single semiconductor detector than that for the six scintillation detectors because of its superior energy resolution and despite its much poorer sensitivity.

A secondary objective of this study was to test this hypothesis by comparing the minimum detectable activity (MDA) achievable with the two types of detector for ^{137}Cs. Theoretical MDA was estimated from background measurements in an anthropomorphic phantom using sensitivity values derived from measurements of ^{137}Cs in the presence of naturally occurring ^{40}K.

CHAPTER TWO

WHOLE BODY COUNTING

2.1 Radiation detection

Gamma photons are uncharged and create no direct ionisation or excitation of the material through which they pass. The detection of gamma radiation is dependent on interactions with matter in which all or part of the photon energy is transferred to an electron in the attenuating material. The main types of interaction in radiation measurements are photoelectric absorption, Compton scattering and pair production.

A gamma photon may interact with an atom of the attenuator and transfer all its energy to an atomic electron; so that the photon completely disappears and the electron is ejected from the atom. The energy of the emitted electron is therefore equal to the energy of incident photon minus the binding energy of the electron. This is known as the photoelectric effect and the ejected electron is called a photoelectron. The photoelectric effect predominates for low energy gamma rays. The process is also enhanced for attenuating materials of high atomic number. The photoelectric absorption probability depends on the atomic number of the attenuator and this is the main reason for the preponderance of high atomic number materials in gamma ray shields.

In Compton scattering, the gamma photon transfers a fraction of its energy to an orbital electron; the photon is deflected and the ejected electron is known as a recoil

electron. Compton scatter probability declines with increasing photon energy and is relatively independent of the atomic number of the attenuating material. The attenuation of photons by Compton scattering is most likely for gamma rays in the intermediate energy range of 100 keV to 10 MeV.

Pair production is absorption of a high energy gamma photon by interaction with the Coulombic field of a nucleus; an electron-positron pair is produced. The initial energy of the photon must be at least equivalent to the rest mass of the electron-positron pair. Since the rest mass of both the electron and the positron is 0.511 MeV, the initial energy of the photon must be at least 1.02 MeV. If the gamma photon undergoing pair production has energy greater than 1.02 MeV, the extra energy appears as kinetic energy of the positron and the electron. After losing its kinetic energy in causing multiple ionisations and excitations in the attenuating material, the positron annihilates with an electron; two annihilation photons (each of energy 511 keV) are normally produced as secondary products of the interaction.

The use of whole body counting goes back to around 1925. The first measurements of in vivo radionuclides were performed on radium dial painters. Since the development of NaI(Tl) detectors in the 1950s, whole body counting has become a standard method for monitoring the internal contamination of workers. It was also used in the late 1950s and early 1960s to detect worldwide fallout that had entered the general population. In the late 1970s and early 1980s, new types of detectors consisting of semiconductor materials such as germanium came into use for whole body counters.

The use of germanium Ge detectors has improved the performance, especially the ability to distinguish between gamma rays that have similar energies (Ishikawa, 2006).

2.1.1 Scintillation gamma ray spectroscopy

The development of thallium-activated sodium iodide in the early 1950s as a scintillation material started the modern period of gamma ray spectroscopy.

Scintillation detectors provided high efficiency for gamma detection and often sufficiently good energy resolution to separate the spectral contribution of multi-energetic gamma ray sources. Following this, the applications of gamma ray spectroscopy using scintillation detectors has developed in a very wide range of scientific fields (Knoll, 2000).

The most popular solid scintillator used for counting photons is a crystal of sodium iodide (NaI) which intentionally contains thallium (Tl) as an impurity. The thallium is very efficient in converting gamma photon energy to light. The material has excellent linearity and a high atomic number through its iodine component. This detector is a called a thallium-activated sodium iodide crystal or NaI (Tl) (Stabin, 2008).

When a gamma photon interacts with a NaI (Tl) crystal by either Compton scattering or photoelectric absorption, some or all of the energy is transferred to a secondary electron. This electron loses its kinetic energy in raising a large number of bound electrons from the valence band to the conduction band. A fraction of these electrons

return to the valence band via the thallium atoms producing visible light (i.e. a scintillation). The most important characteristic of a scintillation detector is the relationship between the energy of an incident gamma photon and the light pulse produced in the detector. The intensity of the visible light produced in the crystal is proportional to the energy deposited in the crystal by the gamma photon. This proportionality feature of the scintillation counter can be used to determine the spectrum of the energy deposited in the crystal (Bomford, 2003).

2.1.2. Semiconductor gamma ray spectroscopy

In the early 1960s semiconductor devices became available as detection media and were called crystal counters. However, modern detectors are referred to as semiconductor detectors. A semiconductor has several advantages: it has superior energy resolution, compact size, relatively fast timing characteristics and an effective thickness which can be varied to match the requirements of the application. This improved energy resolution permits the complete separation of photopeaks in the gamma spectrum of photons whose energies differ by as little as 0.5 keV. These photons would appear as a single photopeak in a spectrum acquired with a NaI (Tl) crystal (Miller, 1972).

The most common semiconductor materials used in radiation detection are germanium (Ge) and silicon (Si); these materials require only a small amount of energy to create useful numbers of charge carriers; the more charge carriers there are, the better the energy resolution. The principal disadvantage of germanium detectors is that the photopeak counting efficiency is about a factor of ten or more less that of

NaI(Tl). The reasons for the low counting efficiency of germanium are its low atomic number compared to iodine (giving a relatively low photoelectric absorption coefficient) and the fact that the thickness of the germanium crystal is limited due to manufacturing difficulties (Miller, 1972).

The main characteristic of semiconductor detectors is their excellent energy resolution when applied to gamma ray spectroscopy. Figure 2-1 shows the comparative pulse height spectra obtained from a living human to identify body background radioactivity using six NaI(Tl) scintillators and two high purity germanium (HPGe) detectors for the same incident gamma ray spectra. It is apparent that the considerable superiority of the germanium system in energy resolution allows the separation of many closely spaced gamma ray energies (Knoll, 2000).

Like the NaI(Tl) crystal, the operation of a germanium crystal depends upon the interaction of radiation with a solid. However, the NaI(Tl) crystal produces a pulse of visible light due to ionisation and excitation within crystal created by the incident radiation while the germanium crystal operates on a completely different principle. When the semiconductor is ionised by radiation, electron-hole pairs are formed. Electrons are raised to the conduction band of the crystalline material leaving holes in the valence band. The electrons then move towards the anode in an applied electric field while the holes drift toward the cathode. The successful operation of a semiconductor detector requires that the material has the capability of supporting large electric field gradients, has high resistivity, and displays long life times and mobility for both electrons and holes. The long life and mobility requirement for the electron-hole pairs is necessary for the effective collection of ion pairs at the

electrodes. If the mobility is too small and the life time too short, most of the electron-hole pairs will be trapped at crystal lattice imperfections or recombine before they can be collected.

Semiconductor detectors must be operated and stored at liquid nitrogen temperature (-196 °C). The small energy gap of germanium (the energy required to raise an electron from the valence band to the conduction band) means that a low temperature is required to reduce thermal noise. HPGe detectors are more expensive to operate than NaI(Tl) detectors because they require frequent refilling with liquid nitrogen (Stabin, 2008).

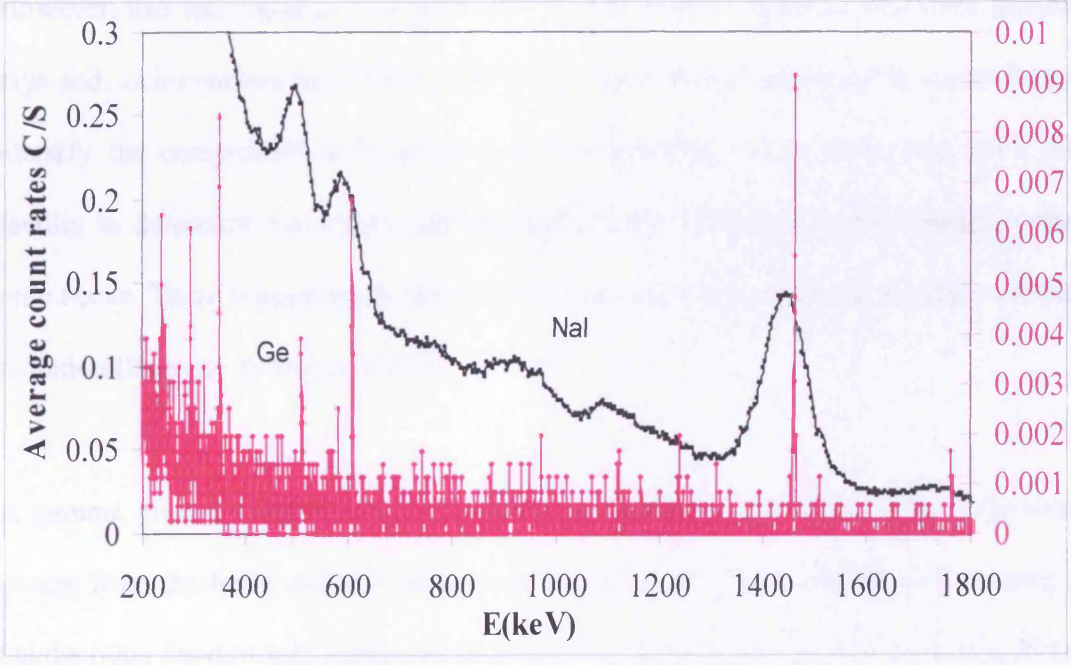


Figure 2-1: Comparative HPGe and NaI(Tl) background spectra in a human being

2.2 Whole Body Counting

Direct measurements with whole body counters are commonly used in radiation protection to identify radioactive material intake and assess the radiation exposure to the individual. The counter may be used measure a radionuclide or mixture of radionuclides which have entered the body as a result of environmental contamination. These measurements may follow the accidental release of radioactive materials or they may be used for the routine monitoring of those in whom there may have been an intake of radioactive material as a result of work activity. Thus a whole body counter may be used to monitor both workers and members of the public.

However, this technique is only applicable to radioactive materials that emit gamma rays and such counters must have sufficiently high energy resolution to separate and identify the components of a mixture of contaminants. They must also have the facility to determine the region and amount of any radionuclide concentration that may occur. These requirements demand the most efficient shielding against external radiation (Barnaby & Smith, 1967).

A gamma photon emitted from a radioactive nuclide within the human body may escape from the body without interaction, especially if it has relatively high energy. On the other hand, it may suffer one or more Compton interactions in the body; if the singly or multiply scattered photon escapes, it will do so with reduced energy. Photons with initial energy greater than 1.02 MeV may interact within the body by pair production generating annihilation radiation. Thus the spectrum of radiation escaping the body will be complex.

The direct measurement of radiation is the most accurate method to determine the quantity and location of radioactive material in the human body. It is an advantage of whole body counting is that it measures body radioactivity directly as opposed to indirect methods such as urine analysis. It can also measure insoluble radionuclides in the lungs. The disadvantage is that it can only be used for gamma emitters (Kramer & Inn, 1991).

2.2.1. Design and construction

With whole-body counter design the following factors must be considered:

1) Amount and type of radioactivity to be measured;
2) Upper and lower range of radionuclide emission energy;
3) Accuracy required;
4) Information on localisation;
5) Amount and variability of local background radiation;
6) Data-handling techniques;
7) Measures to avoid contamination of the counter;
8) Cost.

The applications of the whole-body measurement range from the use of a partially shielded single scintillation detector to measure the intake of a radionuclide primarily by one organ, such as radioiodine by the thyroid gland, to highly complicated semiconductor detectors for the detection of low energy gamma rays from transuranic radionuclides distributed in several body organs. Typically, the former applies to members of the public after an accidental release while the latter applies to workers in

the nuclear industry who may have been occupationally exposed. With this technique, the subject may be sitting, lying or standing during the measurement and the detection system may have single or multiple detectors which may be either be stationary or moving (Andrews, et al., 1973).

The following are some typical geometry arrangements which are often used with NaI(Tl) crystals in whole-body counters:

1) Arc geometry;
2) Chair geometry;
3) Bed geometry with an array of fixed detectors called stationary counters;
4) Scanning bed geometry with one or several detectors called scanning counters.

These will be discussed in turn.

2.2.1.1 Arc geometry

The first attempts to measure total body burdens of radioactivity were made in 1929 with the object of determining the amount of radium absorbed by workers handling the substance. However, accurate quantitative measurements were not achieved until 1937, when a single Geiger-Mueller (G-M) counter was used by Evans (IAEA, 1966) and (Evans, 1937). In Evans' original technique, the G-M tube was used at the centre of an arc with a radius 1 m. The subject was then measured once with the curvature along the ventral aspect of the body. The main disadvantages of the arc technique were the low sensitivity due to the small geometrical efficiency of the arc with a

radius 1-2 m and the low intrinsic efficiency of the Geiger-Mueller counter. The lowest body burden of radium that could be measured at that time was 0.1 microgram which is also the maximum permissible burden of radium in occupationally exposed workers according to the recommendations of the International Commission on Radiological Protection (IAEA, 1966). In later versions, the G-M tube was replaced by a scintillation crystal as shown in Figure 2-2 (IAEA, 1966).

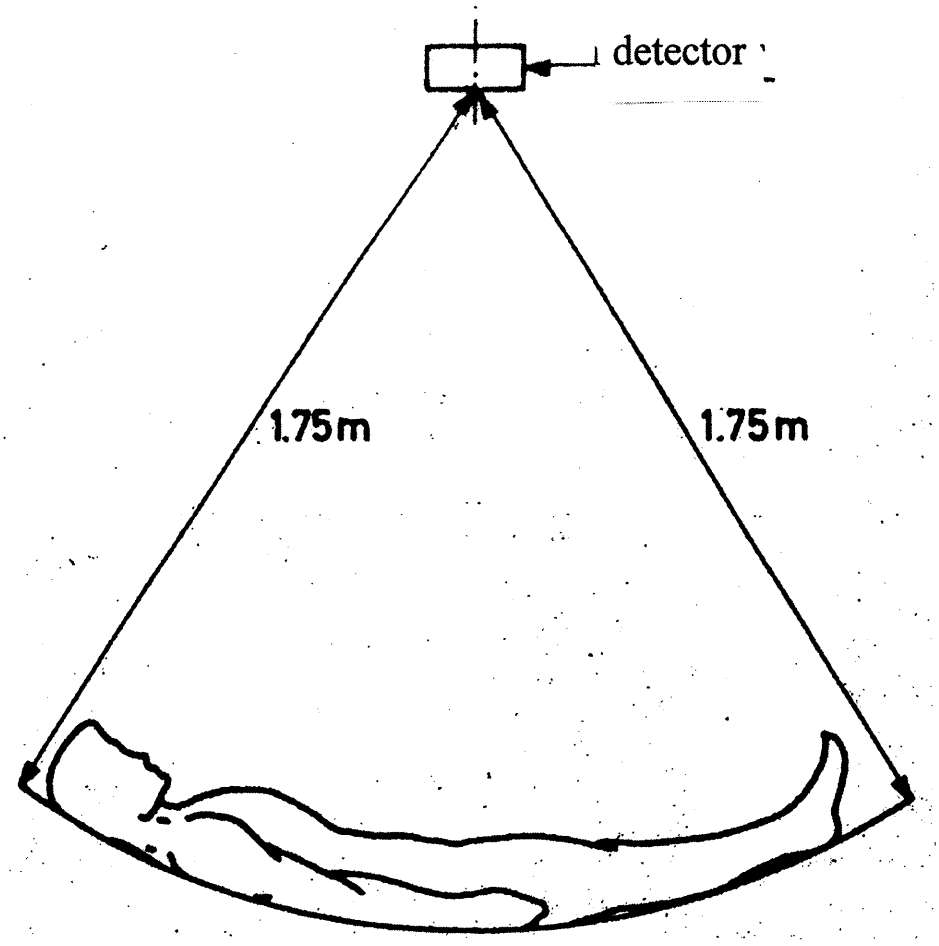


Figure 2–2: Arc geometry whole body counter with one detector (Naversten, 1966).

2.2.1.2 Chair geometry

The chair geometry was used by Miller and Marinelli in the 1950s. This whole-body counting technique has been used with cylindrical NaI(Tl) crystals of varying size as shown in Figure 2-3. In this counting geometry, the whole body (except for the lower legs) is roughly centred on the crystal (IAEA, 1966). The chair technique is not useful for the clinical whole body assay of gamma or x-ray emitters of low photon energy.

Figure 2-3: Chair geometry whole body counter with one NaI(Tl) detector (Ortec, 2010).

2.2.1.3 Bed geometry with an array of fixed detectors

In stationary counters, neither the patient nor the detectors move. In order to decrease the effects of inhomogeneous radioactivity distributions in the human body, several detectors are spread out along the length of the body.

Rundo has described a counter with the subject lying on a stretcher, two detectors being suspended above the patient and two detectors below the stretcher as shown in Figure 2-4. The crystals were arranged in such a way as to minimise response variations (IAEA, 1966).

The earliest measurement of the natural radioactivity content of the body was made by Sievert in 1951. He used a circular array of ten; long cylindrical high-pressure ionisation chambers arranged in the form of a horizontal tube in which the subject lay. With this system the efficiency was improved.

Different systems were developed including a multi-detector geometry in which an uncollimated array of detectors positioned symmetrically above and below the supine body provides an advantageous arrangement for achieving the required counter characteristics.

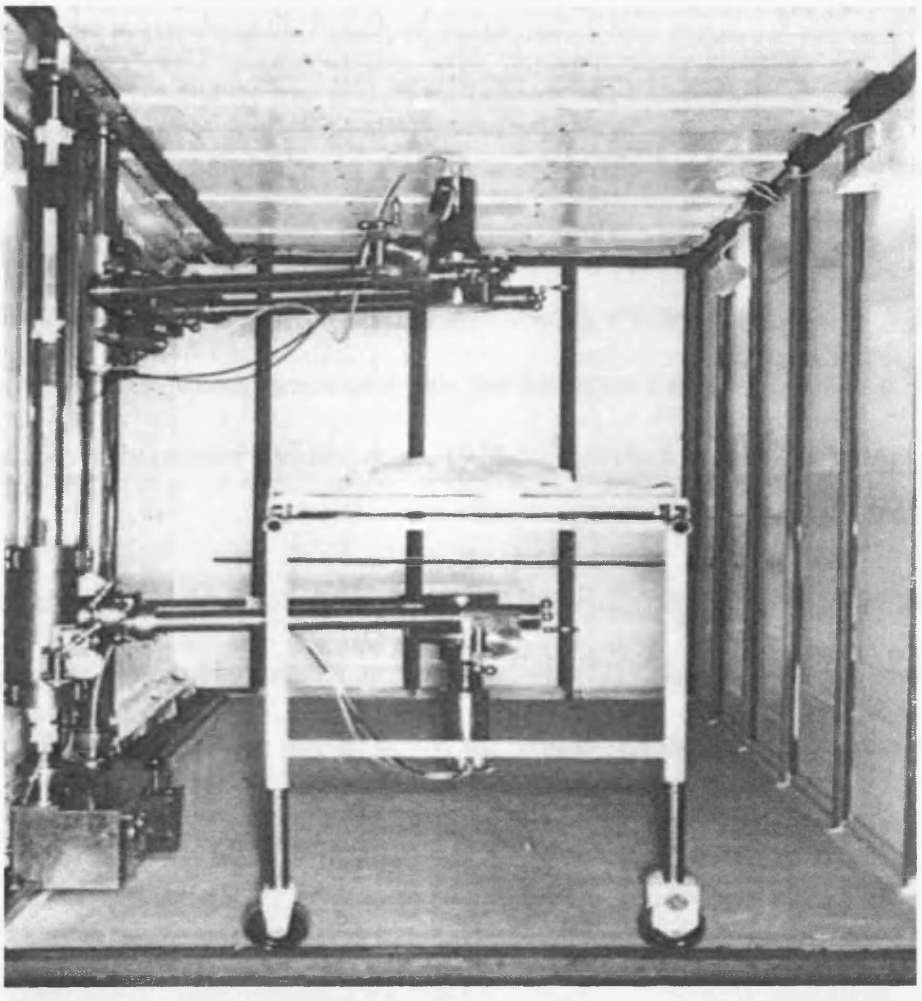


Figure 2-4: Stationary bed geometry whole body counter (Naversten, et al., 1969)

2.2.1.4 Scanning bed geometry with one or several detectors

In scanning counters either the subject or the detectors move. Scanning geometry systems appeared to offer the best compromise with good consistency if either a prone or supine counting mode was used. These systems are usually heavily shielded and the background count rate is low.

If the detectors move along the length of the subject, this requires a shielded enclosure which need only be slightly longer than the subject. For the mode in which the patient moves, a shadow-shield counter is used; in this case the shielding is just around the detector system. Shadow-shield counters usually employ either one or two detectors above and below the subject. These are mounted in a turret shield with the patient lying on a stretcher which is scanned past the detectors. Figure 2-5 shows a shadow shield whole body counter (Boddy, et al., 1975).

The first shadow-shield whole body counter with sensitivity comparable to that of a shielded room system employed a single large NaI (Tl) detector. Here the subject lay on a motorised couch which passed below the detector and was scanned from head to foot in a supine position and from the feet to the head in a prone position.

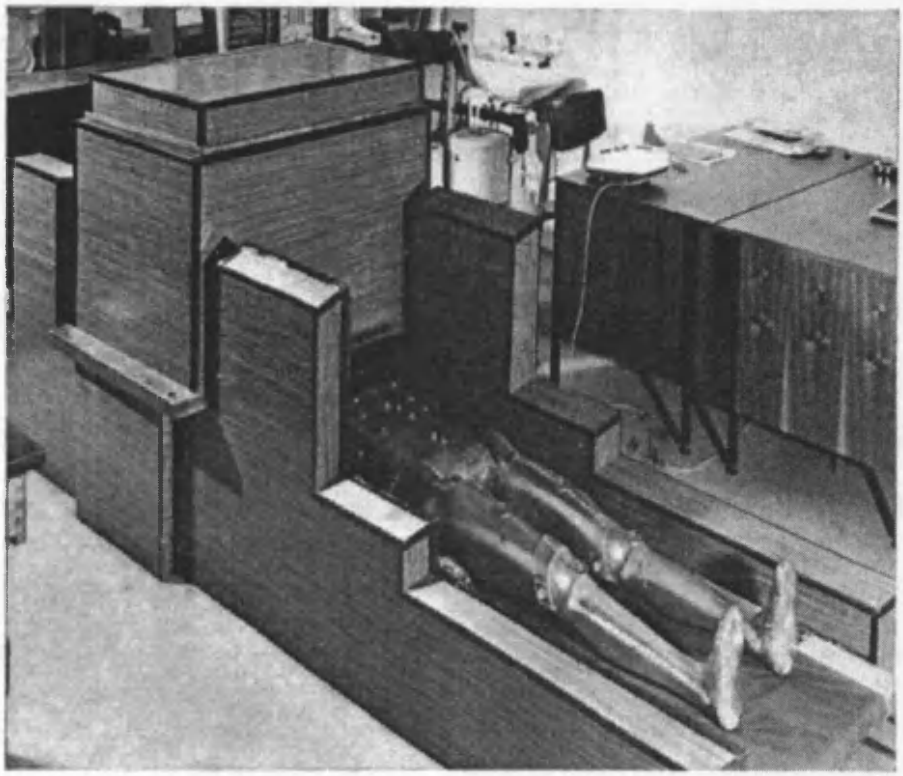


Figure 2-5: Shadow shield whole body counter (Boddy, et al., 1975)

2.3 The Cardiff whole body counter

2.3.1 Description of Cardiff whole body counter

The Cardiff whole body counter consists of two parts: a shielded room and a detection system. The shielded room is incorporated into the construction of the hospital building. During the planning of the University Hospital of Wales in the early 1960s, it was decided to establish a low background steel room. The detection system is based on a multi-detector design. It has six sodium iodide detectors each 15.2 cm in diameter and 10.2 cm thick; these are mounted on a vertical steel ring as shown in Figure 2–6. During the course of the study, two high purity p-type germanium detectors (HPGe) were fixed on to the vertical steel ring. None of the detectors has a collimator.

2.3.1.1 Shielded room

2.3.1.1.1 Physical dimensions and materials

The internal dimensions of the shielded room are length 213 cm, width 152 cm and height 182 cm. It was built by Nuclear Enterprises Ltd, Edinburgh, who used a 15 cm thick steel plate salvaged from the battleship HMS Vanguard. There were two reasons for using old naval steel: firstly it does not contain any radioactive fallout contamination because it was made before the atmospheric testing of atomic and nuclear weapons; secondly, the steel was made before the use of the radionuclide ^{60}Co to measure the corrosion of the internal brick covering of blast furnaces used in the

steel manufacturing industry. This led to the possibility of ^{60}Co being present as a contaminant in recently manufactured steel.

Background count rate was reduced by covering all the internal surfaces with 0.3 cm-thickness of aged lead. This reduced significantly the room background below 0.6 MeV. Additionally, the whole body counter rests on a 5 cm- thick steel support raft and thus the effective thickness of the steel for the base is 20 cm. At one end there are also two manually operated doors which have a staggered overlap when closed.

2.3.1.1.2 Ventilation

Room ventilation is provided using an 18 cm diameter hole in the wall opposite the doors. Situated behind this there is a shielding baffle of 5 cm thick steel and a filtered air ventilation unit which changes the room air approximately twelve times an hour. This prevents the possibility of a build-up of radon decay daughters within the room thereby causing a variation in the background count rate.

2.3.1.2 Detection system

2.3.1.2.1 Support gantry

The detector support gantry was made by J. & P. Engineering Co. Ltd. It comprises a vertical steel ring with an internal diameter of 91 cm. The ring moves on linear bearings running on two horizontal steel shafts which are supported at each end of the

room. The ring is connected to a steel drive shaft with a spring-loaded threaded bush; this drive shaft is supported by a bearing assembly at each end of the room and passes through a hole in the rear wall of the counter where it is directly coupled to a stepping motor drive unit.

The maximum scan length of the gantry is 159 cm and the limit of travel is controlled by micro-switches at each end of the room. In addition to this, the frequency of the drive pulses to the stepping motor can be varied to provide a range of scan speeds.

2.3.1.2.2 The detector units

Mounted on the vertical steel ring are six thallium activated sodium iodide NaI(Tl) scintillation detectors, each consisting of a crystal which is 15.2 cm in diameter and 10.2 cm thick. These are directly coupled via a light guide to a 10.2 cm diameter photomultiplier tube (EMI 9530A). In addition, two p-type co-axial high purity germanium detectors of thickness and diameter 60 x 62.5 mm and 60 x 59.5 mm may be positioned on the ring above the bed. These were installed during this study. The detectors were low-background units and carefully selected materials were used in their construction, with the scintillation detector housings incorporating a magnetic shield around the photocathode region.

2.3.1.2.3 The patient support system

The patient support system consists of an aluminium stretcher with a thin foam mattress. The stretcher is fitted with four wheels for easy transfer from the support trolley onto guide rails inside the counter; it is designed so that the central axis of the detector gantry is 10 cm above the stretcher base.

2.3.1.3 Anti-claustrophobia measures

The system operator is in contact with the subject by means of a two-way audio intercom. Music from a CD/DVD player and a tape recorder can be played to the subject and a closed-circuit television system is used to view the subject during the measurement, as shown in Figure 2–7.

The internal surfaces of the counter are covered with a decorative vinyl paper which has the added advantage of being easily cleaned or removed in the event of any contamination.

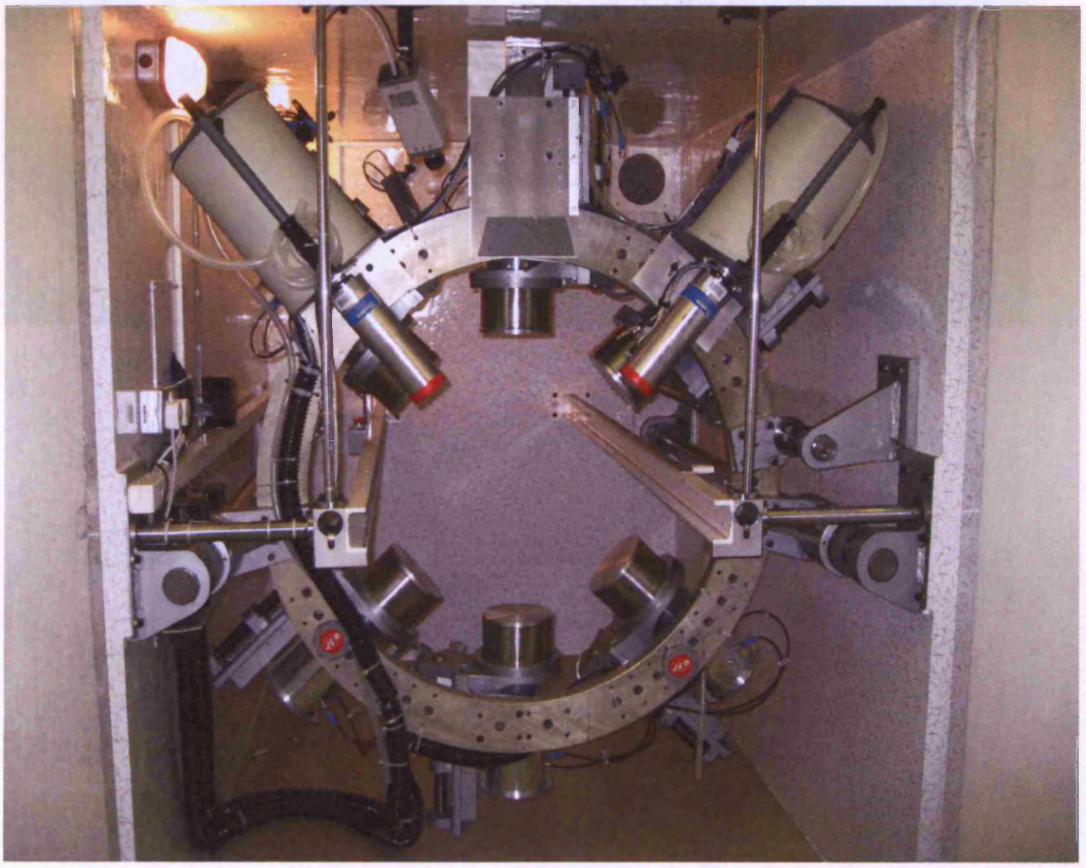
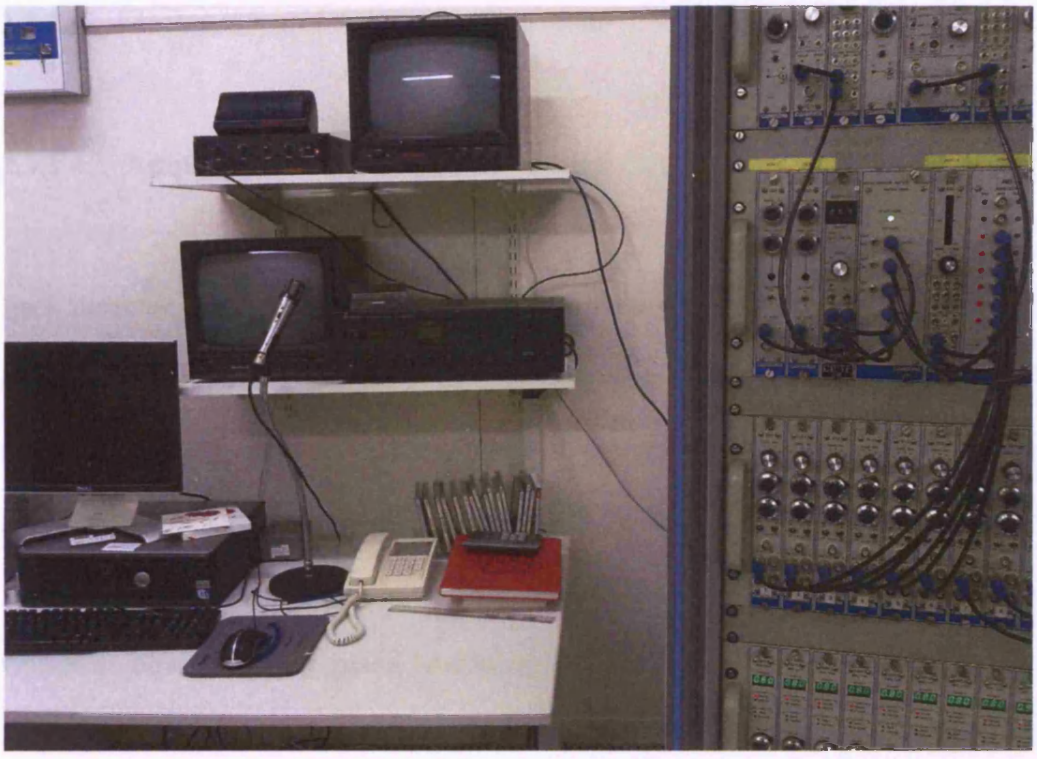
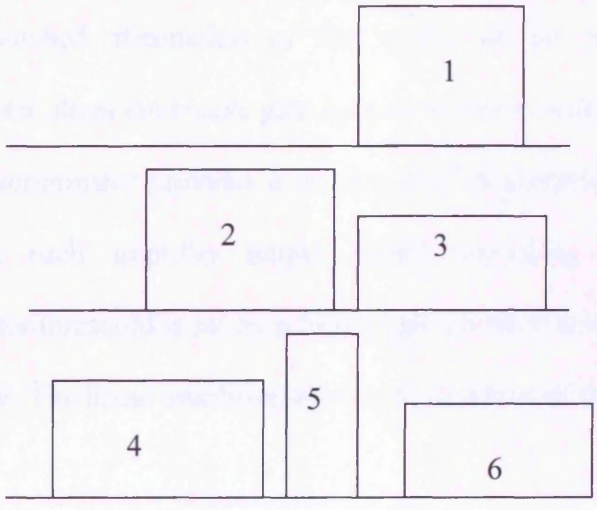


Figure 2-6: Construction of the detection system of the Cardiff whole body counter.





Key

1 and 2	**Closed - circuit television system (subject monitors)**
3	**Tape recorder**
4	**CD/DVD player**
5	**Two-way audio intercom**
6	**CDs**

Figure 2-7: View of the whole body operator's console including anti-claustrophobia measures

2.3.1.4 Electronics and data analysis system

2.3.1.4.1 Amplifier and high voltage modules

Each detector has a separate high voltage supply and every photomultiplier output is connected through a switch to a separate amplifier module. Each amplifier module (Canberra 814A) contains a charge-sensitive bipolar-input pre-amplifier, a linear amplifier with a maximum gain of 600 and an integral discriminator. The 814A module receives the charge output from a scintillation detector and provides a near Gaussian bipolar output pulse. Additionally a five-position rotary switch on the amplifier provides a x1 to x16 coarse gain range in binary steps, this being achieved by the switched attenuation of the output of the pre-amplifier. A fine gain potentiometer alters the coarse gain by continuously variable factors from 1 to 3. The integral discriminator provides a positive 8 V rectangular pulse at the discriminator output for each amplifier output signal exceeding a selected threshold; the discriminator threshold is set by a front panel 10-turn control, which has a range of 50 mV to 10 V. The linear amplifier output can be obtained separately.

2.3.1.4.2 Analogue multiplexer

The Canberra 8224 analogue multiplexer AMX module allows up to eight analogue input signals through a single analogue to digital converter (ADC). Multiplexing provides a cost effective method of handling large numbers of low count rate input signals with one ADC and is ideal for environmental measurements.

The AMX contains one Peak Detect and Hold (PDH) circuit for each of the eight input signals. These analogue memory circuits keep the peak value of each input pulse as a DC voltage level. When a pulse is captured by one of the PDH circuits, the scanner stops and connects the PDH to the ADC input; the AMX then generates a gate pulse which initiates the ADC conversion cycle. When the conversion is complete, scanning resumes.

2.3.1.4.3 Amplifier pulse control

The signal outputs of the amplifier are connected in parallel to the signal input of a mixer-rejector module and the amplifier's discriminator current pulse outputs are similarly connected to the discriminator input of this module. The mixer-rejector module detects any chance coincidence pulses from the detectors and blocks the ADC from analysing these, so preventing any pulse pile-up events being analysed.

The coincidence voltage pulse outputs of the amplifier are connected separately to a router module which allows the six detectors to be acquired separately, in pairs or summed together within different channel groups of the memory. Figure 2–8 shows the electronic scheme and its components.

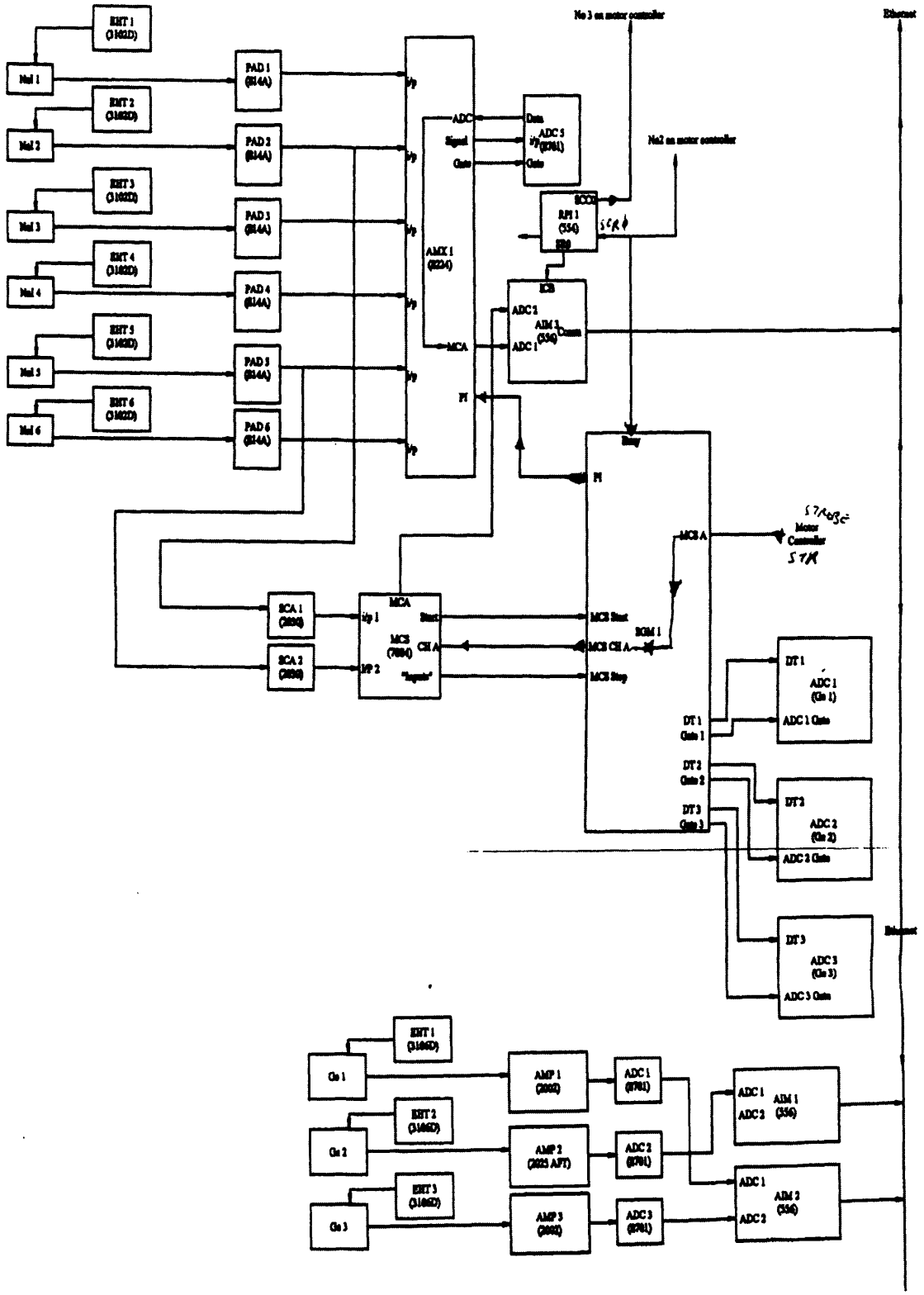


Figure 2-8: Electronic components of the Cardiff whole body counter

2.3.1.4.4 Operational system checks and settings

Generally, the multi-channel analyser (MCA) system is used with standard settings which are regularly checked for any variations. An outline of the relevant settings and checks carried out is provided below.

The overall gain of each detector is checked daily by measuring the channel position of the ^{137}Cs photopeak (662 keV). The stability of the high voltage and amplifier modules is such that the range of the ^{137}Cs photopeak positions for the detectors is rarely more than one channel and therefore high voltage adjustments are not often required. On the MCA, 512 channels are used for the NaI(Tl) pulse height spectra and 4096 channels for the HPGe spectra, with an energy range of 0-2 MeV in both cases. Thus each detector was adjusted to put the 662 keV peak exactly in channel 169 for the NaI(Tl) detectors and in channel 1356 for the germanium detectors.

In use, the spectra from the six scintillation detectors are summed to give a single summed spectrum while spectra from the two semiconductor detectors are acquired separately.

2.4 Clinical applications of whole body counters

Early applications of whole body counters until the 1950s were generally for radiological protection purposes. Counters tended to be established at nuclear research facilities and were not associated with a hospital environment. Clinical uses were started at the end of the 1950s; examples include the measurement of total body

sodium using ^{22}Na by Veall, et al. (1955) and the measurement of total body potassium using naturally occurring ^{40}K.

Over a period of about 40 years, the most frequent routine clinical applications of the Cardiff whole body counter have been haematological investigations such as blood loss, vitamin B-12 absorption and iron absorption. Iron absorption is now used just for research applications and it is unfortunate that the clinical use of iron loss and vitamin B12 absorption have been discontinued due to the unobtainability of the required radiopharmaceuticals. However, more recently, the counter has been increasingly used for the clinical measurement of bile salt absorption. The measurement of total body potassium is still available as a research application. Details of clinical investigations between 2000 and 2009 are shown in Table 2-1.

Investigation type	Radionuclides used	Number of patients	Number of scans
Iron loss[1]	^{59}Fe citrate	3	15
Vitamin B12 absorption[2]	^{57}Co and ^{58}Co B_{12}	55	220
Vitamin B12 absorption[3]	^{57}Co B_{12}	225	975
Bile salt absorption	$^{75}SeHCAT$	120	360

[1]This test discontinued in 2004

[2]This test discontinued in Aug 2001

[3]This test discontinued in October 2009

Table 2-1: Clinical investigations using the Cardiff whole body counter carried out over the last ten years.

2.4.1 Protocol for absorption and loss measurement

For these measurements, a baseline whole body count-rate measurement is made soon after the administration of the radiopharmaceutical; it is assumed that the count-rate is proportional to the in vivo activity. For the absorption measurements, the patient returns for one further count-rate measurement at a set time post baseline. Absorption of the radiopharmaceutical is calculated by dividing the follow-up count rate by the baseline count-rate and expressing this as a percentage which is compared with a reference range. For the loss measurement, follow-up count-rate measurements are made at several time points post baseline. At each time point, the activity loss is calculated by subtracting the percentage absorption (retention) from 100% and the loss rate by fitting an exponential function to the percentage retention values.

Count-rates are measured in the Compton band of the pulse height spectrum for the relevant radionuclide. This is done for forward and reverse whole body scans and with the detectors stationary at the head and feet ends of the patient. An empirically derived fraction of the "end-stop" count-rates is added to the scan count-rates to give the final whole body count-rate. This compensates for reduced counting efficiency at the extremes of the scan range. The combination of Compton band counting and end-stop correction significantly reduces variations in the whole body counter sensitivity with redistribution of activity in the body (Thomson, 1981).

Prior to the administration of the radiopharmaceutical, a patient background whole body count-rate is measured and subtracted from the subsequent measurements. Patients are measured with footwear and outdoor clothing removed. Furthermore,

each time a patient is measured, the count-rate from a phantom containing a reference activity of the relevant radionuclide is also measured. Patient count-rate is expressed as a fraction of the reference count-rate to correct for radioactive decay and for any small variations in sensitivity due to electronic drift. Each whole body count-rate measurement takes 10-15 minutes.

2.4.2 Measurement of Vitamin B-12 absorption

Vitamin B-12 (Cyanocobalamin) is essential for DNA synthesis, blood cell production and the formation of myelin. It cannot be synthesised in the human body and so it must be obtained from dietary sources of animal origin (meat, milk and eggs). Therefore deficiency may be caused by a prolonged vegan diet. The normal daily requirement of Vitamin B-12 is 1-2 μg. Vitamin B-12 is absorbed in the gastrointestinal tract, stored in the liver and eventually excreted in urine. Before it is absorbed by the body, it is first bound to a glycoprotein called Intrinsic Factor (IF), produced by cells in the stomach. This Intrinsic Factor-Vitamin B-12 complex travels from the stomach to the distal ileum where specific receptors in the epithelial lining of the ileum facilitate its absorption. The effects of B-12 deficiency may not show up for several years as there are large stores within the liver. However, a sustained deficiency will eventually result in megaloblastic anaemia – red blood cells do not mature fully, are fragile and have a reduced lifespan. Degeneration of nervous tissue may also occur.

Malabsorption of vitamin B12 is also possible. In pernicious anaemia (IF dependent malabsorption) not enough IF is produced by the stomach cells due to total or partial

gastrectomy or gastric lesions, or due to antibodies that are produced to IF. Another possibility is defective intestinal absorption (IF independent malabsorption), the causes of which include lesions in the small intestine (e.g. due to Coeliac or Crohn's disease), bacterial overgrowth in blind loops of the intestine, or tapeworm infestation.

Most tests of Vitamin B-12 absorption are based on the use of radioactively labelled Vitamin B-12, which has the cobalt atom of its molecular structure replaced by one of the radioisotopes of cobalt, as introduced by Chaiet, et al. (1950).

The test may be performed with a whole body counter using ^{58}Co labelled Vitamin B-12 and ^{57}Co labelled Vitamin B-12 + IF (Bell, et al., 1965). However, ^{58}Co labelled Vitamin B-12 was withdrawn in 2001 and so a two-part test just using ^{57}Co labelled vitamin was developed at the University Hospital of Wales. For the first part of the test, the patient fasts overnight prior to a hospital visit during which the labelled Vitamin B-12 (18.5 kBq) is administered orally as a capsule. The baseline whole body count-rate is then measured as indicated in 2.4.1 above. The count-rate is re-measured at 2 weeks (14 days) to determine the absorption; a value of greater than 40% is normal and the test is complete.

If the result is abnormal (i.e. less than 40%), the absorption of ^{57}Co labelled Vitamin B-12 + IF is measured to distinguish between simple malabsorption (i.e. IF independent malabsorption) and pernicious anaemia (IF dependent malabsorption). The patient attends hospital for a third visit 3-5 weeks after the first visit. A whole body count-rate measurement is made and the result combined with that made at 2 weeks in order to estimate the biological half-life of ^{57}Co Vitamin B-12 in the patient. Another capsule of ^{57}Co Vitamin B-12 plus a capsule of IF are then given. The whole

body count-rate is immediately re-measured and corrected for that due to the first administration. After a further two weeks, a final whole body count-rate is measured and corrected for the estimated contribution of the first administration (using the effective half-life). Thus a 14 day percentage absorption of Vitamin B12 + IF is calculated.

The interpretation of absorption results is shown in Table 2-2.

Measurement	**Value**	**Diagnosis**
Absorption of B12 alone	>40%	Normal
Absorption of B12 alone	<40%	Pernicious Anaemia
Absorption of B12 + IF	Higher than B12 alone	
Ratio (B12+IF)/B12	> 1.3	
Absorption of B12 alone	<40%	Malabsorption
Absorption of B12 + IF	Same or higher than B12 alone	
Ratio (B12+IF)/B12	≤ 1.3	

Table 2-2: Interpretation of the possible results of Vitamin B12 measurement

2.4.3 Measurement of iron loss

This investigation is used for the evaluation of the origin of unclear iron deficiency anaemia.

In Western countries with typical high-energy nutrition containing sufficient amounts of iron, iron deficiency anaemia is regarded as a serious clinical symptom. Because the normal iron loss in adults is in the range 1-2 mg per day, a moderate to severe anaemia is in most cases the consequences of abnormal blood loss (e.g. due to hyper menorrhoea or gastrointestinal bleeding).

Such anaemic patients must undergo a complete gastrointestinal evaluation. However, in some cases, the underlying origin of the iron deficiency anaemia remains unclear due to unrecognised hyper menorrhoea, gastrointestinal trickle bleed or malabsorption. Other non invasive methods (blood pool imaging, angiopraphy) are much less sensitive than whole body counting methods. In females, menstrual loss can be differentiated from gastrointestinal loss.

Patients are intravenously administered 37 kBq of ^{59}Fe in the form of ferrous citrate. The iron is gradually incorporated into red blood cells and a patient baseline whole body count-rate is measured at day 7 (unless the patient is a pre-menopausal female and 7 days is likely to coincide with menstruation). For such a patient, a note is made of the dates of the first and last days of each menstrual period. Routinely, subsequent measurements are taken at 14 day intervals (but again avoiding menstruation if relevant) unless clinical indications suggest more frequent measurements are required.

For each measurement, the percentage retention of activity is calculated and plotted semi-logarithmically against time; the durations of any menstrual periods are also indicated on the graph. Linear regression is used to calculate an average rate of loss over an identified time period; this is compared with the upper limit of normal of 0.1% per day.

2.4.4 Measurement of bile acid absorption

This investigation used for the detection of bile acid malabsorption which results in persistent watery diarrhoea. The radiopharmaceutical ^{75}SeHCAT (23-seleno-25-homo-tauro-cholic acid) is used.

SeHCAT is an analogue of naturally occurring bile acid conjugates. Normally these bile acids are reabsorbed by the terminal ileum. Bile acids may induce diarrhoea if they enter the colon, through inhibition of water and electrolyte transport and possibly by increasing colonic motility. Three types of bile acid malabsorption have been described as follows:

Type I This is associated with terminal ileal resection or with mucosal disease of the terminal ileum.

Type II This is idiopathic (of unknown origin).

Type III This follows cholecystectomy or vagotomy.

Patients with bile acid malabsorption may benefit from the administration of a chelating agent such as cholestyramine.

In the whole body counter test, the patient is administrated with 37kBq ^{75}SeHCAT orally. Absorption is measured at day 7 with normal values being greater than 10%.

2.5 Minimum detectable activity

The minimum detectable activity (MDA) may be regarded as a basic figure of merit for a nuclear counting system such as a whole body counter. It takes into account all the system parameters: the background count-rate, efficiency, counting time and energy resolution; a lower MDA implies improved system performance.

The theoretical MDA is defined in relation to the background count and count rate as follows. If B background counts are detected in a selected energy window in a counting time t:

Minimum detectable count $= 3\sqrt{B}$ Equation 2-1

Here $\sqrt{B}$ is the estimated standard deviation of B from Poisson statistics. Thus

Minimum detectable count rate $= (3\sqrt{B}) / t$ Equation 2-2

It follows that:

$$MDA = \frac{Minimum\ \ detectable\ count\ rate}{detector\ sensitivity}$$ Equation 2-3

Here the detector sensitivity is the count-rate per unit activity (expressed as counts per second per Becquerel).

Therefore

$$\text{Theoretical MDA} = \frac{\frac{3\sqrt{B}}{t}}{Sensitivity} \qquad \text{Equation 2-4}$$

If C counts are detected in time t when a source of known activity A is placed near the detector:

$$Sensitivity = \frac{(C-B)/t}{A} \qquad \text{Equation 2-5}$$

The MDA depends on the background count-rate, the counting time and the sensitivity. The sensitivity, in turn, depends on the detector efficiency and the counting geometry. For a constant background count-rate and sensitivity, the MDA decreases as counting time increases (Sumerling, et al., 1985).

CHAPTER THREE

PERFORMANCE OF CARDIFF WHOLE BODY COUNTER

3.1 Introduction

In the event of an incident involving radioactive materials, there could potentially be a large number of people who require monitoring for internal contamination. If the release contains radionuclides which emit high energy gamma rays, the most appropriate way of providing this monitoring is whole body counting. In addition, from the point of view of radiation protection, monitoring is required for people who are working with radioactive materials. The ability to achieve reasonably accurate quantitation of activity with a whole body counter is a major criterion for its usefulness as a monitoring device. To achieve this goal, efforts need to be made to minimise errors in measurements (e.g. those arising from non-uniform distribution of radioactivity in the body) and to ensure long-tern stability of the detection system.

For most clinical work, absolute measurement of activity is not required and relative measurements usually suffice. Nevertheless, consistency of performance of the detection system is still important.

The performance of the counter is determined by factors such as the background count rate, the detection sensitivity and the energy resolution at relevant gamma ray energies.

3.2 Spectral energy windows

While the entire scintillation or semiconductor spectrum contains potentially useful information about the incident gamma radiation, data analysis is greatly simplified by summing the counts over selected energy bands. The photopeak region provides greatest selectivity among gamma rays of different energy, and often the most favourable counting statistics (Dudley & Haim, 1968).

In order to detect the presence of specific nuclides in an energy spectrum, it is necessary to create energy windows. Each window encompasses a particular part of the energy spectrum and has an upper and lower threshold that can be adjusted.

In this work, a ^{137}Cs photopeak window was set for the range 550-830 keV and a ^{40}K photopeak window for the range 1290-1680 keV with the NaI(Tl) detectors. These windows were deliberately chosen to be wide to ensure that the whole photopeak was included for all the spectra that were analysed. For the HPGe detectors, the energy windows were much narrower since semiconductor detectors have much better energy resolution; the values were 652-670 keV and 1454-1467 keV for ^{137}Cs and ^{40}K respectively. The NaI(Tl) and HPGe windows for the ^{40}K photopeak are compared in Figure 3-1.

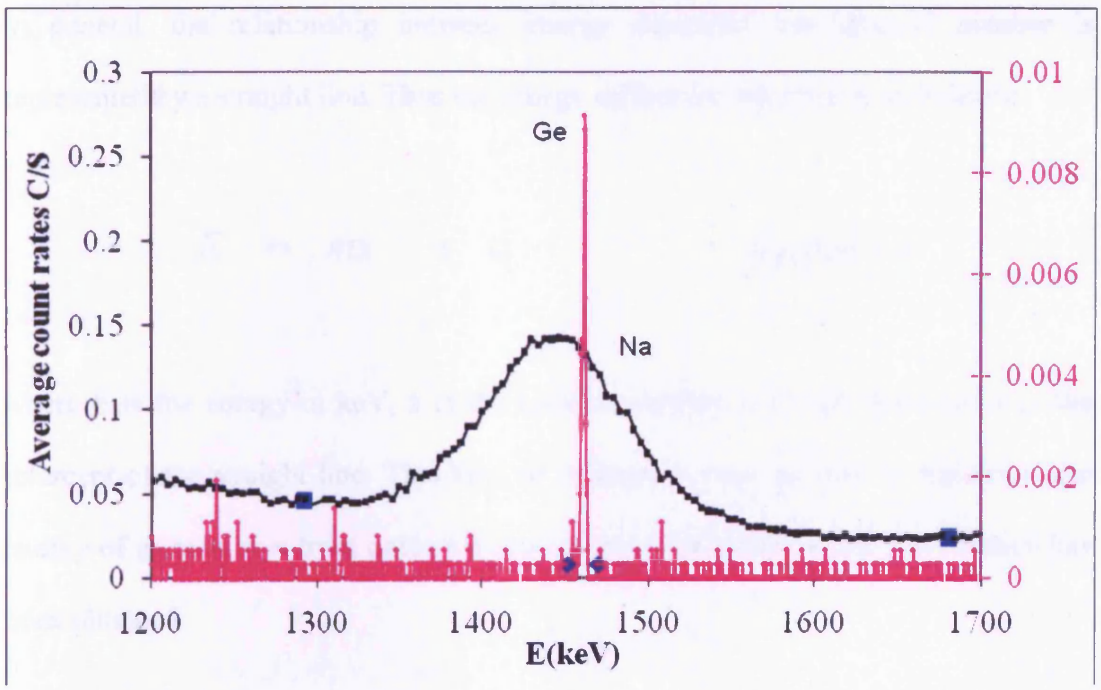


Figure 3–1: Pulse height spectra from a human volunteer for the NaI(Tl) detectors (black) and a HPGe detector (pink). Energy windows for the ^{40}K photopeak are bounded by blue squares for the NaI(Tl) spectrum (1290–1680 keV) and by blue diamonds for the HPGe spectrum (1454–1467 keV).

3.3 Energy calibration and its stability

When a gamma ray enters the detector it causes ionisation and excitation which, either directly or indirectly, release electrons that are collected to form an electric pulse. The total charge in the electric pulse is converted to a voltage which is proportional to the total energy deposited in the detector by the incident gamma ray. The multi-channel analyser (MCA) is the part of the spectrometry system that analyses the pulses according to their voltage; it allocates each pulse to a channel (where each channel corresponds to a small voltage range). To convert the channel number to energy, the MCA must first be calibrated.

In general, the relationship between energy deposited and channel number is represented by a straight line. Thus the energy calibration equation is as follows:

$$E = mx + c \qquad \text{Equation 3-1}$$

where E is the energy in keV, x is the channel number, m is the slope and c is the intercept of the straight line. This kind of calibration may be used to determine the energy of gamma rays from unknown sources once their pulse height distribution has been obtained.

3.3.1 Method

Standard energy calibration sources of ^{137}Cs (662 keV), ^{133}Ba (356 keV) and ^{60}Co (1173 and 1332 keV) were used to establish the relationship between the photopeak energy and the channel number displayed on the multi-channel analyser, and a linear regression line was generated through the data points. .On the MCA, 512 channels are used for the NaI(Tl) pulse height spectra and 4096 channels for the HPGe spectra, with an energy range of 0-2 MeV in both cases.

Prior to energy calibration, any small gain shifts of the NaI(Tl) system were corrected using the ^{137}Cs source and adjusting the fine gain of the amplifiers. This was done by moving the centroid of the 662 keV photopeak to the correct MCA channel (169) for each of the six detectors in turn. The process was repeated for the HPGe detectors such that the photopeak was in channel 1356.

For energy calibration, the three sources were placed on the front of the entrance window of either the germanium or scintillation detectors and measured for 200 seconds in the case of the NaI(Tl) system and 600 seconds for the HPGe detectors. The multiple NaI(Tl) spectra were then summed to produce a single 512 channel spectrum containing the summed response of all six NaI (Tl) detectors. For HPGe, the spectrum from each detector was acquired separately.

The relationship between gamma photopeak energy and the corresponding channel number is linear and a typical graph for the NaI(Tl) system with four points and a best-fit straight line drawn through the points is shown in Figure 3-2. This graph was used to obtain the channel range corresponding to a specific energy window and corrects for any residual minor electronic drifts of the detection system.

In this work, energy calibration was done each day the counter was used. For the scintillation detectors, energy calibration results for a preceding period of about ten years were also available. The stability of the energy calibration was investigated by plotting the slope m and intercept c of equation 3-1 against time and using linear regression and correlation.

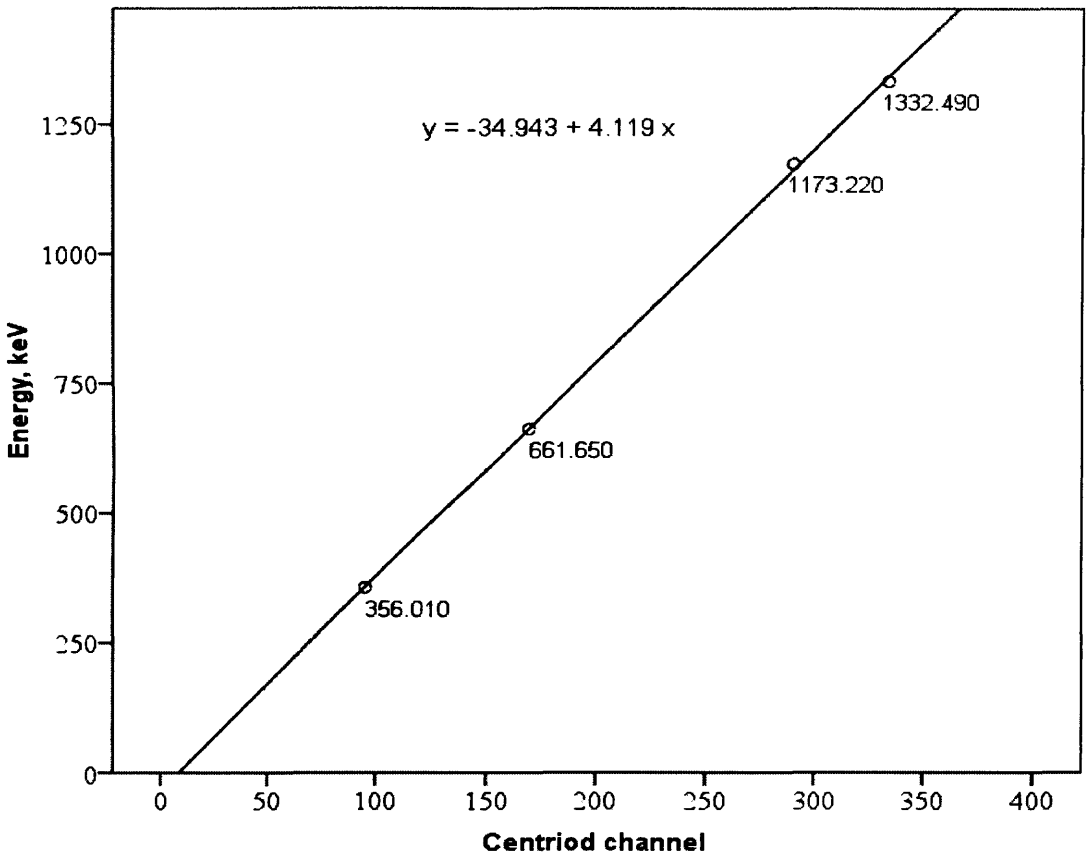


Figure 3-2: Typical energy calibration graph for the scintillation detectors.

3.3.2 Results and discussion

The stability of the high voltage and amplifier modules is such that the range of the ^{137}Cs photopeak positions for the detectors is often not more than one channel.

The variation of the slope (m) and intercept(c) over time for the NaI(Tl) is shown in Figures 3–3 and 3–4. The corresponding data for one of the HPGe detectors (Ge1) are shown in Figures 3-5 and 3–6 and those for the other HPGe detector (Ge2) in Figures 3-7 and 3-8. The HPGe detectors were not used between weeks 16 and 57.

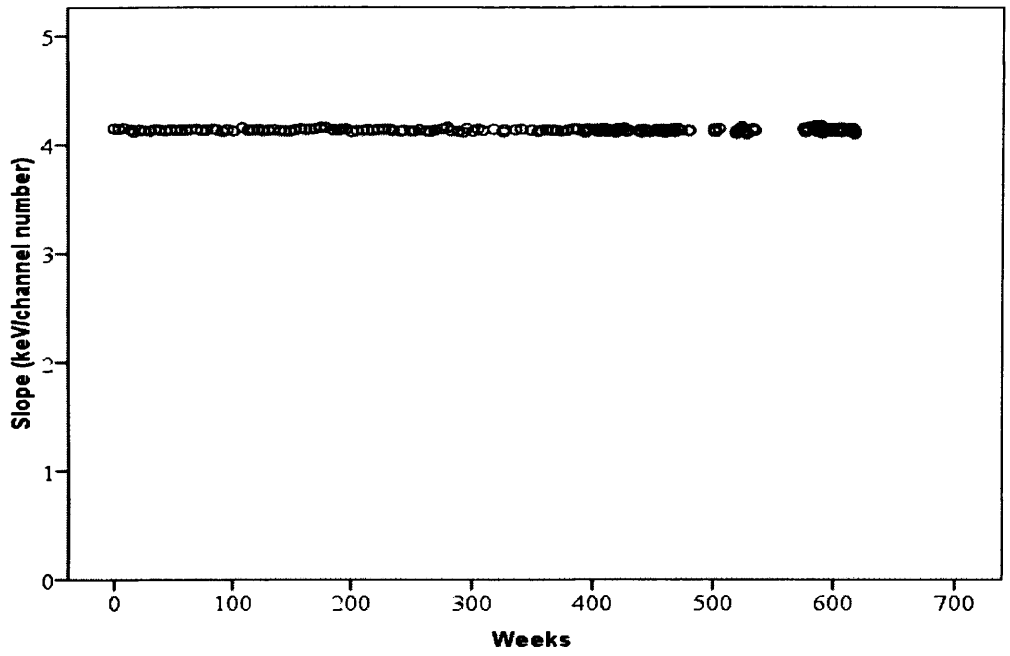


Figure 3–3: Variation in slope m of energy calibration line with time for NaI(Tl) detectors over a period of about 12 years. The measurements were made between 06/01/1998 and 04/11/2009.

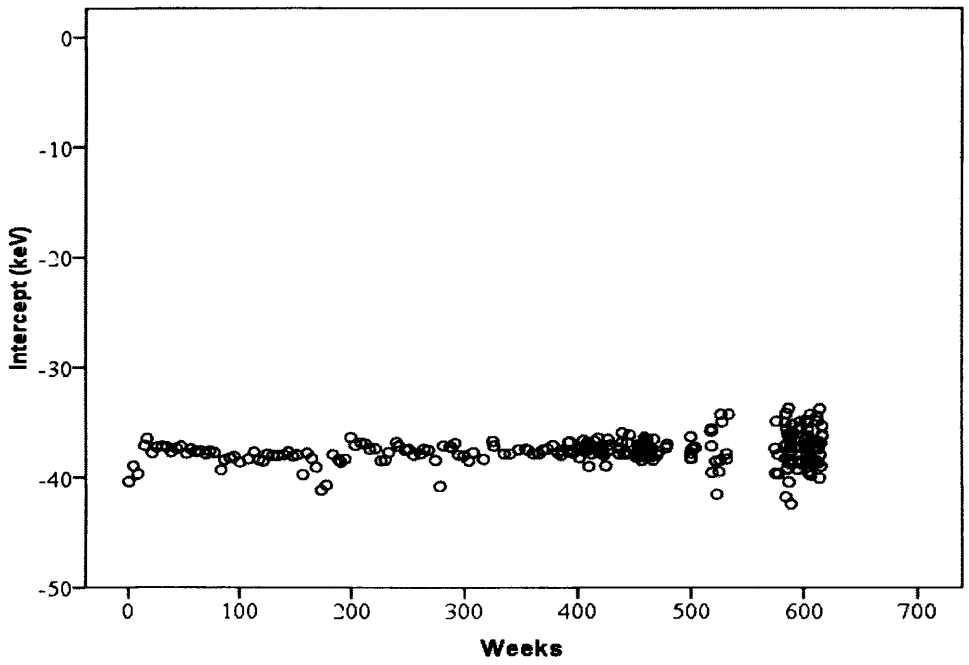


Figure 3–4: Variation in intercept c of energy calibration line with time for NaI(Tl) detectors over a period of about 12 years. The measurements were made between 06/01/1998 and 04/11/2009.

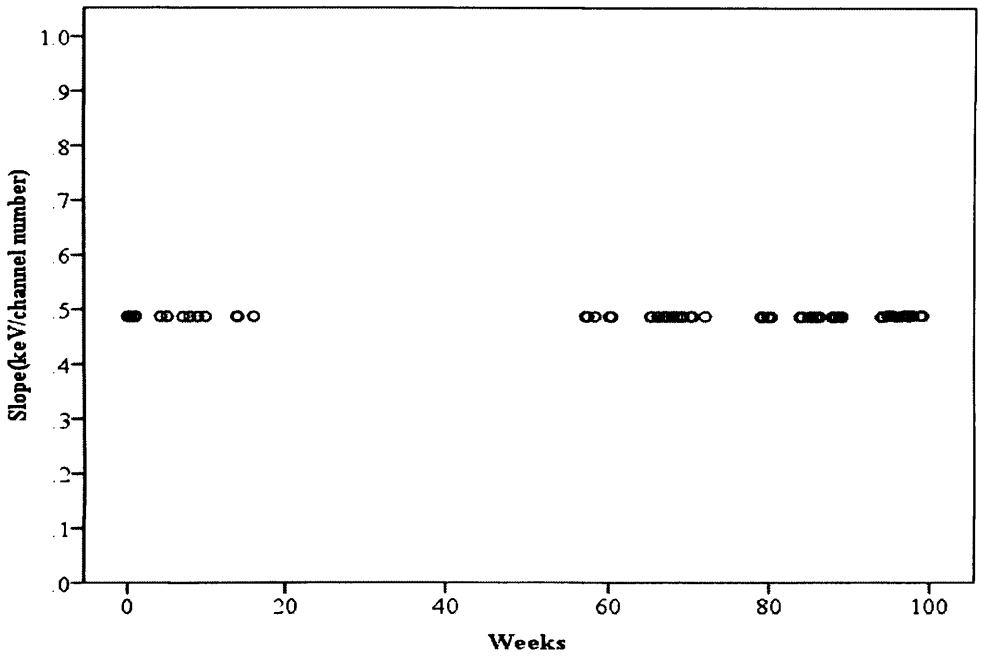


Figure 3–5: Variation in slope m of energy calibration line with time for HPGe detector Ge1 over a period of about 2 years. The measurements were made between 11/12/2007 and 04/11/2009.

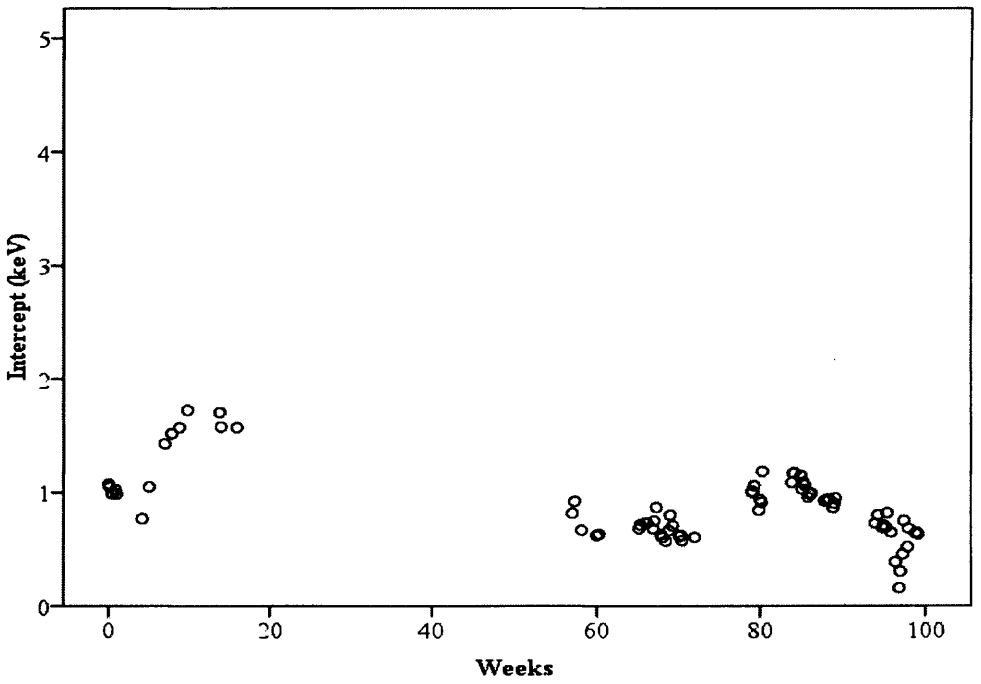


Figure 3–6: Variation in intercept c of energy calibration line with time for HPGe detector Ge1 over a period of about 2 years. The measurements were made between 11/12/2007 and 04/11/2009.

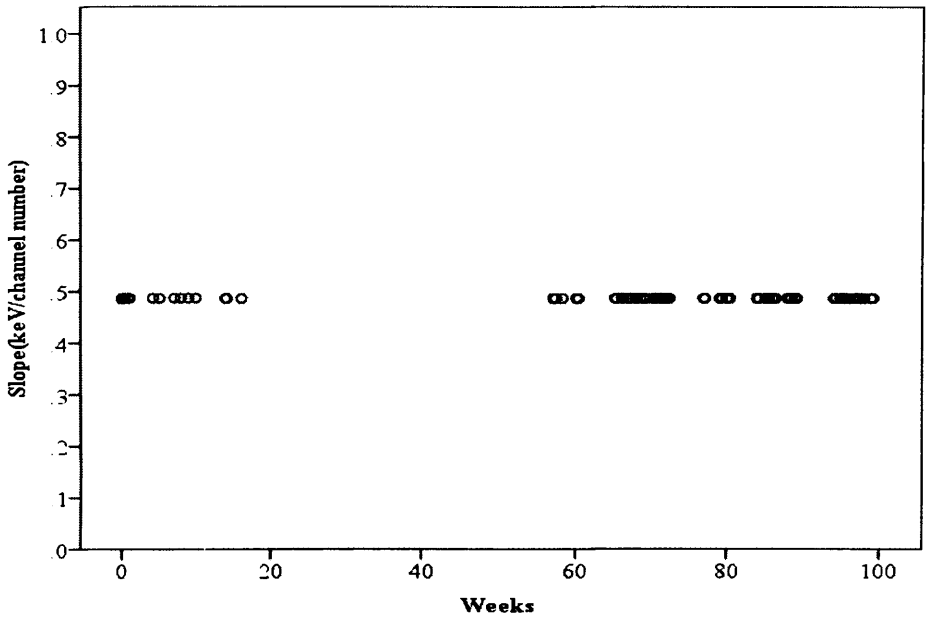


Figure 3–7: Variation in slope m of energy calibration line with time for HPGe detector Ge2 over a period of about 2 years. The measurements were made between 11/12/2007 and 04/11/2009.

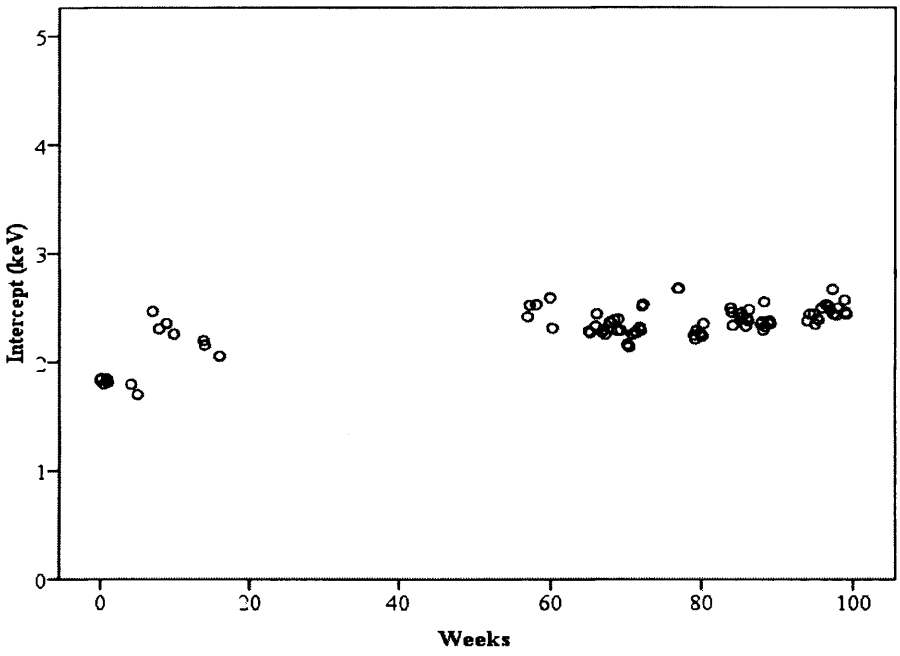


Figure 3–8: Variation in intercept c of energy calibration line with time for HPGe detector Ge2 over a period of about 2 years. The measurements were made between 11/12/2007 and 04/11/2009.

The values of the slopes of the energy calibration lines are as expected: about 4 keV per channel for the NaI(Tl) detectors and about 0.5 keV per channel for both HPGe detectors. For the scintillation detectors, the variation in the slope is less than 0.01% per annum over a period of about 12 years; the corresponding value for the semiconductor detectors is less than 0.1% per annum over 2 years. In all three cases the slope of the energy calibration line is very stable. This is to be expected since the gain was adjusted before energy calibration to ensure that the centroid of the ^{137}Cs photopeak was in its designated channel.

The expected value of the intercept of each energy calibration line is zero. For the NaI(Tl) detectors, the measured value is about -39 keV, which is small compared with the total energy range of 2 MeV. The average variation of the intercept is about 0.3 % per annum although the variation increases with time. For the HPGe detectors, the intercept is only about 1-2 keV. There is some variation in the values of the intercept for both detectors but this is to be expected when the values are so close to zero.

Overall, the results indicate that energy calibration is stable for both the scintillation and semiconductor detectors.

3.4 Energy resolution and its stability

In radiation spectroscopy, the function of radiation detectors is to measure the energy distribution of the incident radiation. A further factor of importance in the detection of gamma rays is the ability of the system to resolve photopeaks which are close together in energy (Ouseph, 1975). The response function of the detector is the photopeak. The

For a semiconductor detector, the factors influencing energy resolution are:

1. Statistical variation in the number of electron-hole pairs produced for a given amount of gamma energy deposited (the limiting factor);
2. Variation in the fraction of number of electro-hole pairs collected by the applied voltage.

The reason why the energy resolution of a semiconductor detector is far superior to that of a scintillation detector is the much greater number of electron-hole pairs produced in the former per unit of gamma energy deposited compared with the number of photoelectrons produced in the latter (Ouseph, 1975).

3.4.1 Method

Three point sources of ^{137}Cs, ^{133}Ba and ^{60}Co were placed in the front of the detector windows and their spectra acquired to energy calibrate the detection system. From the energy calibration report and using the energy calibration equation, the FWHM of the main photopeaks in the spectrum were determined. The FWHM was automatically calculated by the software by fitting a Gaussian curve to each photopeak. The relative energy resolution of the detection system was calculated as a FWHM divided by photopeak centroid multiplied by 100.

In addition, linear regression analysis was used investigate the stability of the energy resolution of the NaI(Tl) detectors over 12 years and that of the HPGe detectors over the course of this study.

3.4.2 Results and discussion

Table 3-1 shows the average energy resolutions obtained using the NaI(Tl) and HPGe detectors.

Source and energy (keV)	Detector type	No. of points	Mean energy resolution (%)	Std. Error of Mean (%)	Std. Deviation (%)
Ba-133 (356)	NaI(Tl)	263	12.369	0.210	2.870
	Ge 1	79	0.509	0.005	0.048
	Ge 2	79	0.495	0.008	0.075
Cs-137 (662)	NaI(Tl)	263	8.954	0.029	0.387
	Ge 1	79	0.324	0.003	0.028
	Ge 2	79	0.295	0.004	0.038
Co-60 (1173)	NaI(Tl)	263	4.911	0.020	0.276
	Ge 1	79	0.219	0.003	0.026
	Ge 2	79	0.183	0.002	0.021
Co-60 (1332)	NaI(Tl)	263	5.074	0.025	0.338
	Ge 1	79	0.197	0.003	0.026
	Ge 2	79	0.167	0.002	0.017

Table 3-1: Average energy resolution (%) obtained for ^{137}Cs, ^{133}Ba and ^{60}Co sources using NaI(Tl) and HPGe detectors

Scintillation detectors used in gamma ray spectroscopy normally show an energy resolution in the range of 5-10 percent, whereas semiconductor detectors have an energy resolution of less than 1 percent (Knoll, 2000). In this study, the average energy resolution of the combined six NaI(Tl) detectors for the ^{137}Cs photopeak is about 9% and this value concurs with the British Standard for a single detector (less

than 10%). For HPGe it is about 0.3% which also corresponds well with the British Standard (less than 2%) (British Standard, 2006).

The energy resolution of the HPGe detectors is about 30 times better than that of the NaI(Tl) detectors. The germanium detectors therefore have superior ability to identify unknown radioactive nuclides in the human body.

The superior resolution of the germanium detector means that there is a much reduced possibility of misinterpretation of spectral information. In particular, it would be possible to interpret the very complex spectra that could be produced immediately following fallout release. While the efficiency of germanium detectors is lower than that of scintillation detectors, the increased energy resolution means that low intensity peaks can be more easily distinguished from the background continuum (Youngman, 2003).

There are a number of possible sources of variation in the response of the detector which result in a finite energy resolution. These include any drift of the operating characteristics of the detector during the course of the measurements, sources of random noise within the detector and instrumentation system and statistical noise arising from the discrete nature of the measured signal itself. Statistical noise represents the most important source of variation in the signal and sets a limit on the detector's performance (Knoll, 2000).

Linear regression analysis of energy resolution at 662 keV with time indicates an average deterioration of 1.2 % per annum for the NaI(Tl) detectors (Figure 3-9); this value is the slope of the regression line expressed as a percentage of the intercept.

This is likely to be associated with detector ageing and consequential greater variation in the factors contributing to energy resolution listed in 3.4 above. Greater gain mismatch between the six individual detectors with time may also degrade energy resolution. Over a two year period, there was no overall change in the energy resolution of the HPGe detectors (Figures 3-10 and 3-11).

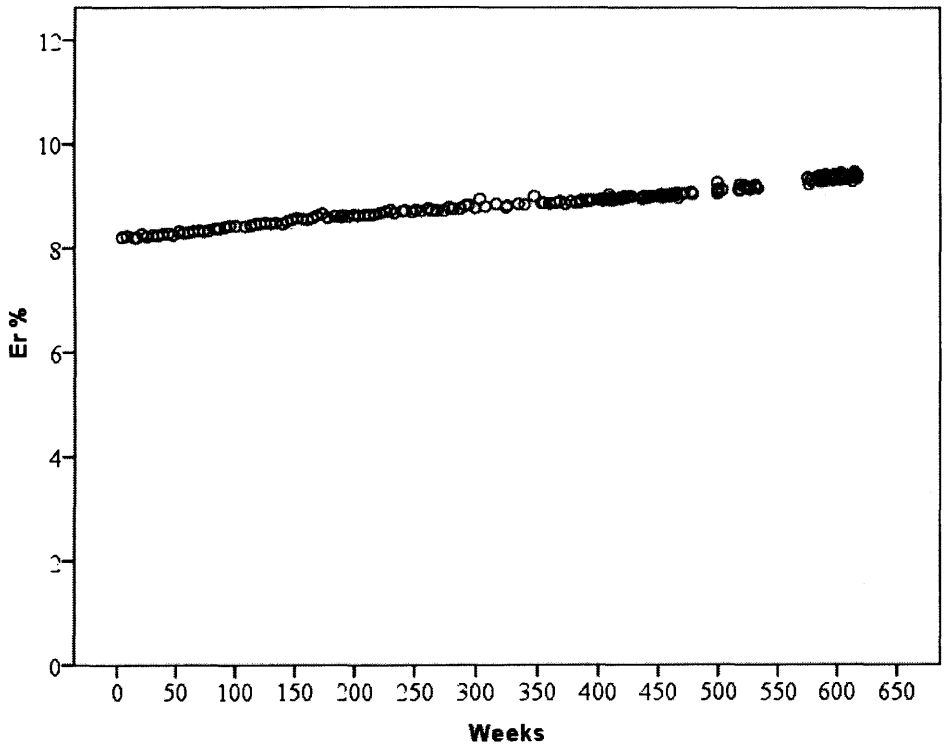


Figure 3–9: Energy resolution over a time for a ^{137}Cs source using NaI(Tl) detectors. The measurements were between 06/01/1998 and 04/11/2009.

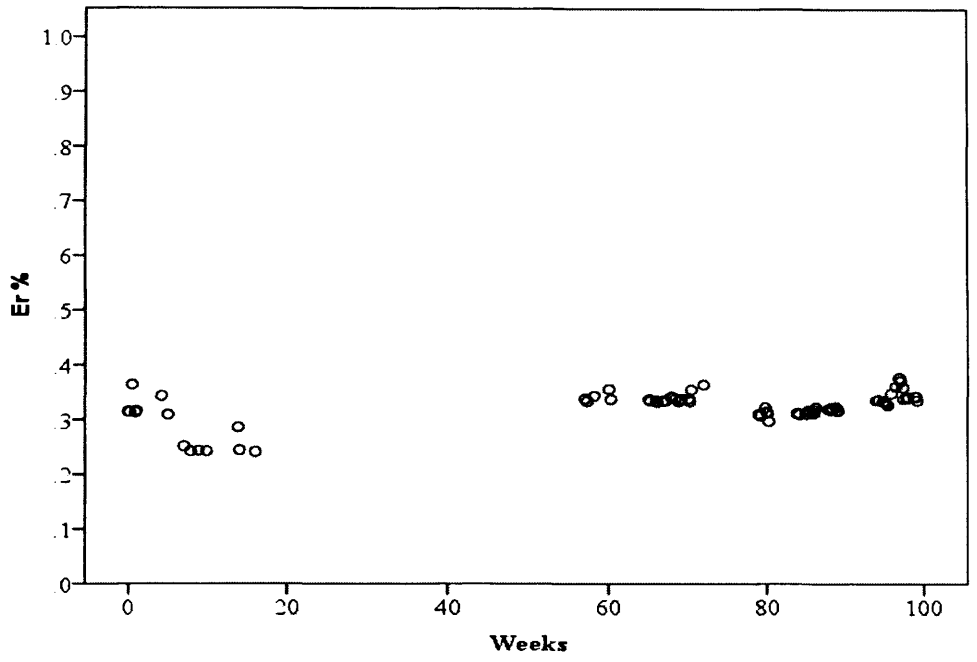


Figure 3–10: Energy resolution over a time for a ^{137}Cs source using the Ge1 detector. The measurements were 11/12/2007 to 04/11/2009.

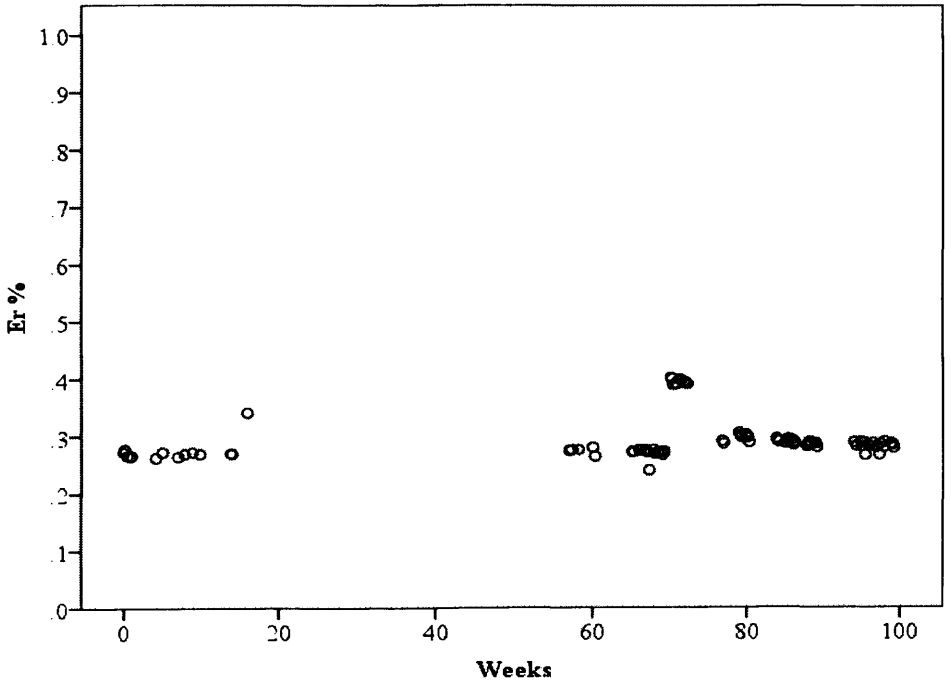


Figure 3–11: Energy resolution over a time for a ^{137}Cs source using the Ge2 detector. The measurements were 11/12/2007 to 04/11/2009.

3.5 Consistency of sensitivity

A gamma ray must undergo a significant interaction in the detector before detection is possible. Because this type of radiation can travel large distances between interactions, detectors are invariably less 100% efficient.

For the sensitivity of the detection system to be stable, the count rate per unit activity for a given radionuclide and source-detector geometry should not vary with time of the measurement. Historical data for a ^{57}Co check source obtained by the staff of the Medical Physics Department at University Hospital of Wales were used in investigate the count rate stability of the whole body counter. This check source was used in conjunction with clinical measurements of vitamin B12 absorption. No data for a ^{137}Cs source were available in the Department because ^{137}Cs had not measured routinely over a period of time.

3.5.1 Method

A single ^{57}Co source was measured by Medical Physics Department staff using the six NaI(Tl) detectors over a period of about 15 months in 2005-2007; the counting time was 290 seconds on each occasion. Count-rates were determined for the photopeak energy window of 90–140 keV. Count-rates from a background phantom were subtracted and the net count rates were corrected for radioactive decay. Again linear regression analysis was used to investigate the variation of corrected count-rate with time.

3.5.2 Results

Figure 3-12 shows a plot of the natural logarithm of the background subtracted but uncorrected count-rate against the decay time in days. The measured ^{57}Co half-life ($T_{1/2}$) was 266.25 days which is within 2% of the accepted value of 271.79 days (Baum, et al., 2002).

The variation of decay corrected count rate with decay time is shown in Figure 3-13.

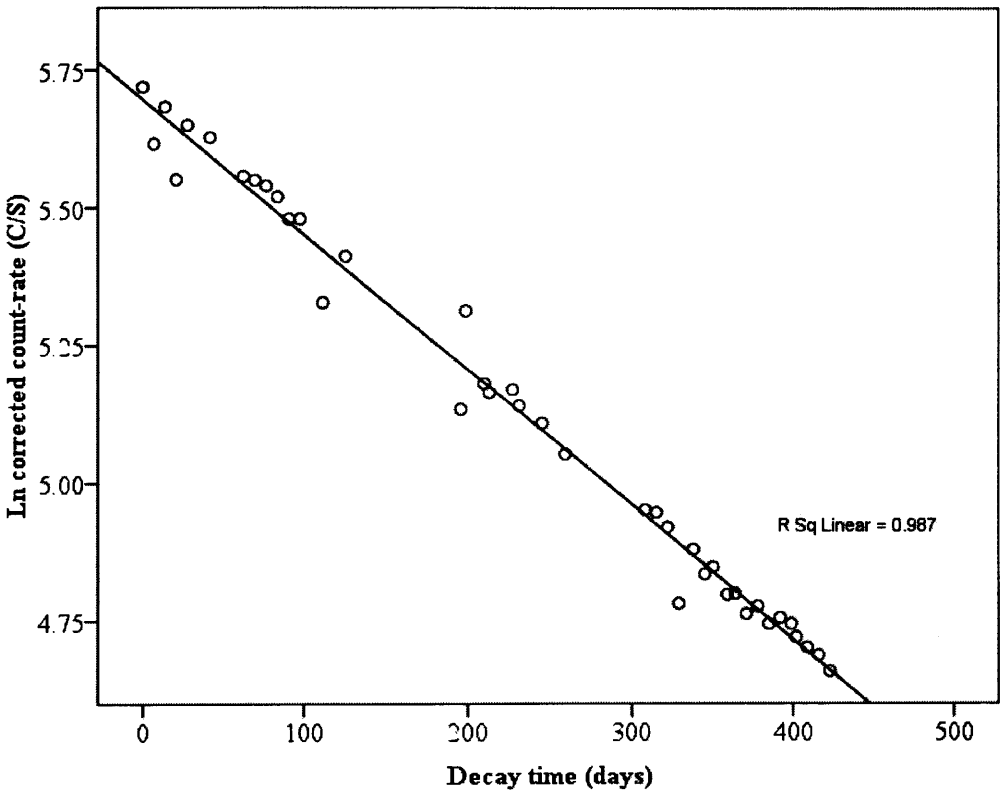


Figure 3–12: Variation of the natural logarithm of the background subtracted count rate with time for a ^{57}Co source.

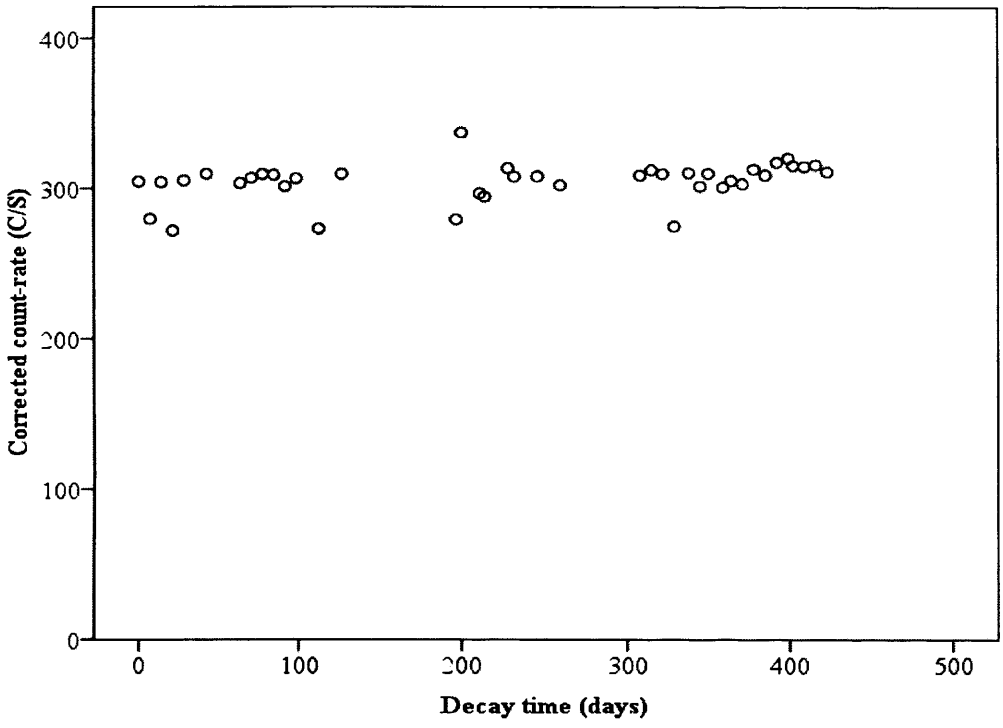


Figure 3–13: The stability of count-rate for the whole body counter over time using NaI(Tl) detectors.

Linear regression analysis of the relationship between the decay corrected count rates and time (Figure 3-13) revealed a gradient (+4% per annum) which is significantly different from zero. However, the photopeak energy of ^{57}Co is much lower than that of ^{137}Cs and the counting window occupies only 13 channels or so. Since each channel represents approximately 4 keV, there is an error of ±2 keV associated with both the lower boundary (90 keV) and upper boundary (140 keV) of this window and this is a source of count-rate variation. Therefore it is difficult to draw conclusions about the stability of sensitivity for ^{137}Cs from this data.

3.6 Variation in shielding room background count rates

The most important sources of natural background radiation recorded by detectors are given below (Knoll, 2000):

1. Natural radioactivity of the component materials of the detector itself. Some ordinary materials used in the construction of the detector, such as Pyrex glass in a scintillation detector, contain either potassium or thorium as a normal component and therefore have a slightly increased background activity. Stainless steel normally has low background activity while aluminium often has some uranium or radium impurity. Brass is generally of low activity as long as its lead content is low. In scintillation counters, the glass envelope of the photomultiplier tube and the tube base or socket materials are also potential sources of background.

2. The natural radioactivity of auxiliary apparatus, supports and shielding placed in the immediate surrounding area of the detector. The shielding placed around a detector to reduce background from cosmic rays or terrestrial radiation may itself introduce a significant background count-rate. Also radioactivity in equipment such as the TV camera and patient bed will increase the room background.

3. Radiations from the activity of the earth's surface and the walls of the room in which the detectors are housed.

4. Radioactivity in the air surrounding the detector. The ambient air may contribute a measurable amount of background; the most important radioactive gases are radon (^{222}Rn) and thoron (^{220}Rn), the daughter products of uranium and thorium present in construction materials.

5. The primary and secondary components of cosmic radiation. The secondary radiation produced from cosmic ray interactions in the earth's atmosphere also introduces a significant component of detector background.

The background spectrum should be measured when no source is present. One characteristic of background count-rate is its variability with time and an assessment of background should state whether it is constant or whether it needs to be measured each time prior to subject measurement.

The background count rate from a typical radiation detector may show an observable variation over periods of hours or days. In experiments in which the count rate is high, small background fluctuations are typically much lower then the inherent statistical fluctuation of the measurement itself and in such situations, a single background determination is a sufficient measurement on which to base background subtracted measured count-rates.

However, when low level activities are counted, the fluctuation in background may be of the same order as the source strength and therefore must be carefully considered. Although the component of the background due to radioactivity of the detector and

surrounding material will be constant, variation in the background may arise either from changes in cosmic ray intensity or in airborne radioactivity (Knoll, 2000).

In the case of a shielded room scanning whole body counter, background also depends on the position of the detectors.

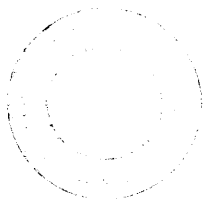
3.6.1 Method

The background count-rate in the shielded room was obtained using the six NaI(Tl) detectors while stationary with no radionuclide source present. The background count-rate was measured at three positions along the central axis of the detector ring with and without the patient bed. The first position at zero cm was at the front (door end) of the room, the second position at 72 cm was at the room centre and the third position at 144 cm was at the closed end of the room. Count-rate measurements were obtained for the ^{137}Cs energy window with a counting time of 1,500 seconds.

Ten measurements of background were made at each detector ring position with and without the bed over a short period of time (about 6 hours). In addition, ten measurements were made at the three positions with and without the bed over a long period of time (19 weeks).

3.6.2 Results and discussion

Background count-rates for the ^{137}Cs window are shown in Tables 3-2 and 3-3 over the short and long time periods respectively.



	N	Minimum (C/S)	Maximum (C/S)	Mean (C/S)	Standard deviation
FNB	10	6.885	7.204	7.070	0.112
CNB	10	6.761	7.088	6.862	0.095
ENB	10	6.631	6.808	6.710	0.062
FWB	10	7.156	7.537	7.372	0.109
CWB	10	6.991	7.448	7.204	0.153
EWB	10	6.618	6.844	6.716	0.079

F: front (door end), C: centre, E: closed end, WB: with bed, NB: no bed

Table 3-2: Variation in background count-rates for the ^{137}Cs energy window over a short time period (6 hours).

	N	Minimum (C/S)	Maximum (C/S)	Mean (C/S)	Standard deviation
FNB	10	6.823	7.191	6.967	0.140
CNB	10	6.686	7.154	6.906	0.159
ENB	10	6.110	6.549	6.362	0.138
FWB	10	6.868	7.536	7.172	0.209
CWB	10	6.917	7.582	7.214	0.210
EWB	10	6.323	7.299	6.637	0.289

F: front end (door end), C: centre, E: closed end, WB: with bed, NB: no bed

Table 3-3: Variation in background count-rates for the ^{137}Cs energy window over a long time period (19 weeks).

At all positions of the detectors, background count-rates are greater with the patient bed than without it. The significance of the count-rate differences is shown in Table 3-4. The differences are small but statistically significant except at the closed end of the shielded room for the short-term time period. This indicates that the construction material of the bed contains some radioactivity which adds to the background count-rate in the room. Therefore before measuring a subject, room background with the bed in position should be measured and subtracted from the subject count-rate.

Differences	**Short term significance (p-value)**	**Long term significance (p-value)**
FWB - FNB	<0.000	0.02
CWB – CNB	<0.000	0.002
EWB - ENB	0.835	0.018

F: front (door end), C: centre, E: closed end, WB: with bed, NB: no bed

Table 3–4: The significance of differences in background count-rate for the ^{137}Cs energy window with and without the bed at the three detector positions over short and long time periods.

In general, the background count-rate decreases as the detectors are moved from the front (door) end of the shielded room to the centre of the room and then to the rear (closed) end. The significance of differences in background count-rates at the three detector positions with and without the bed is shown in Table 3-5. The differences are statistically significant except for that between the centre and front (door) end with the bed in position. This indicates that there is a better shielding effect against

external radiation sources at the closed end. It is likely that the higher background count-rate at the front end is due to increased radiation penetration through the imperfect door overlap and the door hinges.

Differences	Short term significance (p-value)	Long term significance (p-value)
FNB – ENB	<0.000	<0.000
FNB – CNB	0.002	0.02
CNB – ENB	0.008	<0.000
FWB – EWB	<0.000	<0.000
FWB – CWB	0.034	0.227
CWB - EWB	<0.000	<0.000

F: front (door end), C: centre, E: closed end, WB: with bed, NB: no bed

Table 3–5: The significance of differences in background count-rate for the ^{137}Cs energy window at the three detector positions with and without the bed over short and long time periods.

For four of the six possible combinations of detector position and bed presence/absence, the background count-rates measured over the short term do not differ from those measured over the long term (Table 3–6). However, in all cases the standard deviation of the background count-rate was greater in the long term than in the short term as would be expected.

Differences	Significance (p-value)
FNS – FNL	0.085
CNS – CNL	0.46
ENS – ENL	<0.001
FWS – FWL	0.018
CWS – CWL	0.909
EWS – EWL	0.427

NS: no bed in short term, NL: no bed in long term, WS: with bed in short term, WL: with bed in long term, F: front (door end), C: centre, E: closed end.

Table 3–6: The significance of differences in background count-rate for the ^{137}Cs energy window measured over short and long time periods.

The overall conclusion from this work is that it is advisable to measure the background count-rate each day that subject measurements are made with the bed in position.

CHAPTER FOUR

MEASUREMENT OF ^{137}Cs IN THE PRESENCE ^{40}K IN A PHANTOM

4.1 Introduction

One of the hypotheses in this work is that the theoretical minimum detectable activity of ^{137}Cs is lower for a single semiconductor detector than that for the ring of six scintillation detectors because of its superior energy resolution and despite its poorer sensitivity. This was tested by comparing the theoretical minimum detectable activity achievable with the two types of detector for ^{137}Cs from background count-rate measurements in an anthropomorphic phantom (Bush phantom) using sensitivity values derived from count-rate measurements of ^{137}Cs sources in the presence of naturally occurring ^{40}K.

4.2 Bush phantom

It has already been explained that in recent years there has been increasing concern about the environmental effects of releases of radioactivity from nuclear sites and from the major accident at the Chernobyl reactor in particular. It has also been shown that the technique of whole body counting is well established for measuring gamma emitting radionuclides in the human body. To obtain accurate activity measurements, the counter calibration must take into account the body habitus and distribution of the radionuclides in each individual. This can be achieved by giving a known activity of a given radionuclide to an individual so that he/she acts as his/her own standard.

However, this method is not generally acceptable because of the increased radiation dose to the human being.

Alternative, although less accurate, methods of calibration rely on the use of an anthropomorphic phantom. The most popular and widely used is known as the Bush phantom. It consists of 10 polyethylene compartments representing the the head, neck, thorax, lumbar, thighs, calves, and arms. The compartments contain a solution of the radionuclide. The dimensions and cross sections were initially given by Bush (1946) and it was used originally to simulate a patient for investigating energy absorption in radium therapy.

There are several practical disadvantages to the Bush phantom. Because of its bulk, it is inconvenient to store and to transport a separate phantom for each radionuclide of interest. There is always a risk that the phantom may leak and possibly contaminate a whole body counter (Fenwick, et al., 1991).

The Bush phantom is used principally as a calibration standard for reference measurements of homogeneously distributed radioactive elements that emit mid and high energy photons. When filled with a known amount of radioactivity, the phantom can be used to calibrate the whole body counter by relating the observed response (count rate) to the known amount of radioactivity. Each compartment is usually filled with an aqueous radioactive solution of the same concentration so that the amount of radioactivity is proportional to the volume of each compartment. This simulates a homogeneous distribution of radioactivity throughout the body. The standard phantom

represents a reference adult male but smaller sizes representing a reference adult female and a child are also available.

Two adult male Bush phantoms were used in this study; one contained a source of ^{137}Cs in the presence of ^{40}K while the other contained distilled water. The latter was used for background measurements. Figure 4-1 shows one of the Bush phantoms; the volume of each compartment is given in Table 4-1.

Compartment	Volume (ml)
Head	3,600
Neck	1,300
Thorax	17,200
Lumbar	10,060
Arm	4,100
Thigh	6,600
Calf	4,400

Table 4-1: Volume of the Bush phantom compartments used in this work

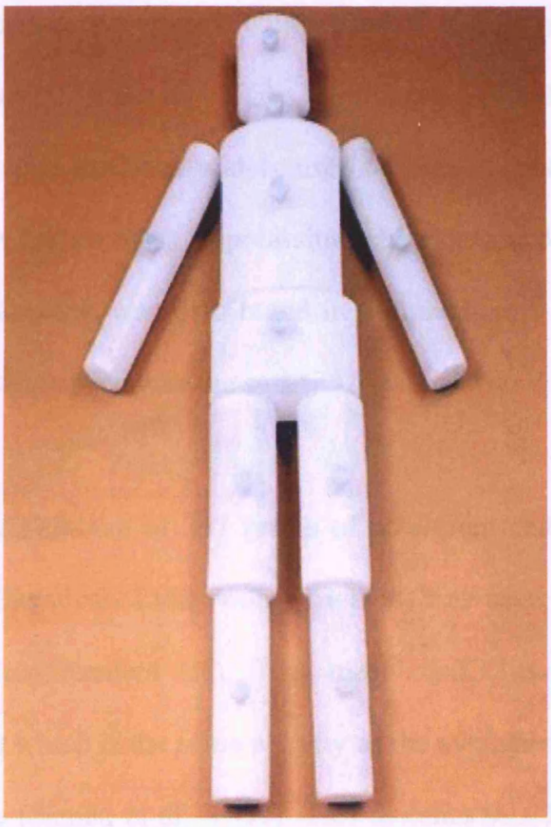


Figure 4-1: Bush phantom consisting of ten polythene compartments made to the specification given by Bush (1946)

4.3 ^{40}K solution and water-filled background phantoms

One of the Bush phantoms was filled with different concentrations of a soluble potassium salt (potassium chloride KCl) containing naturally occurring ^{40}K. Potassium chloride solution has been widely used to simulate potassium in the body (Samat, et al., 1997). A known mass of potassium chloride was dissolved in distilled water to make a solution; this was distributed in the phantom's compartments such that the salt concentration in each was the same.

In this work, a reference amount of 267 grams of potassium chloride (KCl) dry salt (AnalaR grade, BDH Chemicals Ltd., Poole, England) was used; this contains about 140 grams of potassium element (K). This mass of KCl salt is equivalent to approximately 4200 Bq which is the same activity as the average natural body content of ^{40}K in an adult male (Samat, et al., 1997). This assumes 99.9% purity by mass as stated by BDH Chemicals. The mass of the dry KCl salt was determined using digital weighing scales (Oertling NA114, GEC Avery, Orpington, England). Solutions of various concentrations were prepared by dissolving fractions (from 10% to 100% in 10% steps) of the reference mass in distilled water.

For each total mass of KCl, a fractional mass was apportioned to each compartment in proportion to the compartment volume. It follows that each compartment also contained the same fractional activity of ^{40}K.

At each concentration of KCl, solid or vial sources with known activities of ^{137}Cs were lowered into each compartment in turn such that the source was suspended at the

centre of the compartment. The use of solutions of ^{137}Cs presented too great a contamination risk. The count-rate of this phantom was used to measure the sensitivity of the whole body counter for ^{137}Cs in the presence of ^{40}K.

The second Bush phantom was filled with distilled water. Each day on which measurements were made with the $^{137}Cs/^{40}K$ phantom, background count-rates were measured with the distilled water phantom. This represented the absorption and scattering of ambient background gamma radiation that occurs when a human subject is measured. The background Bush phantom was used to estimate the theoretical minimum detectable activity.

4.4 Increasing ^{40}K activity with fixed activity of ^{137}Cs

The consequence of increasing the amount of ^{40}K on ^{137}Cs photopeak count-rate, counter sensitivity for ^{137}Cs and thus the theoretical minimum detectable activity of ^{137}Cs was investigated. The Bush phantom was filled with various concentrations of potassium chloride solutions to simulate natural potassium in the body. The activity of ^{40}K varied from 10% to 100% of the average value in the reference adult male.

4.4.1 Method

The sensitivity calibration of the whole body counter for ^{137}Cs was determined by placing a solid point source of activity 37 kBq in each compartment of the Bush phantom in turn while the phantom was filled with a particular concentration of KCl solution. This was then repeated for other concentrations. The phantom was also

measured without the ^{137}Cs source. For each combination of source location and KCl concentration, the phantom was placed on the bed for a total counting time of 1 hour (forward and reverse scans).

Measurements of photopeak count-rate were obtained at 662 keV (^{137}Cs) and 1460 keV (^{40}K) using the energy windows described in section 3.1. Manual determination of photopeak count rate was done using the following procedure. Source counts from the NaI(Tl) and HPGe detectors were obtained and the same energy windows were used to obtain the background counts for the two types of detector (from a measurement of the water-filled background phantom). From these two measurements the net photopeak count rate was determined by subtracting the background count rate from that due to the source. The count-rate in the ^{137}Cs energy window was corrected for the contribution of the ^{40}K Compton continuum (Youssef, et al., 1999); the fraction of the net count-rate in the ^{40}K window that appeared in the ^{137}Cs window was estimated from ^{40}K phantom scans with no ^{137}Cs source present. The average value of this factor was 0.478 and this was used for the experiments described in this chapter and for the work described in chapter 5.

For each KCl concentration and with the ^{137}Cs source in each compartment of the phantom, the sensitivity of detection was calculated by dividing the corrected count-rate by source activity as given by Equation 2-5 in section 2.5. At each KCl concentration, the average sensitivity was then calculated.

For each set of measurements at a particular KCl concentration, background count-rates in the ^{137}Cs and ^{40}K windows were obtained by measuring the water-filled

Bush phantom; the same counting time was used. The theoretical Minimum Detectable Activity (MDA) was calculated using the average sensitivity at that concentration (Equation 2-4 in section 2.5).

4.4.2 Results

The results are shown in Table 4-2 for the combined ring of six NaI(Tl) detectors and for the two HPGe detectors (Ge1 and Ge2) individually.

^{40}K activity (% of reference adult male value)	**Sensitivity (count-rate/kBq)**			**Theoretical MDA (Bq)**		
	NaI(Tl)	**Ge1**	**Ge2**	**NaI(Tl)**	**Ge1**	Ge2
10%	8.233	0.110	0.124	24.01	65.24	57.91
20%	8.156	0.101	0.129	24.31	74.79	57.05
30%	8.268	0.136	0.103	24.61	54.35	76.65
40%	8.472	0.113	0.139	24.29	64.89	59.85
50%	8.241	0.123	0.106	24.31	59.41	70.74
60%	8.594	0.137	0.126	23.68	58.76	59.73
70%	8.243	0.121	0.119	24.37	59.38	64.93
80%	8.267	0.097	0.117	24.4	78.42	65.71
90%	8.108	0.110	0.102	24.55	67.75	68.53
100%	8.341	0.121	0.101	24.62	64.69	59.68
Mean	8.292	0.1169	0.1166	24.32	64.77	64.08
SD	0.145	0.013	0.013	0.29	7.44	6.40

Table 4-2: Sensitivity and theoretical minimum detectable activity (MDA) for ^{137}Cs. The sensitivity values were obtained with a single solid source of ^{137}Cs for several percentages of the reference activity of ^{40}K in a Bush phantom. The MDA values were obtained using a separate water-filled Bush phantom.

4.5 Increasing ^{137}Cs activity with two different activities of ^{40}K

The activity of the solid ^{137}Cs source (37 kBq) is relatively large and so four liquid sources of ^{137}Cs with lower activities (nominal 5, 3, 1 and 0.5 kBq) were prepared. Each liquid source was of volume 10 ml and contained in a nominal 10 ml glass vial. The measurements described in section 4.4 were repeated for each of the four vial sources with two concentrations of ^{40}K (100% and 80% of the reference value).

4.5.1 Method

A liquid stock solution of ^{137}Cs was available in the Medical Physics Department. This was transferred to a pre-weighed glass vial (type P6) and the weight of vial plus stock was measured using the digital scales. The volume of the stock solution was calculated assuming a physical density of 1 g/ml and made up to approximately 4 ml with water. The P6 vial was weighed again. Each weight measurement was repeated five times in order to calculate mean and standard deviation (SD). The final volume of diluted stock solution was calculated as (4.2290 ± 0.0002) ml.

The activity of the ^{137}Cs stock solution was measured using a secondary standard radionuclide calibrator (FIDELIS from Sothern Scientific Ltd., Lancing, England and National Physical Laboratory, Teddington, England). An automated series of 3200 measurements was made. The mean ± SD activity of the diluted stock solution was (67.0 ± 2 1) kBq. Subsequently 5.8 ml of water was added to give a final diluted stock solution volume of about 10 ml. The vial was reweighed again and the activity concentration of the solution was determined to be (6.73 ± 0.21) kBq/ml.

From the final diluted stock solution, four ^{137}Cs sources with approximate activity 5, 3, 1 and 0.5 kBq were prepared. The individual volumes of final diluted stock solution were (0.7443 ± 0.0002) ml, (0.4521 ± 0.0002) ml, (0.1490 ± 0.0002) ml, and (0.0783 ± 0.0002) ml respectively while the corresponding activities were (5.01 ± 0.15) kBq, (3.04 ± 0.09) kBq, (1.00 ± 0.03) kBq and (0.53 ± 0.02) kBq. The ^{137}Cs sources were prepared in sealed glass vials (of nominal volume 10 ml) to reduce the risk of contamination and each one was made up to a total volume of about 10 ml with water.

The four ^{137}Cs sources were placed at the centre of each compartment of the phantom filled with two concentrations of ^{40}K representing 80% and 100% of that naturally occurring in a reference male adult. The phantom was scanned for 1 h and a spectrum was acquired for each source configuration. Background measurements were also made with the water-filled phantom in the same manner as before and subtracted from the ^{40}K phantom measurements. Furthermore, the net count-rates were corrected for the ^{40}K Compton continuum count-rate in the ^{137}Cs counting window. Thus corrected count-rates in the ^{137}Cs photopeaks were obtained from each spectrum.

4.5.2 Results

Pulse height spectra for the 0.5 kBq ^{137}Cs source in the lumbar compartment of a Bush phantom containing ^{40}K are shown in Figure 4-2. The sensitivity and theoretical MDA values for ^{137}Cs with different concentrations of ^{40}K using NaI(Tl) and HPGe detectors are given in Tables 4-3 and 4-4.

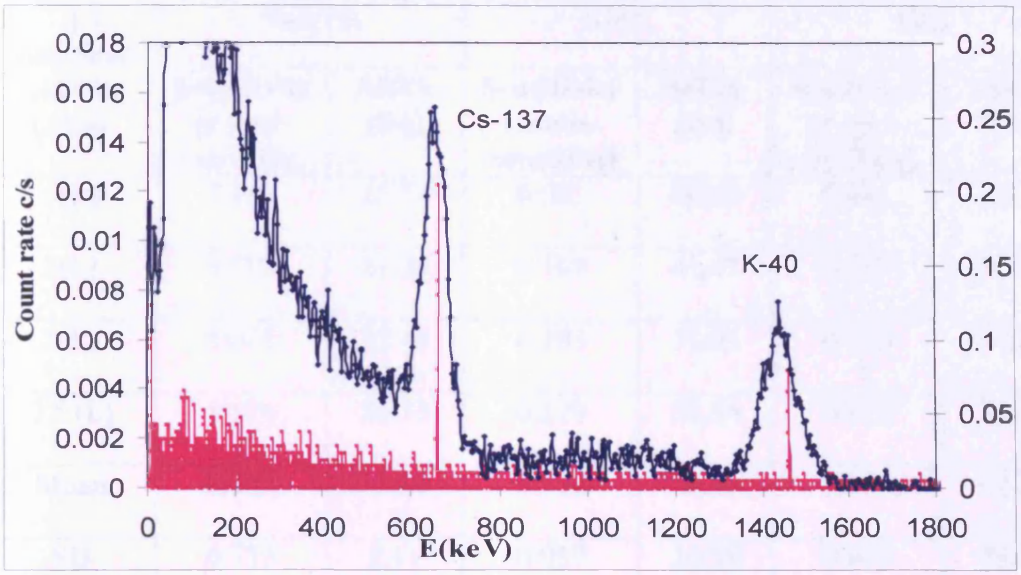


Figure 4–2: Spectra from NaI(Tl) (blue) and HPGe (pink) detectors obtained from a 0.5 kBq ^{137}Cs source positioned in the lumbar compartment of a Bush phantom containing ^{40}K. (100%)

^{137}Cs nominal activity (kBq)	NaI(Tl)		Ge1		Ge2	
	Sensitivity (count-rate/kBq)	MDA (Bq)	Sensitivity (count-rate/kBq)	MDA (Bq)	Sensitivity (count-rate/kBq)	MDA (Bq)
5	8.009	25.06	0.093	83.48	0.102	73.158
3	8.259	24.598	0.124	62.204	0.120	69.922
1	8.289	27.137	0.087	79.833	0.120	75.738
0.5	8.241	25.00	0.143	56.236	0.109	77.668
Mean	8.200	25.45	0.112	70.44	0.113	74.12
SD	0.129	1.14	0.026	13.26	0.009	3.35

Table 4–3: Sensitivity and theoretical Minimum Detectable Activity MDA values for ^{137}Cs. The sensitivity values were obtained with vial sources of ^{137}Cs in a Bush phantom containing 80% of the reference activity of ^{40}K. The MDA values were obtained using a separate water-filled Bush phantom.

^{137}Cs nominal activity (kBq)	NaI(Tl)		Ge1		Ge2	
	Sensitivity (count-rate/kBq)	MDA (Bq)	Sensitivity (count-rate/kBq)	MDA (Bq)	Sensitivity (count-rate/kBq)	MDA (Bq)
5(L)	7.995	25.74	0.082	89.53	0.071	110.28
3(L)	9.510	21.25	0.167	41.47	0.189	39.60
1(L)	8.025	25.43	0.103	71.05	0.114	62.43
0.5 (L)	8.896	23.13	0.129	58.56	0.118	69.22
Mean	8.607	23.89	0.120	65.15	0.123	70.38
SD	0.733	2.11	0.037	20.28	0.049	29.46

Table 4–4: Sensitivity and theoretical Minimum Detectable Activity MDA values for ^{137}Cs. The sensitivity values were obtained with vial sources of ^{137}Cs in a Bush phantom containing 100% of the reference activity of ^{40}K. The MDA values were obtained using a separate water-filled Bush phantom.

4.6 Discussion

As expected, the sensitivities of the two HPGe detectors are essentially equal. Furthermore, the sensitivity of the NaI(Tl) detectors is about 70 times greater than that of an individual HPGe detector due to the much larger detector volume and the greater linear attenuation coefficient of the former. The sensitivity values calculated in the second set of experiments (Tables 4-3 and 4-4) are similar to those found in the first set (Table 4-2) although there is a tendency for greater variation. This is expected since the count-rates measured in the former were lower as a result of using lower activity sources but the same counting time.

The results for the first set of experiments (Table 4-2) show that for the NaI(Tl) detectors, the mean value of theoretical MDA was 24.31 Bq, whereas for the two germanium detectors it was 64.77 Bq and 64.08 Bq. The theoretical MDA for one HPGe detector is only about 2.7 times greater than the value for the ring of six NaI(Tl) detectors despite the much greater sensitivity of the latter. This reflects the relatively low photopeak background count-rate for HPGe that results from the much better energy resolution. The theoretical MDA values found in the second set of experiments (Tables 4-3 and 4-4) were comparable but showed greater variation as a result of the greater sensitivity variations.

The results of both sets of experiments indicate that the hypothesis that MDA is better (i.e. lower) for a single HPGe detector compared with the ring of six NaI(Tl) detectors must be rejected.

If spectra from the two semiconductor detectors were combined (as they have been for the scintillation detectors), the minimum detectable count-rate would increase by about $\sqrt{2}$ while the sensitivity would approximately double. This means that the theoretical MDA would decrease by a factor of $\sqrt{2}$ (Equation 2-4) to about 45 Bq, which is still greater than that of the ring of six NaI(Tl) detectors. If n identical HPGe detectors were available, the theoretical MDA would decrease by $\sqrt{n}$ if their spectra were combined. Thus it would require 6 such detectors to give approximately the same theoretical MDA since $\sqrt{6}$ is 2.45. Coincidentally, this is the same as the number of scintillation detectors in the ring. However, the volume of detector material would differ by more than a factor of 10, being 1.11×10^4 cm^3 for the scintillation detectors and 1.05×10^3 cm^3 for the semiconductor detectors.

CHAPTER FIVE

MEASUREMENT OF ^{137}Cs IN HUMANS

5.1 Introduction

The major hypothesis of this work is that the in vivo activity of ^{137}Cs has decreased over the last 20 years and that current values are significantly lower than those previously found in Cardiff. This hypothesis was tested by measuring the in vivo activity of ^{137}Cs in (1) Cardiff whole body counter patients between 1993 and 2007 and (2) a group of volunteers in 2007. This was done by analysing their background gamma emission spectra and comparing the results with previous data from Cardiff and other parts of Wales. Statistical analysis was done using the Statistical Package for the Social Sciences (SPSS). This part of the work was approved by the Ethics Committee of the Cardiff University School of Engineering.

5.2 Historical background spectra of patients

The whole body counter background spectrum comprises all the pulses registered by the detection system when no radiation source is present. Background originates from many sources including radioactivity (natural and artificial) in the materials of counter's construction (including the detectors), shielding materials, the walls of the laboratory and the air surrounding the detectors (e.g. radon and its daughters) (Knoll, 2000). The background spectrum obtained from a phantom or human being includes all of the above plus a contribution from gamma emitting radionuclides in

the phantom or in the body; for the latter, the photopeak due to naturally occurring ^{40}K will always be prominent.

Background patient spectra measured by staff of the Medical Physics Department at the University Hospital of Wales were investigated for the presence of ^{137}Cs. The background spectra were taken before the administration of radiopharmaceuticals for clinical whole body tests such as the measurement of blood loss, vitamin-B12 absorption and iron absorption in the period 1993 and 2007. Such spectra were also taken as an integral part of the measurement of total body potassium (which does not involve the administration of radioactivity). These spectra were used to calculate the activity of ^{137}Cs in a patient population as a result of releases of the radionuclide into the environment, in particular the Chernobyl accident.

5.2.1 Method

Each day a patient was measured for a clinical procedure, the background spectrum was also obtained for a phantom which contained no added radioactive sources. Background measurements were made on a total of 813 patients (who were not otherwise exposed to radioactivity) over the time period 1993 to 2007 by Medical Physics Department staff using the installed whole body counter at the University Hospital of Wales. The detection system consisted of six NaI(Tl) detectors.

Initially data were displayed as six individual 512 channel spectra, one from each detector. There were subsequently summed to give one spectrum per patient or phantom. Count rates were obtained in the ^{137}Cs and ^{40}K energy windows; the ^{137}Cs

count-rates were corrected for background and for the contribution of the Compton continuum due to ^{40}K as described in chapter 4. The corrected ^{137}Cs count-rates were used to calculate ^{137}Cs body activity using the calibration factor determined for a Bush phantom with 100% of the reference activity of ^{40}K and a 37 kBq source of ^{137}Cs again as described in chapter 4; this value was 8.341 counts per second per kBq. Negative results were rejected from data analysis. Subsequently, the mean and standard deviation of the activity of ^{137}Cs in patients was calculated for each calendar year. These data for Cardiff patients were compared with the results of previous measurements of volunteers at Cardiff in 1986 and 1988 and at Bangor (north Wales) in 1987 (Boddy, et al., 1989).

In addition, for each calendar year between 1993 and 2007, patient and phantom background spectra were separately summed to give one spectrum of each type per year.

5.2.2 Results

Example summed spectra taken from patients and the Bush phantom in 1993 are illustrated in Figure 5-1.

Some photopeaks are clearly visible in Figure 5-1. The peak at 511 keV represents gamma rays due to positron annihilation. There are two lower energy peaks due to radon daughters which emit gamma rays at 240, 300, and 350 keV; the poor energy resolution of the scintillation detectors means that these energies are not completely resolved. Another radon daughter is ^{214}Bi which gives a photopeak at 610 keV. The

highest energy peak at about 1460 keV is compatible with ^{40}K. These peaks are due to naturally occurring radionuclides.

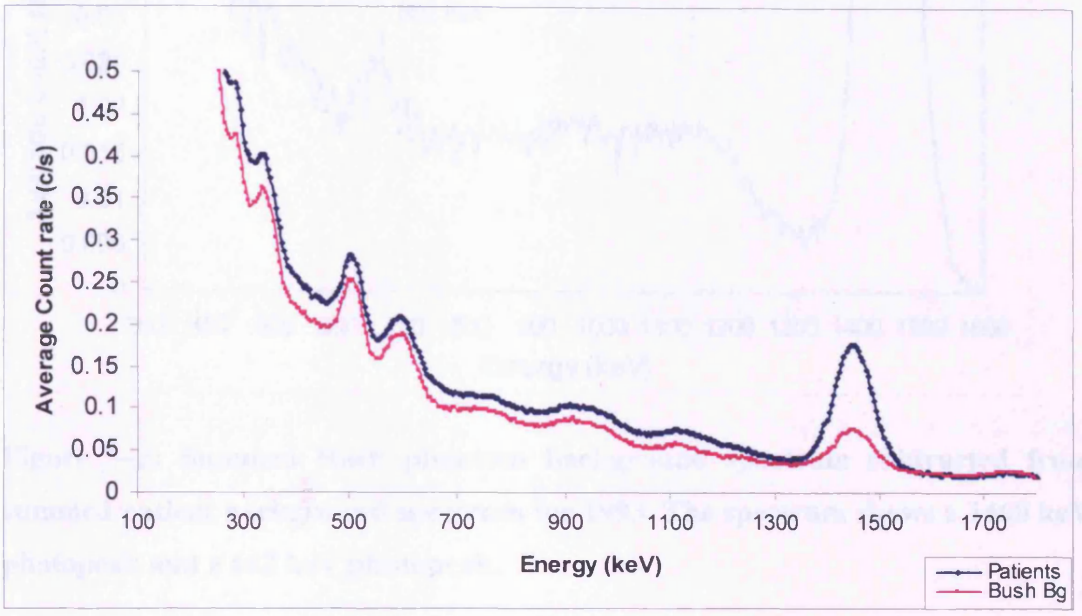


Figure 5-1: Summed whole body counter background spectra for 1993. Patients are shown in blue and the Bush phantom in red. The main features are photopeaks due to naturally occurring radionuclides such as ^{40}K.

Figure 5-2 shows an example of a net patient summed spectrum after subtraction of the phantom summed spectrum. Clearly visible is the ^{40}K photopeak due to naturally occurring radioactivity in the human body. There is also a photopeak at 662 keV due to ^{137}Cs. However, analysis of the 662 keV peak is confounded by a variable and unknown contribution from ^{214}Bi which emits gamma rays of energy 610 keV (Dendy, et al., 1992). The energy resolution of NaI (Tl) detectors is too poor to distinguish between the ^{137}Cs photopeak and the ^{214}Bi photopeak; therefore the two appear as a single peak.

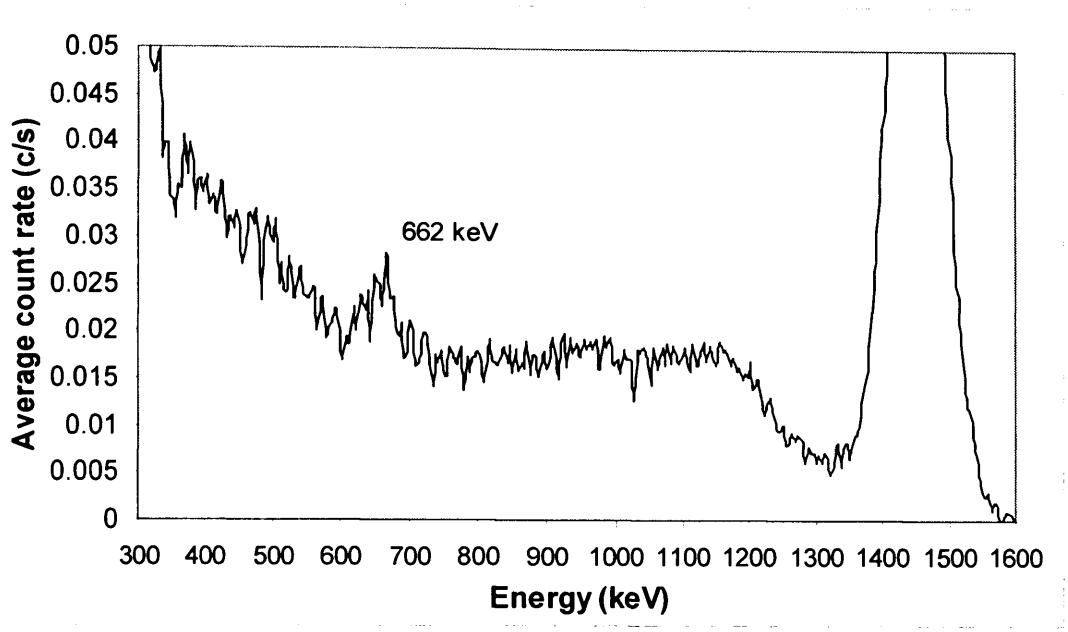


Figure 5–2: Summed Bush phantom background spectrum subtracted from summed patient background spectrum for 1993. The spectrum shows a 1460 keV photopeak and a 662 keV photopeak.

Table 5-1 and Figures 5-3 and 5-4 show the activity of ^{137}Cs in patients for each year of measurement. Only patients with positive values of corrected ^{137}Cs count-rate (and hence activity) have been included; thus the total number (546) is less than the 813 mentioned above. Mean patient activities were above the minimum theoretical detectable activity (MDA) of whole body counting (approximately 24 Bq) but there were some individual values below the MDA. In addition, there was large variation between individuals. The mean body burden of ^{137}Cs over fifteen years was 67.28 Bq; the maximum value was 1081.91 Bq and the minimum activity was 0.03 Bq, although the latter is below the theoretical MDA.

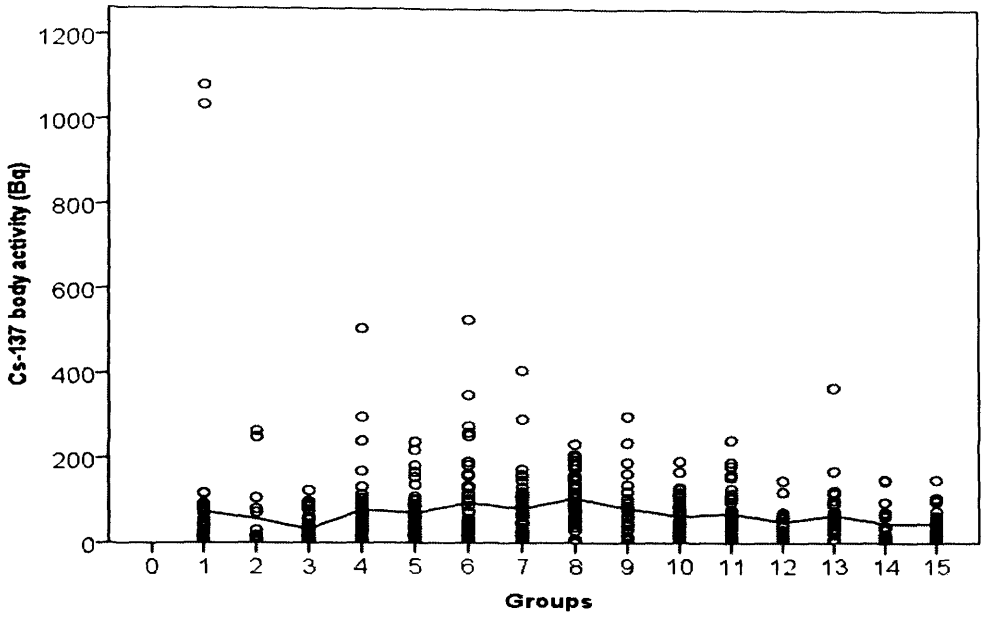


Figure 5-3: Activity of ^{137}Cs in individual patients for each year between 1993 (group 1) and 2007 (group 15). The line represents the mean activity for each year.

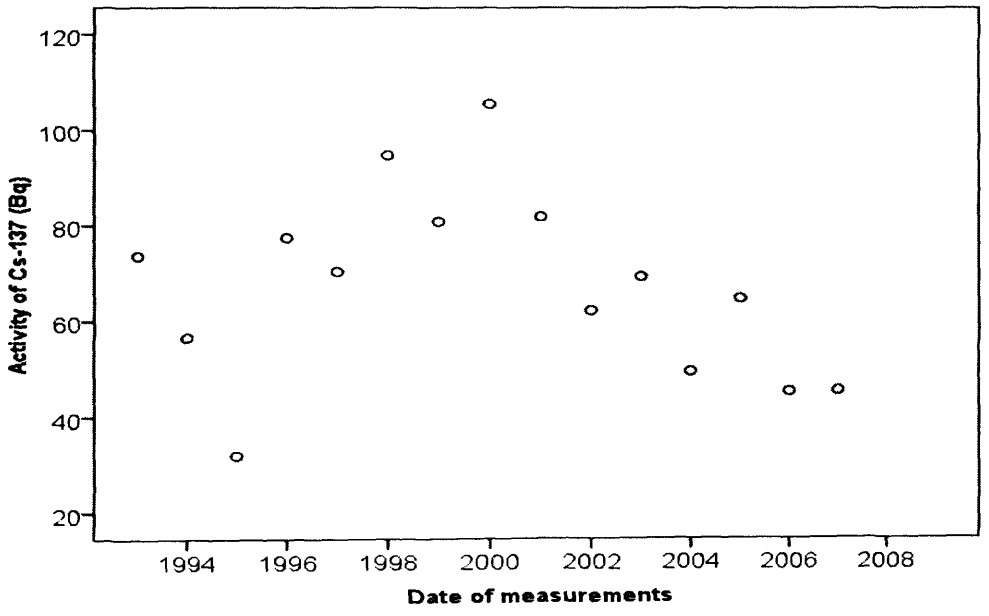


Figure 5–4 Average ^{137}Cs body content (Bq) of patients for each year between 1993 and 2007.

Date of measurement	Number of patients	Minimum body activity (Bq)	Maximum body activity (Bq)	Mean body activity (Bq)	Std. Deviation
1993	53	0.980	1081.910	73.678	199.150
1994	16	2.291	263.975	56.644	84.095
1995	38	0.040	123.917	31.971	30.648
1996	42	0.493	506.303	77.503	90.218
1997	40	1.021	238.307	70.429	57.453
1998	47	0.411	527.422	94.678	105.179
1999	45	5.720	407.809	80.766	74.904
2000	44	0.061	234.120	105.397	57.525
2001	29	0.030	298.695	81.778	69.138
2002	44	1.034	192.718	62.196	44.114
2003	42	3.605	242.866	69.321	54.005
2004	18	4.447	147.068	49.416	37.557
2005	35	0.608	367.659	64.724	64.600
2006	22	0.997	150.550	45.265	43.982
2007	31	0.675	149.377	45.421	36.364

Table 5-1: Activities of ^{137}Cs in patients measured between 1993 and 2007.

Differences between the mean activities of ^{137}Cs in the various years were investigated. Analysis of variance (ANOVA) revealed these to be statistically significant with $p = 0.035$ (i.e. $p < 0.05$) as illustrated in Table 5-2. The interpretation

of these data is that the variation in activity between groups (years) is greater than the variation within groups. An unpaired t-test showed that the decrease in mean activity from 1993 (73.68 Bq) to 1995 (31.97 Bq) was not significant but that the increase from 1994 (56.6 Bq) to 2000 (105.40 Bq) was significant ($p < 0.05$).

	Sum of Squares	df	Mean Square	F	p-value
Between Groups	197319.725	14	14094.266	1.805	0.035
Within Groups	4146984.228	531	7809.763		
Total	4344303.954	545			

df = degrees of freedom

Table 5–2: Analysis of variance (ANOVA) of the differences between mean ^{137}Cs body activity in the period between 1993 and 2007 ($p < 0.05$).

Taking the mean activity in 1994 as representative of body burden of ^{137}Cs in Cardiff at the beginning of the investigation period and using the data of Boddy, et al. (1989), the unpaired t-test showed no significant difference with values found in May and June 1986 immediately after the Chernobyl explosion. However, there had been a significant overall decrease since July 1986 and 1988 ($p < 0.05$).

5.3 Background spectra of volunteers

In 2007, ^{137}Cs body activity was measured in a group of 14 adults (7 males and 7 females). All the subjects were residents of Cardiff and most were employees of the Medical Physics Department. The subjects were not exposed to possible contamination with ^{137}Cs as a result their work.

Background spectra from these volunteers were obtained with the scintillation detectors.

5.3.1 Method

The scan procedure was divided into two phases: (1) calibration, which was performed every day before any measurements were made and (2) measurement of ^{137}Cs activity.

The whole body counter was calibrated by acquiring spectra from a ^{137}Cs source placed centrally under the six NaI(Tl) detectors. The gain of each detector was adjusted to place the 662 keV peak exactly in channel 169 (corresponding to 512 MCA channels over an energy range of 2 MeV). Energy calibration was obtained by acquiring spectra for a combination of ^{137}Cs, ^{133}Ba and ^{60}Co sources for 200 seconds.

To estimate the background counting rate, a background phantom was measured before measuring a volunteer. The counting time for the phantom was the same as that for the volunteer.

Prior to visiting the Medical Physics Department at the University Hospital of Wales, each volunteer was given written information about the study (Appendix B). On arrival, the volunteer was asked to remove outer clothing, shoes and any jewellery etc. After measurement of height and weight, the subject was placed supine on the counter bed. Just before the bed was slid into the whole body counter, the scanning procedure was carefully explained to the subject.

After the volunteer's details were entered into the whole body counter computer, the gantry carrying the scintillation was scanned form feet to head and then in the reverse direction. The total scanning time was 30 minutes. Volunteers were able to talk to the operator during the scan, which helped to reduce anxiety.

After the scan, the subject was asked to complete a questionnaire (Appendix A). Information was gathered about the place of residence and how long he/she had lived there, any occupational exposure to radioactivity either directly or indirectly from a partner, his/her personal details and dietary habits. The dietary questions enquired about the frequency of intake of five foodstuffs known to be possible sources of radioactivity: fish, shellfish, meat, poultry and milk.

For the combination of six NaI(Tl) detectors, count-rates in the ^{137}Cs window were corrected for background, corrected for the contribution of the Compton continuum from ^{40}K and converted to activity as previously described.

The average ^{137}Cs activity in the volunteers was compared with that of Cardiff whole body counter patients in the same year (2007) and in 2000 (the year during the investigation period in which patient activity was greatest). Comparisons were also made with previous measurements on volunteers in Cardiff in 1986 and 1988, in Rhyl in 1987 and in Bangor in 1987. Rhyl and Bangor are located in north Wales, a region that was heavily area affected by rainfall following the Chernobyl incident (Boddy, et al., 1989).

5.3.2 Results

The age range of the 14 volunteers was 18-61 years and the weight range was 49-83 kg. One negative activity value (in a male volunteer) was rejected from the analysis. The average activity of ^{137}Cs in the remaining 13 subjects was 51.14 Bq; the minimum activity was 6.54 Bq whereas the maximum was 100.82 Bq (Table 5-3). The mean activity was above the limit of theoretical MDA of the whole body counter.

Subject	^{137}Cs activity (Bq)	Sex	Age (y)	Weight (kg)	Height (m)	BMI (kg/m^2)
1	36.665	F	53	NA	NA	NA
2	33.225	M	21	70.9	1.73	23.61
3	85.017	F	26	91.4	1.69	31.96
4	88.592	M	21	62.9	1.81	19.12
5	23.882	F	18	49.0	1.50	21.78
6	86.369	M	26	83.0	1.83	24.78
7	12.874	F	61	75.4	1.60	29.45
8	64.432	M	54	NA	NA	NA
9	53.691	F	42	66.8	1.63	25.20
10	100.818	F	44	63.9	1.58	25.58
11	6.536	M	38	75.1	1.69	26.29
12	49.428	M	35	65.8	1.64	24.55
13	23.264	F	24	87.4	1.68	31.11
14*	-0.285	M	23	74.0	1.69	25.94
Mean	51.138		35.62	72	1.67	25.77
SD	31.556		14.32	12	0.10	3.85

NA: Not available * excluded from the analysis, BMI: body mass index

Table 5-3: Demographic details and ^{137}Cs body activity for 13 subjects measured in 2007.

The activity in this group of volunteers was compared with that in Cardiff whole body counter patients in 2007 and 2000 using an unpaired t-test; the results are shown in Table 5-4.

Group	Number, n	^{137}Cs Activity (Bq)	
		Mean	SD
Volunteers 2007	13	51.14	31.56
Patients 2007	31	45.42*	36.36
Patients 2000	44	105.40**	57.53

Compared with Volunteers 2007: * not significant, ** $p < 0.05$

Table 5-4: Body activity of ^{137}Cs in a group of Cardiff volunteers measured in 2007 compared with Cardiff whole body counter patients in 2007 and 2000 (the year during the investigation period when activity was greatest).

The 2007 Cardiff volunteers were compared with six other groups using the z-test since only mean values were available. The results are shown in Table 5-5 and illustrated in Figure 5-5. In 1986, the same group of six Cardiff volunteers was measured on five occasions between 6th May and 2nd July.

Group	Number, n	^{137}Cs Activity (Bq)	
		Mean	SD
Cardiff Volunteers 2007	13	51	32
Cardiff Volunteers 06/05/86	6	43*	-
Cardiff Volunteers 12/05/86	6	36*	-
Cardiff Volunteers 02/06/86	6	55*	-
Cardiff Volunteers 18/06/86	6	76**	-
Cardiff Volunteers 02/07/86	6	105***	-
Cardiff Volunteers 1988	40	133***	-
Bangor Volunteers 1987	135	287***	-
Rhyl Volunteers 1987	92	193***	-

Compared with Volunteers 2007: * not significant, ** $p < 0.05$, *** $p < 0.001$

Table 5-5: Body activity of ^{137}Cs in a group of Cardiff volunteers measured in 2007 compared with volunteers in Cardiff, Bangor and Rhyl in 1986-87.

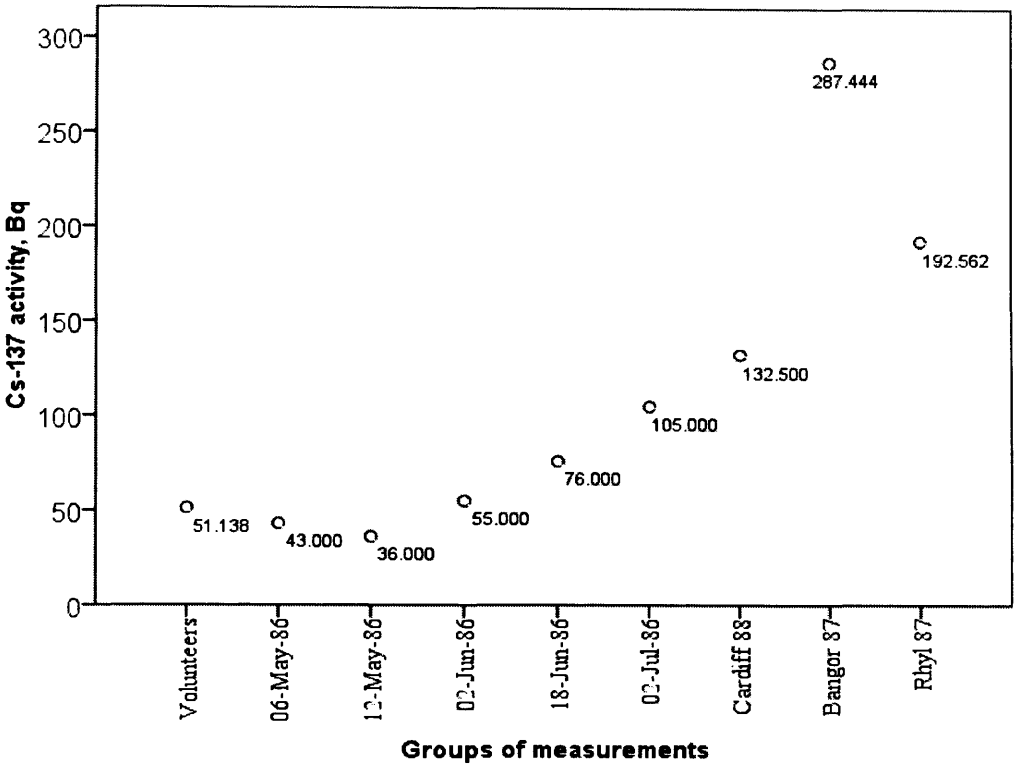


Figure 5-5: Body activity of ^{137}Cs in a group of Cardiff volunteers measured in 2007 compared with volunteers in Cardiff, Bangor and Rhyl in 1986-87.

An attempt was made to correlate ^{137}Cs body content with age, sex, diet and other factors. This gave no significant trend of any sort. As an example, the mean (SD) activity in females (n=7) was 48.03 (33.54) Bq while that in males (n=6) was 54.76 (31.80) Bq; an unpaired test revealed no significant difference. Figure 5-6 shows ^{137}Cs activities in successive female and male volunteers.

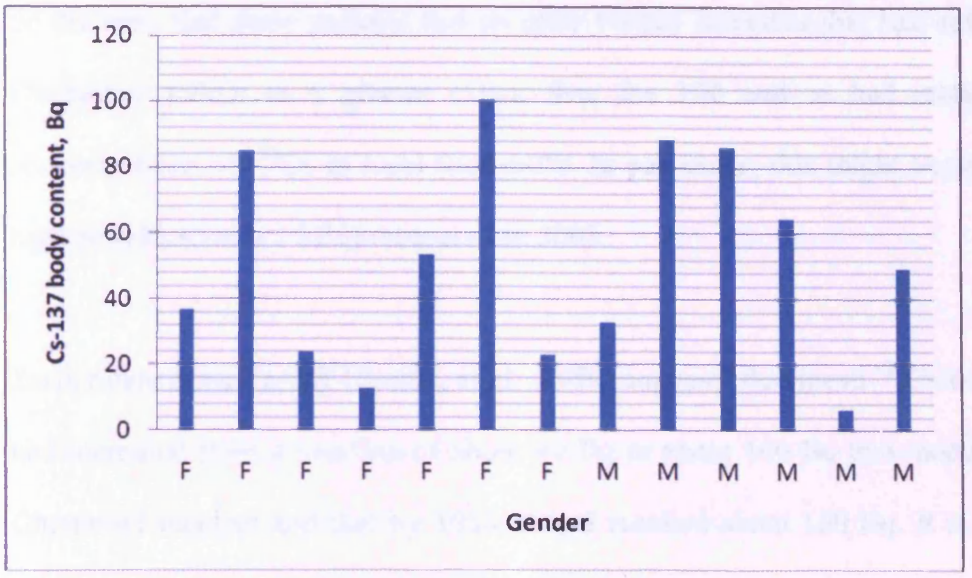


Figure 5-6: ^{137}Cs body activity in 13 successive female (F) and Male (M) subjects.

5.4 Discussion

For individual Cardiff whole body counter patients between 1993 and 2007, the ^{137}Cs photopeak is not visible. However, it can be seen in the summed patient background spectrum for the first of these years (1993) after subtraction of the summed phantom background spectrum (Figure 5-2). Thereafter, the photopeak becomes progressively less visible suggesting the gradual disappearance of ^{137}Cs post Chernobyl.

Analysis of the patient background spectra suggests that the mean body burden of ^{137}Cs in the early to mid 1990s was about 60 Bq and that this rose to a maximum of about 100 Bq in 2000. Thereafter it decreased reaching a value of about 40 Bq in 2007 (Figures 5-3 and 5-4, Table 5-1). There was a large variation between individual values of body content at any one time and it is likely that this was due to differences in factors such as dietary habits and individual variations in metabolism. It might also

be the case that some patients had recently visited countries that had suffered from Chernobyl fallout to a greater extent than the UK and so had relatively large concentrations of ^{137}Cs in local foodstuffs. In particular, this might explain the two high activities (over 1 kBq) measured in 2003.

Earlier data from Cardiff (Boddy, et al., 1989) suggests that mean ^{137}Cs body activity had increased from a baseline of about 40 Bq to about 100 Bq two months after the Chernobyl incident and that by 1988, it had reached about 130 Bq. It is not known when and at what value the activity reached a maximum but the patient data suggest a decrease by 1993-95. This might have been due to a combination of the gradual removal of ^{137}Cs from the land to the sea by rainfall and factors such as restrictions on the availability of food deemed to have unacceptably high content of radioactivity. The subsequent further increase to 2000 indicated by the patient data might have been caused by an easing of these restrictions and a greater willingness by individuals to travel to countries known to have been affected by Chernobyl fallout. The mean activity at the end of the measurement period (40-50 Bq) is comparable to that found in Cardiff pre-Chernobyl.

The mean body burden of ^{137}Cs found in a small group of Cardiff subjects in 2007 (51 Bq) did not differ significantly from the mean value for Cardiff patients in the same year (45 Bq). However, it was significantly lower than the mean value for patients in 2000 (105 Bq) suggesting that there has been a real decrease during the course of this decade (Table 5-4).

The 2007 mean activity is similar to that of Cardiff volunteers in the immediate aftermath of Chernobyl, before sufficient time had elapsed for activity to accumulate in the body (Table 5-5 and Figure 5-5). However, it is significantly less than the value in June 1986 (by a factor of about 2) and in 1988 (by a factor of about 2.5) indicating an overall decrease over a period of about 20 years. It is also much less than the mean activities in residents of Bangor and Rhyl 1-2 years after the explosion; both these cities are in north Wales, which was more severely affected by Chernobyl fallout than the Cardiff area. In 1986, the mean activity in a small group of six subjects in Swansea was 187 Bq. Again this is significantly greater than the 2007 value for Cardiff volunteers even though Swansea is in south Wales about 65 km to the west. However, the mean Swansea value was heavily influenced by an activity of 520 Bq in one subject.

There was no significant difference in the mean activity for male and female volunteers (Figure 5-6). Furthermore, no correlation was found between activity and other factors such as age, height, weight, body mass index, BMI (weight/(height)^2) and diet. This is not surprising since the number of volunteers with valid measurements (13) was very small; it would require a much larger number to investigate such relationships with adequate statistical power.

Overall, the results indicate that the hypothesis that current values of ^{137}Cs activity in Cardiff subjects are lower than values reached after Chernobyl is proven. However, the pattern of decrease does not follow a simple trend with a primary peak some time between 1988 and 1993 and a secondary peak at about 2000.

CHAPTER SIX

DISCUSSION

6.1 Introduction

The human body is exposed to natural background radiation every day from the ground, building materials, air, food, the universe and even substances in the body itself. Humans are therefore exposed both externally, through cosmic radiation and radiation from naturally occurring radioactive materials outside the body, and internally, through natural radionuclides biologically present in the body, inhaled air and ingested foodstuffs. Terrestrial radiation is the largest natural cause of exposure and contributes about 85% of the average annual dose (Mason, 2002).

In the United Kingdom, the greatest contribution to background ionising radiation dose comes from radiation of natural origin, which cannot be controlled. The average person receives an annual effective dose of 2.7 mSv, of which about 2.2 mSv is due to natural radiation (Hughes, et al., 2005). In addition, people are exposed to low and high energy radiation from man-made sources such as medical applications, consumer products, the atmospheric testing of nuclear weapons, the operation of nuclear power stations and nuclear accidents. The radiation dose to the public in the UK from human activity is generally small compared with the dose from naturally occurring radionuclides (Harrison & Phipps, 2002).

The most radiologically important radionuclides released from atmospheric testing and nuclear accident fallout are strontium-90 (^{90}Sr) and caesium-137 (^{137}Cs). These radionuclides are absorbed from the soil by plants and thereby enter the human food chain resulting in internal exposure from ingestion; in addition, there is an external dose from gamma radiation which is emitted by ^{137}Cs.

^{137}Cs in the environment in the UK today mainly originates from atmospheric nuclear weapons tests and the Chernobyl accident. Nuclear facilities and other accidents contribute only a very small fraction of the total amount of ^{137}Cs. Following the Chernobyl accident, radiocaesium was detected in sheep grazing in certain upland areas in the UK, which had been affected by heavy rainfall in the days following the accident. Restrictions were put in place on about 9,700 farms and 4,225,000 sheep across the UK. The average annual dose from nuclear sources in the UK is about 6 μSv (Hughes et al., 2005) compared with peak values of more than 0.1 mSv in the 1960s (Hughes 1993, 1999). Caesium-137 delivers a whole body external beta/gamma dose of 3.2 μSv, while the main contributions to the ingestion dose of 2.7 μSv comes from ^{90}Sr and ^{14}C.

In vivo measurements of ^{137}Cs activity were made after the Chernobyl accident in a small group of six volunteers using the whole body counter at the University Hospital of Wales, Cardiff (Burch & Owen, 1986). The mean activity increased continuously reaching a value of 107 Bq on 2nd July 1986. This was double the value in southern England, while the levels in north Wales were double those in south Wales (Ham, 2003). Also ^{137}Cs activity was measured in a larger group of volunteers as part of a UK-wide national survey of radioactivity in the general public (McKenzie, et al.,

1989). Mean activity was 173 Bq with a range from less than 25 Bq to 423 Bq. These values were similar to those found at measurement sites in the south of England but less than those found in Bangor, Edinburgh, Glasgow and Seascale for example. In this survey, the maximum individual activity was 4194 Bq and this was found in a resident of north Wales.

Human body burden measurements using whole body counters are commonly used in radiation protection to identify radioactive material intake and assess the radiation exposure to the individual. However, this technique is only applicable to radioactive materials that emit gamma rays and such counters must have sufficiently high energy resolution to separate and identify the radionuclides as contaminants. Another useful property is the facility to determine the region and amount of any radionuclide concentration that may occur (Barnaby & Smith, 1967). Whole body counters are also used clinically, for example in haematological investigations such as blood loss, vitamin B-12 absorption and iron absorption.

The Cardiff whole body counter at the University Hospital of Wales consists of six NaI(Tl) scintillation detectors; each has crystal size of 15.2 cm in diameter by 10.2 cm thick mounted on a vertical steel ring. Two germanium detectors were positioned on the ring above the scanning bed in this study; one was 60 mm in diameter and 62.5 mm thick while the other one was 60 mm diameter and 59.5 mm thick.

The technique of whole body counting is well established for measuring gamma emitting radionuclides in human body. To obtain the best accuracy and good results, the counter was calibrated every day that it was used for measuring people.

6.2 Performance of the whole body counter

The performance of the counter is determined by factors such as the background count rate, the detection sensitivity and the energy resolution at relevant gamma ray energies. Therefore the stability of the electronics is a most important characteristic The performance of the detection system (NaI(Tl) and germanium detectors) was tested and found to be satisfactory.

^{137}Cs and ^{40}K photopeak energy windows with the NaI(Tl) detectors were deliberately selected to be wide to ensure that the whole photopeak was included for all the spectra that were analysed. For the HPGe detectors, the energy windows were much narrower since semiconductor detectors have much better energy resolution as shown in Figure 3-1.

Energy calibration was obtained by using standard energy calibration sources of ^{137}Cs (662 keV), ^{133}Ba (356 keV) and ^{60}Co (1173 and 1332 keV) to convert the photopeak channel number to energy. Energy calibration was done each day the counter was used. The stability of the energy calibration for a preceding period of time was investigated by using linear regression and correlation of the slopes and intercepts of the calibration lines. With all three detectors, the slope of the energy calibration line is very stable. This is to be expected since the high voltage and amplifier modules are stable and the gain was adjusted at each use so that the ^{137}Cs photopeak was in its designated channel.

The variation in the slope for the scintillation detectors is less than 0.01% per annum over a period of about 12 years; the corresponding value for the semiconductor detectors is less than 0.1% per annum over 2 years. The average variation of the intercept for the NaI(Tl) detectors is about 0.3 % per annum although the variation increases with time. For the HPGe detectors, the intercept is only about 1-2 keV. Therefore, there is some variation in the values of the intercept for both detectors but this is to be expected when the values are so close to zero.

Generally, the results indicate that energy calibration is stable for both the scintillation and semiconductor detectors.

The average energy resolution for the ^{137}Cs photopeak of the combined six NaI(Tl) detectors is about 9% and this value agreed with the British Standard for a single detector (less than 10%) while for HPGe it is about 0.3% which also corresponds well with the British Standard (less than 2%) (British Standard, 2006). The energy resolution of the HPGe detectors is about 30 times better than that of the NaI(Tl) detectors. The germanium detectors therefore have greater ability to identify unknown radioactive nuclides in the human body and much reduced possibility of misinterpretation of spectral information.

A plot of energy resolution at 662 keV with time for the NaI(Tl) detectors indicates an average deterioration of 1.2 % per annum (as determined by linear regression analysis). This is expected to be associated with detector ageing and greater variation in the factors contributing to energy resolution listed in the section 3.4. Another factor that may degrade energy resolution is greater gain mismatch between the six

individual detectors with time. For the HPGe detectors there was no overall change in the energy resolution over a two year period.

In order to estimate the benefits of using high purity germanium detectors instead of the typically used NaI (Tl) detectors for whole body counting, some features were compared. The advantage of a higher resolution by a factor 30 is observable. With the improved energy resolution of Ge, photopeaks are better resolved, and therefore peak areas and centriod values are easier to determine. It follows that the radionuclide identification capability is noticeably improved. Figure 6-1 shows a visible peak of ^{214}Bi and no presence of ^{137}Cs in a Ge spectrum and illustrates the ability of this to distinguish between ^{214}Bi and ^{137}Cs photopeaks due to its good energy resolution. In the case of NaI(Tl) spectra, the ^{214}Bi and ^{137}Cs photopeaks emerge as a single photopeak and this will interpreted as a ^{137}Cs photopeak present in the spectrum.

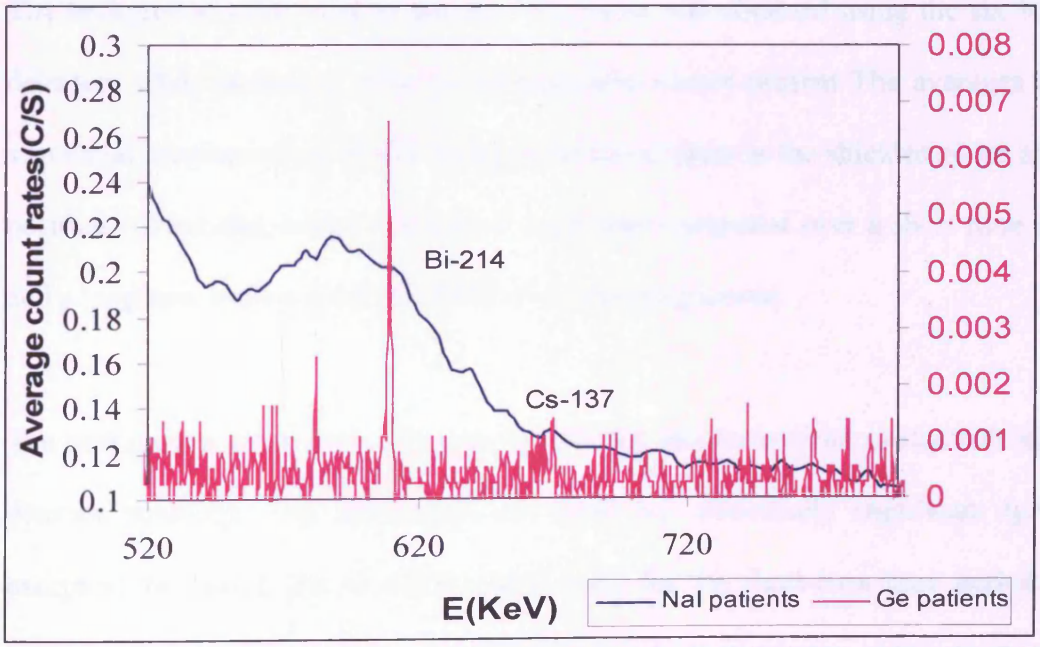


Figure 6–1: Comparison of the performance of HPGe with NaI(Tl) detectors to distinguish between ^{214}Bi (610 keV) and ^{137}Cs photopeaks (662 keV).

The sensitivity of the detection system should be stable with time i.e. the count rate per unit activity for a given radionuclide and source-detector geometry should not vary with time of the measurement. Historical data for a ^{57}Co were used in investigate the count rate stability of the whole body counter.

Linear regression analysis of the relationship between the decay corrected count rates and time (Figure 3-13) revealed a gradient (+4% per annum) which is significantly different from zero. However, the photopeak energy of ^{57}Co is much lower than that of ^{137}Cs and the counting window occupies only 13 channels or so. Since each channel represents approximately 4 keV, there is an error of ±2 keV associated with both the lower boundary (90 keV) and upper boundary (140 keV) of this window and this is a possible source of count-rate variation. Therefore it is difficult to draw conclusions about the stability of sensitivity for ^{137}Cs from this data.

The background count-rate in the shielded room was obtained using the six NaI(Tl) detectors while stationary with no radionuclide source present The averages of ten sequential measurements of the background count rates in the shielded room at three positions (front end, centre and closed end) were compared over a short time period and a long term period using the SPSS statistics programme.

The background count rates are greater with the patient bed than without it at three detector positions. The differences are small but statistically significant ($p>0.05$) except at the closed end of the shielded room for the short-term time period. This indicates that the construction material of the bed contains some radioactivity which adds to the background count-rate in the room. Therefore before measuring a subject,

room background with the bed in position should be measured and subtracted from the subject count-rate.

In general, the background count-rate decreases as the detectors are moved from the front (door) end of the shielded room to the centre of the room and then to the rear (closed) end. The significance of differences in background count-rates at the three detector positions with and without the bed is shown in Table 3-5. The differences are statistically significant except for that between the centre and front (door) end with the bed in position. This indicates that there is a better shielding effect against external radiation sources at the closed end. It is likely that the higher background count-rate at the front end is due to increased radiation penetration through the imperfect door overlap and the door hinges.

For four of the six possible combinations of detector position and bed presence/absence, the background count-rates measured over the short term do not differ from those measured over the long term (Table 3–6). However, in all cases the standard deviation of the background count-rate was greater in the long term than in the short term as would be expected.

The overall conclusion from this work is that it is advisable to measure the background count-rate each day that subject measurements are made with the bed in position

6.3 Measurements of ^{137}Cs in the presence of ^{40}K in a phantom

The sensitivity of the whole body counter and the values of minimum detectable activity (MDA) are fundamental for verifying whether the in vivo monitoring system is suitable for determining radionuclide activities in the human body through routine monitoring or in radiological emergency conditions. The theoretical minimum detectable activity was measured for the two types of detector for ^{137}Cs from background count-rate measurements in an anthropomorphic phantom (Bush phantom). The calculation used sensitivity values derived from count-rate measurements of ^{137}Cs sources in the presence of naturally occurring ^{40}K by two set of experiments as explained in the sections 4.4 and 4.5.

The mean value of theoretical MDA of the NaI(Tl) was 24.31 Bq for a counting time of one hour, whereas for the two germanium detectors it was 64.77 Bq and 64.08 Bq. The results illustrate that the theoretical MDA for a single HPGe detector is about 2.7 times higher than that for the ring of six NaI(Tl) detectors. This is because the sensitivity of the NaI detectors is about 70 times greater than that of a germanium detector due to the larger crystal volume.

The results of both sets of experiments indicate that the hypothesis that MDA is better (i.e. lower) for a single HPGe detector compared with the ring of six NaI(Tl) detectors must be rejected. If spectra from the two semiconductor detectors were combined (as they have been for the scintillation detectors), the minimum detectable count-rate would increase by about $\sqrt{2}$ while the sensitivity would approximately double. This means that the theoretical MDA would decrease by a factor of $\sqrt{2}$ (Equation 2-4) to

about 45 Bq, which is still greater than that of the ring of six NaI(Tl) detectors. If n identical HPGe detectors were available, the theoretical MDA would decrease by $\sqrt{n}$ if their spectra were combined. Thus it would require 6 such detectors to give approximately the same theoretical MDA since $\sqrt{6}$ is 2.45. Coincidentally, this is the same as the number of scintillation detectors in the ring. However, the volume of detector material would differ by more than a factor of 10, being 1.11×10^4 cm^3 for the scintillation detectors and 1.05×10^3 cm^3 for the semiconductor detectors.

6.4 Measurement of ^{137}Cs in humans

Radiocaesium-137 activities in the human body were assessed after the Chernobyl accident in Cardiff over a time period between 1993 and 2007. For individual Cardiff whole body counter patients, the ^{137}Cs photopeak is not visible. Analysis of the patient background spectra suggests that the mean body burden of ^{137}Cs in the early to mid 1990s was about 60 Bq and that this rose to a maximum of about 100 Bq in 2000. Thereafter it decreased reaching a value of about 40 Bq in 2007 (Figures 5-3 and 5-4, Table 5-1). There was a large variation between individual values of body content at any one time and it is likely that this was due to differences in factors such as dietary habits and individual variations in metabolism. It might also be the case that some patients had recently visited countries that had suffered from Chernobyl fallout to a greater extent than the UK and so had relatively large concentrations of ^{137}Cs in local foodstuffs.

Earlier data from Cardiff (Boddy, et al., 1989) suggests that mean ^{137}Cs body activity had increased from a baseline of about 40 Bq to about 100 Bq two months after the

Chernobyl incident and that by 1988, it had reached about 130 Bq. It is not known when and at what value the activity reached a maximum but the patient data suggest a decrease by 1993-95. This might have been due to a combination of the gradual removal of ^{137}Cs from the land to the sea by rainfall and factors such as restrictions on the availability of food deemed to have unacceptably high content of radioactivity. The subsequent further increase to 2000 indicated by the patient data might have been caused by an easing of these restrictions and a greater willingness by individuals to travel to countries known to have been affected by Chernobyl fallout. The mean activity at the end of the measurement period (40-50 Bq) is comparable to that found in Cardiff pre-Chernobyl.

Comparing the mean body burden ^{137}Cs of volunteers in 2007 (51 Bq) with Cardiff patients in the same year (45 Bq) showed that there was no significant difference. However, it was significantly lower than the mean value for patients in 2000 (105 Bq) suggesting that there has been a real decrease during the course of this decade. Also it is significantly less than the value in June 1986 (by a factor of about 2) and in 1988 (by a factor of about 2.5) indicating an overall decrease over a period of about 20 years. It is also much less than the mean activities in residents of Bangor and Rhyl 1-2 years after the explosion; both these cities are in north Wales, which was more severely affected by Chernobyl fallout than the Cardiff area. The mean activity in a small group of six subjects in Swansea in 1986 was 187 Bq. Again this is significantly greater than the 2007 value for Cardiff volunteers even though Swansea is in south Wales about 65 km to the west. However, the mean Swansea value was heavily influenced by an activity of 520 Bq in one subject.

Comparisons of body burdens of ^{137}Cs for Cardiff patients in 2004 and 2005 were made with body burdens at Volincy and Starograd in Belarus which are about 200 km from the Chernobyl Nuclear Power Plant (CNPP) for the years 2004 and 2005 (Dederichs, et al., 2010). The values are significantly greater than those for Cardiff patients. The same is true for Cardiff volunteers in 2007. The mean values of ^{137} Cs body burden are shown in Table 6-1.

Year and place of measurement	**Mean value of ^{137}Cs body burden (Bq)**
Cardiff patients in 2004	49
Cardiff patients in 2005	64
Volincy in 2004	10,350
Volincy in 2005	6,750
Starograd in 2004	840
Starograd in 2005	520
Cardiff volunteers in 2007	51

Table 6-1: The mean value of ^{137}Cs body burden of Cardiff and Belarus people (Dederichs, et al., 2010).

The ^{137} Cs body burden in the population of Kiev, Minsk and Gomel, which are relatively close to the CNPP and were heavily contaminated by the Chernobyl accident, had a mean value of 3.86 Bq/kg in 2004 [Morita, et al., 2005] This is much greater than the body burden of Cardiff volunteers in 2007 expressed in the same units, the mean value of which was 0.73 Bq/kg. Unfortunately the weights of Cardiff patients measured in 2004 were unavailable and so it was not possible to make a direct comparison for the same year of measurement.

Overall, the results indicate that the hypothesis that current values of ^{137}Cs activity in Cardiff subjects are lower than values reached immediately after Chernobyl is proven.

6.5 Future work

A development that will surely occur is the use of Monte Carlo simulation techniques for calculating radiation detection efficiency. Such techniques should contribute to a general increase in accuracy of the data produced from whole body counter measurements.

At the University Hospital of Wales, the phantom used is Bush phantom. There are several practical disadvantages to the use of a Bush phantom. Because of its bulk, it is inconvenient to store and to transport a separate phantom for each radionuclide of interest. There is always a risk that the phantom may leak and possibly contaminate a whole body counter. Using the Monte Carlo technique to simulate different sizes of phantom with various radionuclides may lead to more accurate calibration factors for individual subjects while also preventing the risk of contamination of the laboratory.

In common with other countries, the UK government is proposing to increase the amount of electricity produced by nuclear power plants for two main reasons: (1) increasing unreliability in the supply of fossil fuels for conventional power plants and (2) heightened concern about carbon emission from conventional plants. In the light of such developments, it would be sensible to make a more extensive measurement of values of ^{137}Cs (and possibly other radionuclides) in the local population. Such values would serve as a baseline and a point of comparison should there be increased body

burdens in the future as a result of normal plant operations or accidental releases. This indicates an important and continuing role for whole body counters.

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Appendix A

Cardiff University **Prifysgol Caerdydd**

Institute of Medical Engineering and Medical Physics

Survey of Radioactivity in Human Subjects

QUESTIONNAIRE FOR VOLUNTEERS

Reference number:	
Date of measurement:	
Title:	
Surname (family name):	
Given name(s):	
Date of birth:	
Sex:	
Weight (kg):	
Height (m):	

Home contact details:

Address	
Post code	
Telephone	
E-mail	

Work contact details:

Address	
Post code	
Telephone	
E-mail	

Give brief details of residence and work over the last 10 years:

From (year):	To (year):
Occupation:	.....
Place:	.....
Exposure to radioactivity:	.....
Travel during this period:	.....

Have you ever been exposed to radioactivity as a result of medical investigations or treatment?

Yes	
No	

If yes, please give details.

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Have other members of your household ever been exposed to radioactivity as a result of occupation and/or medical investigations/treatment?

Yes	
No	

If yes, please give details.

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Diet

How often do you eat:	Shellfish	Fish	Poultry	Meat
more than once a week				
less than once a week but more than once a month				
less than once a month				
never				

Milk consumption (litres per week):

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Is there any other information you feel would be relevant to this investigation?

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Appendix B

Cardiff University **Prifysgol Caerdydd**

Institute of Medical Engineering and Medical Physics

Survey of Radioactivity in Human Subjects

INFORMATION FOR VOLUNTEERS

1 Title of study

The study is called a 'Survey of Radioactivity in Human Subjects'.

2 Introduction

You are being invited to take part in a research study. Before you decide whether you wish to participate, it is important that you understand why the research is being done and what it will involve. Please take time to read the following information and discuss it with others if you wish. You are welcome to ask us for clarification or further information and to take time to consider whether or not you wish to take part.

3 What is the purpose of this study?

Radioactivity is a source of radiation. The human body contains naturally occurring radioactivity but it may also contain some artificial (i.e. man-made) radioactivity. Radioactivity may be introduced into the body from the environment by processes such as ingestion through the mouth, breathing or absorption through the skin; similar processes apply to animals and plants and so radioactivity may be present in food and drink. Artificial radioactivity may be present in the environment as a result of human activities such as industry, power generation and warfare. We wish to detect and measure both naturally occurring and artificial radioactivity in human subjects and to relate our observations to factors such as place of residence, employment, travel and diet. Our results should also serve as a baseline against which future measurements may be compared.

4 Why have I been chosen?

There are no specific criteria for the recruitment of volunteers for this study. However, we would like you to tell us if you dislike enclosed spaces (suffer from claustrophobia) or have any conditions that affect your mobility or ability to lie reasonably still for about 30 minutes.

5 Do I have to take part?

It is up to you to decide whether or not to take part. If you decide to participate, you will ask to sign a consent form and you will be given this information leaflet and a copy of the consent form to keep. If you decide to take part, you will still be free to withdraw at any time without giving a reason.

6 What will happen to me if I take part?

You will be asked to complete a questionnaire which will include some personal details such as name, address, date of birth, sex, diet, occupation(s), place(s) of residence, travel, known exposure to radioactivity (including medical procedures) and known exposure to radioactivity of other members of your household. You will also be asked to attend the Medical Physics Department at the University Hospital of Wales, Cardiff where first of all we will ask you remove your shoes and any watches, jewellery and other metal objects (where possible). We will then measure your height, weight and lean body mass in light indoor clothing and ask you to lie on a bed in a whole body counter for about 30 minutes and to keep reasonably still for this time. The whole body counter is in the form of a small enclosed room with a ring of gamma radiation detectors which move along (but do not touch) your body from feet to head and back again. During this measurement, we will be able to see you (through closed circuit television), we will be able to talk to you and you will be able to talk to us. To help pass the time, we could play you some music and you are welcome to bring your own CD. However, please note that we cannot accept responsibility for any loss or damage to your CD.

7 What do I have to do?

There is no lifestyle or dietary restrictions and you may continue your normal daily activities. However, we would like you to wear light indoor clothing for the measurements themselves; ideally clothing that has been washed recently to reduce the possibility of small amounts of radioactivity from the workplace or environment being present. If possible, we would also like you not to wear any jewellery or have other metal objects on your person. On arrival, we will ask you to remove your shoes and any watches, coins etc.

8 What are the possible disadvantages of taking part?

Some people who dislike enclosed spaces may find the whole body counter claustrophobic. There is also a maximum distance between the couch and the radiation detectors and so it may not be possible to measure some people in the whole body counter. The measurement of radioactivity does not involve any additional exposure to radiation; we are just measuring what is already in your body.

9 What are the potential benefits of taking part?

There are unlikely to be any direct benefits for you but we will give you an estimate of the amount (activity in Becquerel) of one particular type of artificial radioactivity (caesium-137) and one particular type of naturally occurring radioactivity (potassium-40) in your body. However, we anticipate that for many individuals, the activity of caesium-137 will be expressed as less than the minimum that we can measure. We

will also indicate whether we have detected other types of radioactivity. However, please note that the whole body counter is capable of detecting only one type of radiation (gamma radiation). It cannot measure radioactivity that emits only other types of radiation (such as alpha or beta radiation).

10 What if something goes wrong?

If you are harmed by taking part in this research project, there are no special compensation arrangements. If you are harmed due to someone's negligence, you may have grounds for legal action but you may have to pay for it. Regardless of this, if you wish to complain or have any concerns about any aspect of the way you have been approached or treated during the course of this study, you are welcome to discuss matters with the organisers.

11 Will my participation in this study be kept confidential?

All information that is collected about you during the course of the research will be kept confidential. Any information about you that leaves the university will have your name and address removed so that you cannot be identified from it.

12 What will happen to the results of the study?

The study is part of research work being undertaken by Mrs Elkhadra Elessawi who is a student registered for the degree of PhD in the School of Engineering, Cardiff University. The results will appear in her PhD thesis and will be prepared for

presentation at scientific meetings and publication in a scientific journal. Subjects will not be identified in the thesis or in any presentation, report or publication.

13 Who is organising and funding the study?

The study is jointly organised by Mrs Elkhadra Elessawi, Dr Ann Edington and Dr Wil Evans of the Institute of Medical Engineering and Medical Physics, Cardiff University. Funding for the PhD studentship for Mrs Elessawi is provided by the Government of Libya.

14 Who has reviewed the study?

The study has been approved by the Ethics Committee of the School of Engineering, Cardiff University.

15 Contacts for further information

If you have any queries about this research, please contact Mrs Elkhadra Elessawi on telephone number 029 2087 4000 Ext 77900 (e-mail: elessawie@cardiff.ac.uk), Dr Ann Edington on 029 2087 4825 (e-mail: edingtona@cardiff.ac.uk) or Dr Wil Evans on 029 2074 2009 (e-mail: evanswd1@cardiff.ac.uk).