RADIATION

HARNESSING IT SAFELY TO BENEFIT OUR DAILY LIVES

ROYAL SOCIETY TE APĀRANGI

NGĀ KAUPAPA
CONTENTS

Kupu whakataki
Introduction

Radiation is ever-present in our daily lives — in both natural and generated forms. Scientists have identified various risks and benefits from the use of, and exposure to, different kinds of radiation. This knowledge allows us to safely use radiation while mitigating the possible risks to our health and wellbeing, for example in communication technologies, and medical diagnostics and treatment.

This factsheet discusses the radiation we encounter in our everyday lives and explains how we harness it safely. We have selected examples to illustrate where radiation – from radio waves to gamma rays – may be commonly encountered. It is not intended to be a comprehensive review.

He aha tērā?
What is radiation?

Radiation is the transfer of energy away from a natural or generated source, from which it ‘radiates’ [1]. Some types of radiation are best described as physical particles (for example, alpha and beta particles) whereas other forms are best described as waves (for example, radio and microwaves).

IN MORE DETAIL

The electromagnetic spectrum consists of the various forms of radiation that are best described as waves. Each form of electromagnetic radiation is characterised by wavelength or frequency and, for some forms, by the energy it carries **(FIGURE 1)**.

Wavelength is inversely proportional to frequency. If the wavelength is very short, as it is for gamma rays, the radiation is usually considered to be in the form of particles known as photons, whose energy is proportional to the frequency.

For longer wavelengths, such as radio waves, the properties of the radiation, and the way it interacts with the human body, are best described as a wave. At intermediate wavelengths, such as light, both the wave and photon properties can be useful in describing and explaining the radiation’s properties and interactions.

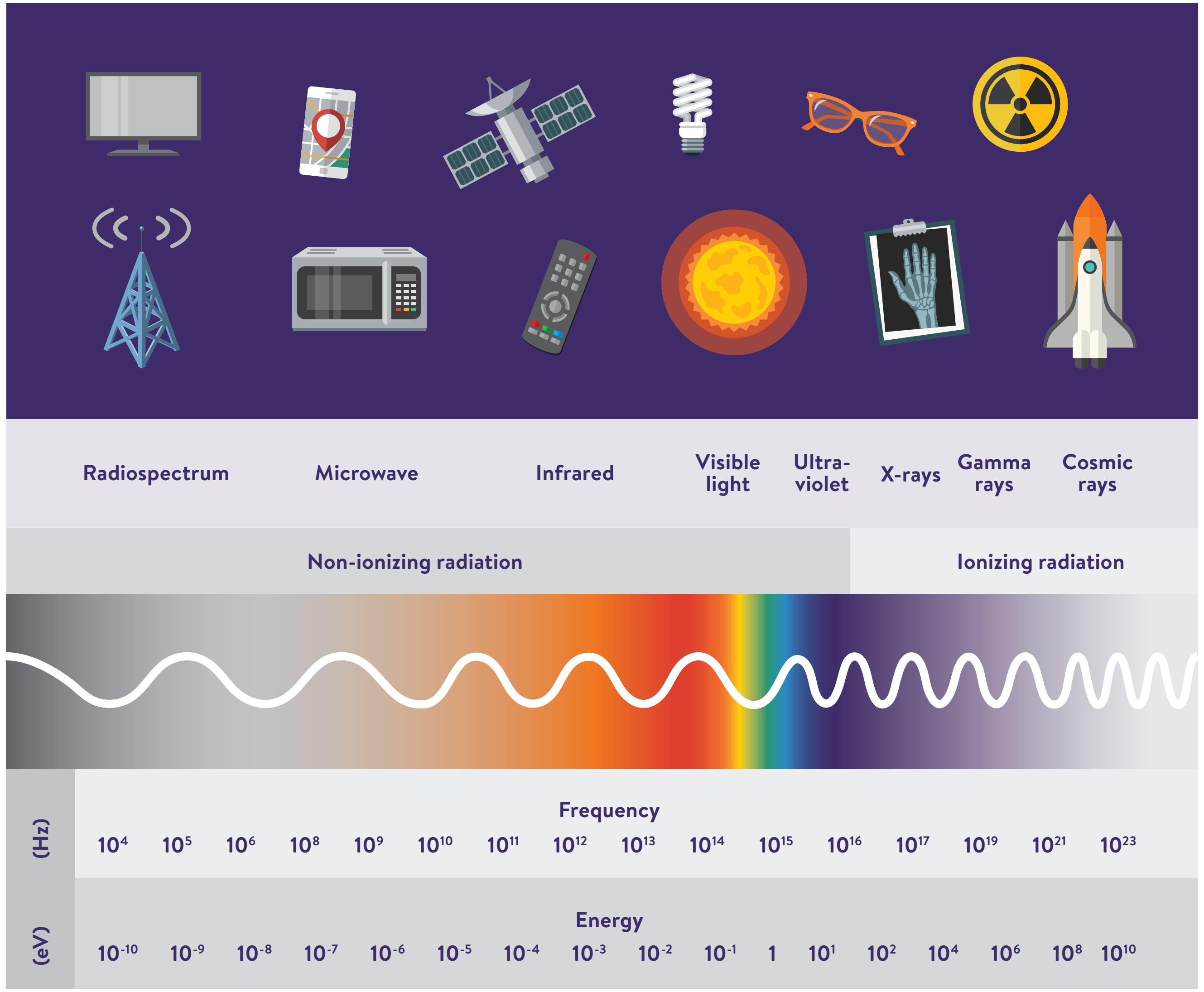


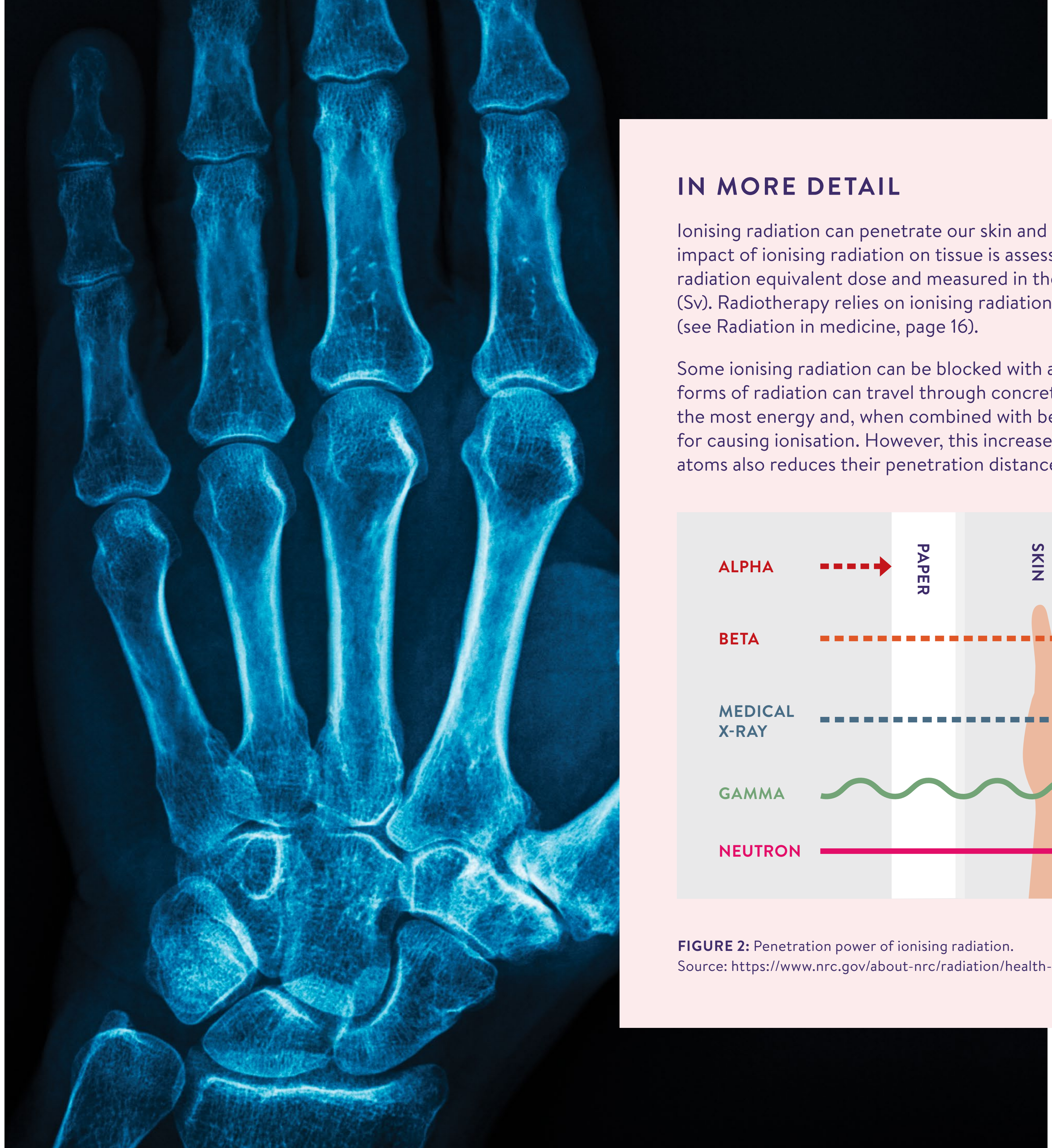
FIGURE 1: The electromagnetic spectrum. Source: Diagram adapted from UNEP 2016 [2]. https://www.unep.org/resources/report/radiation-effects-and-sources

Radiation can be classified into two types: **ionising radiation** and **non-ionising radiation**. Ionising radiation is considered to be more harmful to the human body as it can damage our cells at a molecular level, including damaging DNA.

Ionising radiation carries enough energy to eject electrons from atoms (ionisation), converting a neutral atom into a positively charged ion, which can in turn change the chemical composition of biological material [2]. Examples of ionising radiation include energetic subatomic particles (for example, alpha and beta particles) and certain forms of electromagnetic radiation (X-rays and gamma rays).

Non-ionising radiation does not have sufficient energy to eject electrons from atoms and is generally considered to be less harmful to the human body. Examples of non-ionising radiation are UV light, visible light, infrared radiation, microwaves, and radio waves. Although UV is not ionising radiation, it is energetic enough to cause chemical changes and, like ionising radiation, can generate cancer-causing mutations in DNA.

Radioactivity is the spontaneous decay (that is, breaking apart) of certain elements (for example, uranium and some forms of carbon). In this process, radiation is released in the form of energetic particles or photons.



IN MORE DETAIL

Ionising radiation can penetrate our skin and damage cells. The biological impact of ionising radiation on tissue is assessed in a quantity called the radiation equivalent dose and measured in the international units of Sieverts (Sv). Radiotherapy relies on ionising radiation damaging cancer cells (see Radiation in medicine, page 16).

Some ionising radiation can be blocked with a sheet of paper, whereas other forms of radiation can travel through concrete **(FIGURE 2)**. High-energy particles carry the most energy and, when combined with being 'charged', have the greatest potential for causing ionisation. However, this increased likelihood of interaction with electrons in atoms also reduces their penetration distance.

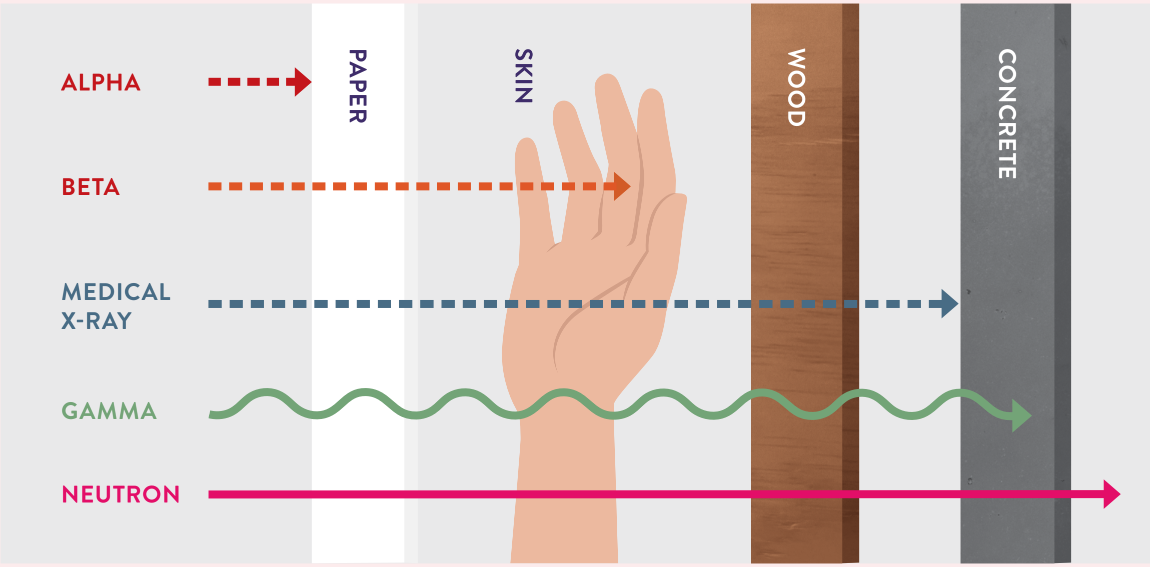


FIGURE 2: Penetration power of ionising radiation.
Source: https://www.nrc.gov/about-nrc/radiation/health-effects/radiation-basics

Tūhuratanga
Discovery of radiation

Radiation in the form of electromagnetic waves covers a spectrum of frequencies, but until 1800, visible light was the only known part of that spectrum. Subsequently more forms of electromagnetic radiation have been discovered, from low-energy radio waves to high-energy gamma rays (**FIGURE 1**). Other types of radiation that are not electromagnetic waves have also been discovered, most notably alpha, beta, and neutron particles.

1800 Infrared

Astronomer **William Herschell** discovers infrared radiation, which he calls 'radiant heat'. His experiments showed that what we detect as heat is actually a form of electromagnetic radiation with longer wavelengths than the red light part of the visible spectrum [3].

1801 Ultraviolet

Chemist, physicist, and philosopher **Johann Wilhelm Ritter** discovers ultraviolet radiation. Ritter's experiments on the degradation of silver chloride in sunlight revealed that the degradation was strongest at shorter wavelengths to the violet part of the visible spectrum, now known as ultraviolet [4].

1887 Radio waves

Physicist **Heinrich Hertz** confirms the existence of radio waves, which are the basis of so many of our modern communication systems [5]. His experiments also generated and detected radio waves in the microwave region. The use of microwaves was developed for radar in the 1940s [6].

1895 X-rays

Physicist **Wilhelm Röntgen** discovers that X-rays could show bones inside the human body. Röntgen received the first Nobel Prize in Physics in 1901 for his discovery, which sparked the use of X-rays in medical practice and inspired further research into these 'remarkable rays' [7].

1898 Radioactivity and radioactive decay

Marie and **Pierre Curie** discover that radiation is emitted from uranium as it decays into other substances, including radium and polonium. In 1903, **Henri Becquerel** shared the Nobel Prize in Physics with the Curies, for their discovery of spontaneous radioactivity [2]. In 1911, **Marie Curie** also received the Nobel Prize in Chemistry for her work on radium and polonium. Her discoveries led to medical applications of radiation in tumour treatment [8].

1898 Alpha and beta particles

New Zealand-born physicist **Ernest Rutherford** discovers and names alpha and beta particles in the radiation emitted by uranium. In 1908, he is awarded the Nobel Prize in Chemistry for this discovery and for his research into the chemistry of radioactive substances [4].

1900 Gamma rays

Chemist and physicist **Paul Villard** observes that the radiation emitted by radium salts can penetrate lead foil but is not deflected by magnetic fields. This discovery was later confirmed by Rutherford, who named this radiation gamma rays [9].

1932 Neutron

Physicist **James Chadwick**, while studying radiation from beryllium, proves atoms contain an uncharged particle. He named these particles neutrons. In 1935, he received the Nobel Prize in Physics for this discovery [10].

1940 Microwaves

Physicists **John Randall** and **Henry Boot** create a radar device that operates in the microwave region. This use of microwaves in radar became invaluable during wartime, because it allowed for a smaller, lighter, and more powerful device than radio wave-based radar [11].

Ngā pūtake tūturu
Natural sources of radiation

Naturally occurring radiation surrounds us, and much of it is essential to life. Along with other living things, we have evolved alongside this ever-present radiation from the Earth, the Sun, and the cosmos. For example, the light and heat radiation we receive from the Sun fuels plants to grow and warms the surface of the Earth.

Most ionising radiation that humans are exposed to comes from natural sources **(FIGURE 3)**. Only about 20 percent of ionising radiation comes from generated sources, mostly in certain medical applications [2]. Ionising radiation can cause biological mutations – changes in a cell's DNA. Some mutations cause health problems like cancer.

The cosmos and cosmic radiation

Earth is constantly bombarded with radiation from the Sun and from outside our solar system [12]. The number of high-energy charged particles and gamma rays that make up this radiation decreases as they collide with atoms such as nitrogen and oxygen in the Earth's atmosphere. At higher altitudes, including during air travel, we are therefore more exposed to cosmic radiation [13], [14]. In addition, background cosmic microwave radiation surrounds us, a phenomenon that a theory on the origins of our universe attributes to remnants of the Big Bang [15].

The Sun

Much of the radiation given off by the Sun is in the form of electromagnetic radiation, predominantly light and heat, that is absorbed by the Earth's atmosphere and surface. Infrared radiation is experienced as warmth. UV radiation can cause sunburn, eye damage, and skin cancers, but also allows our skin to produce vitamin D, which is essential for healthy bones.

The Sun also gives rise to the solar wind, a stream of very high-energy particles consisting mostly of protons and electrons. The Earth has a magnetic field around it that is generated by the movement of molten metal (mostly iron and nickel) in its core. This magnetic field largely protects us from these high-energy particles, but in the polar regions they can collide with gases such as oxygen and nitrogen in the atmosphere [16]. These collisions give rise to intense bursts of coloured light that we see as the aurora (aurora borealis in the northern hemisphere and aurora australis in the southern hemisphere) [17]. Occasionally, during a strong surge in the solar wind, for example, the aurora can be seen further away from the poles.

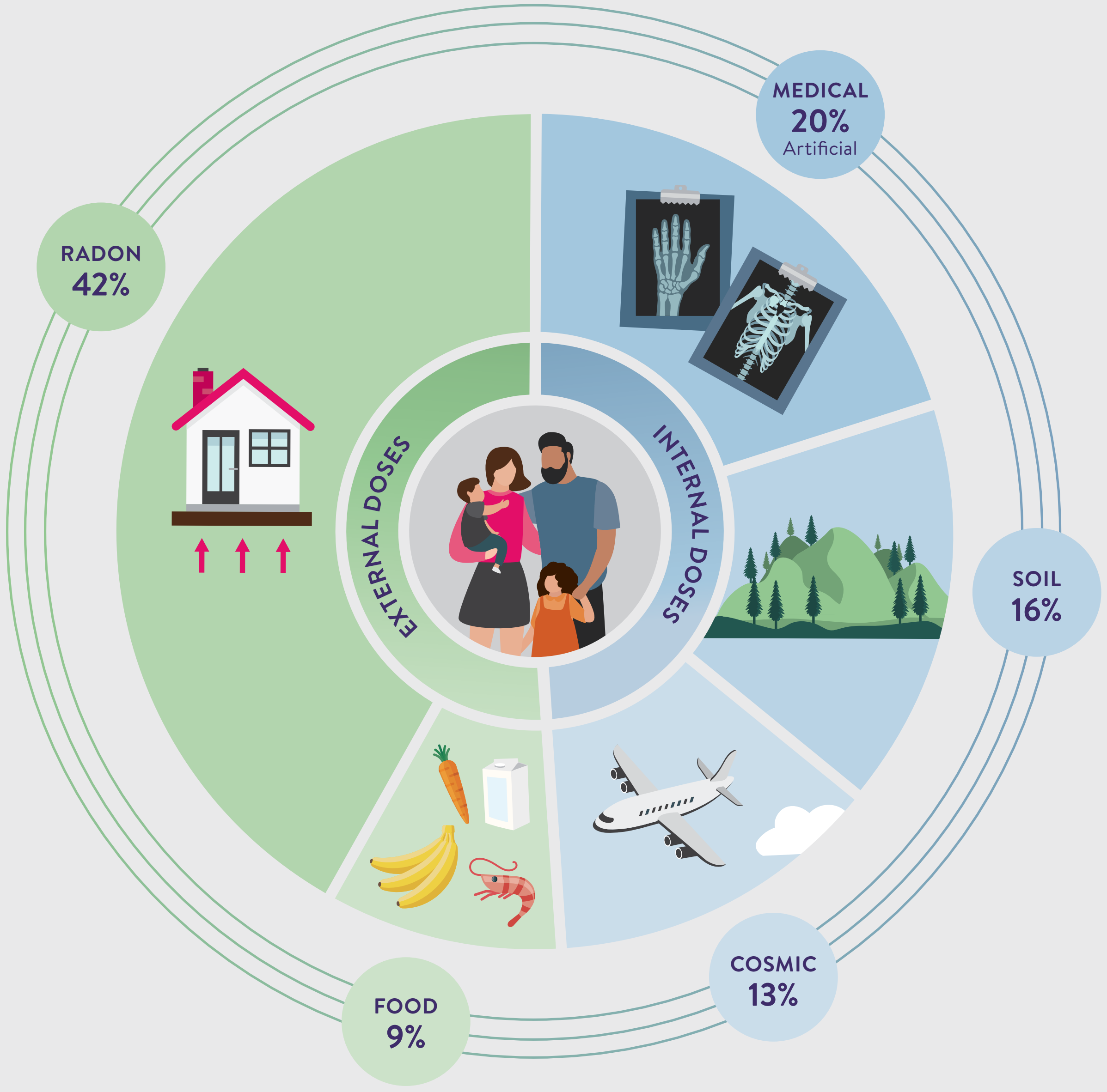
Space weather, including solar storms, can disrupt electricity supplies [18], satellite communications, navigation, and air travel [19].

IN MORE DETAIL

UV radiation can be separated into three separate bands, of which UVA (the longest wavelength band) accounts for most of the UV radiation from the Sun. Medium-wavelength UVB is mostly absorbed by the ozone layer above the Earth. UVC, the shortest wavelength UV band, is completely absorbed by the Earth's atmosphere above the ozone layer, and we are not exposed to it from natural sources. It can, however, be generated artificially.

Worldwide distribution of radiation exposure

FIGURE 3: Global public exposure to ionising radiation comes mostly from natural sources (about 80 percent). Source: Diagram adapted from UNEP 2016 [2]

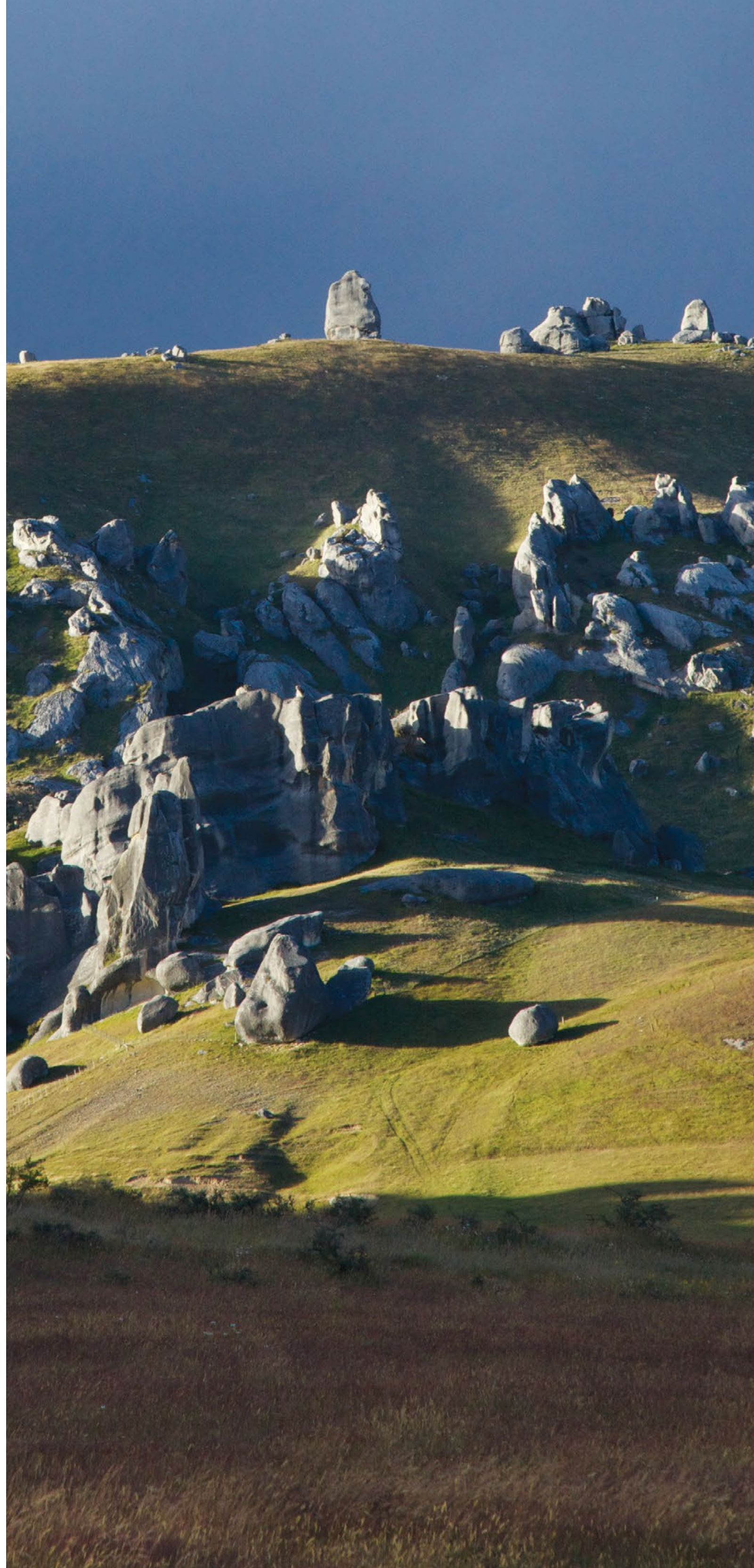


Natural radioactivity

The geology of a country – the rocks that make up the landmass – exposes people to radiation from the Earth's naturally occurring radioactive elements. Some types of rock are radioactive due to their chemical makeup.

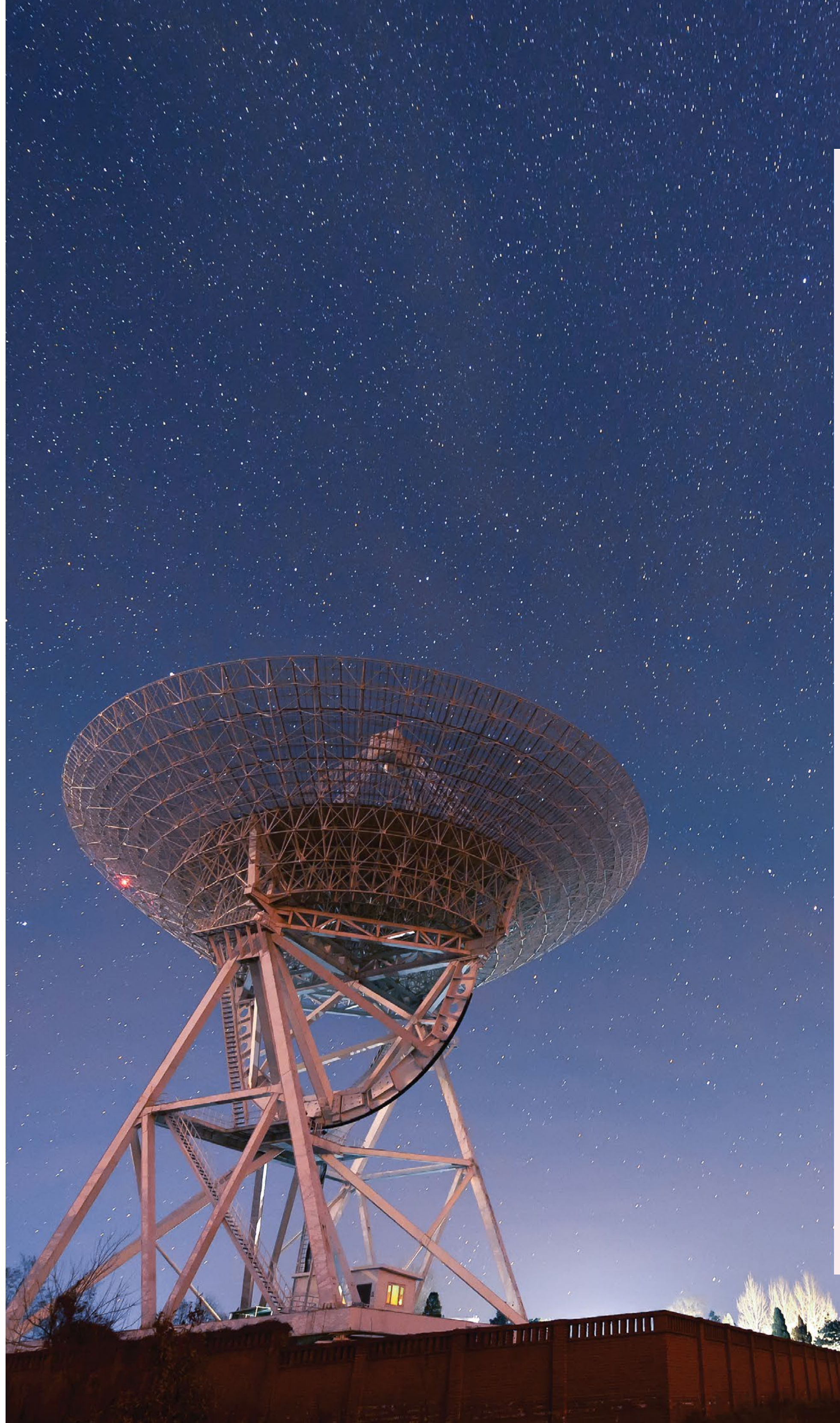
Globally, radon gas is a substantial contributor to background ionising radiation levels and, after smoking, a leading cause of lung cancer [20]. Radiation from radon gas, produced by some radioactive rocks, is present in different quantities in different geographical areas. Radon is an inert gas that forms as an intermediate step during the radioactive decay of uranium. It seeps out of the soil and can accumulate in buildings, especially in basements as it is heavier than air. Radon is radioactive itself, decaying to other radioactive products that can attach to dust particles and lodge in the lungs. A recent New Zealand Ministry of Health survey of radon gas shows that levels in New Zealand homes are low compared to several European countries [21].

Uranium, a radioactive element, is found naturally in many places on Earth, including New Zealand. Uranium is also found in some superphosphate fertilisers that we apply to soils to improve growth in crop plants. However, research has demonstrated that the accumulation of uranium in fertilised soil in New Zealand is low [22].



Ngā pūtake ka whakaputaria
Generated sources of radiation

Generated sources of radiation have delivered many benefits to our lives, from light bulbs to bar heaters, and communication networks to medical treatments and diagnostics. All these activities generate radiation that interacts with our body in some way. Just as for natural sources of radiation, the potential health risks of artificially generated radiation vary greatly depending on the type of radiation, exposure time, and amount of energy transferred.



Ngā whakamahinga
How do we use radiation

Communication systems

We use radio waves in many of our modern-day communication systems. Some examples are mobile phones, Wi-Fi networks, short-range communications such as Bluetooth, radio and television broadcasts, baby monitors, remote garage door openers, radio-controlled cars and drones, and satellite communication systems. Astronomers use radio telescopes (specifically designed radio antennas) to detect signals from space that cannot be detected by optical telescopes.

Mobile or 'cell' phones contain both a radio transmitter and a receiver. Mobile phones use higher frequencies than radio or television broadcasts and, at this higher frequency, the waves travel shorter distances and are less able to be picked up inside buildings. Large numbers of transmitters are used across the country, each one covering a limited area, or cell (hence the name). When you use your phone on the move, it automatically hands over transmission from cell to cell, seamlessly, so that you do not lose the connection.

IN MORE DETAIL

Radio waves are a form of non-ionising electromagnetic radiation. They can be transmitted over very long distances, including to and from spacecraft, or used for short-distance communication, such as in wireless headphones. Initially, radio was used for communication with ships at sea [23], but before long, radio transmitters were being erected around the world, beaming out radio waves in public broadcasts. The first licensed public radio broadcast in New Zealand was in 1922 [5].

A wide range of frequencies is used for radio communication. When you tune into your favourite radio station your radio receiver is picking up the specific frequency of that particular station. To prevent interference between different radio stations, frequencies are allocated by the government, through Radio Spectrum Management [24]. Regulation of the radio spectrum is necessary: if two nearby transmitters operated at the same frequency, the radio receiver would be unable to distinguish one from the other.

Each generation of mobile phone technology, 1G, 2G, 3G, 4G, has been capable of sending and receiving data at higher rates. 5G, the newest generation of mobile phone technology, is initially using frequencies slightly higher than those used by existing mobile technologies [25], [26]. Eventually, 5G will use an even higher frequency range, and higher bandwidths, to allow even faster download speeds. Note that higher frequency doesn't mean higher or more dangerous exposure to radio waves.

Radiation in medicine

Radiation in many forms (both ionising and non-ionising) is used in the diagnosis of some illness and disease, and for the treatment of certain conditions. Medical imaging began with the discovery by Wilhelm Röntgen in 1895 that X-rays could be used for seeing bones inside the human body, and other medical applications of radiation have followed.

At the low frequency (non-ionising) end of the electromagnetic spectrum, magnetic resonance imaging (MRI) is used to 'see' soft tissues and organs. It uses a combination of powerful magnets and radio waves to give very detailed images of parts of the body [27]. MRI images of the brain, organs, nerves, ligaments, and muscles provide a wide range of diagnostic benefits.

Microwaves (non-ionising) have several uses in medicine. Their ability to cause the local heating of tissue is useful for treating muscles (physiotherapy), stopping bleeding from blood vessels, and in some cancer treatments [28], [29].

Visible light, or phototherapy, can be used to treat jaundice in newborn babies, as well as treating seasonal affective disorder, a form of depression in the winter months when exposure to natural daylight is reduced [30]. Visible light is also used in endoscopes for diagnosis, in microscopes to characterise cell types, and in genome sequencing machines. Lasers are used in many medical settings, including dentistry and eye surgery (ophthalmology).

UV light is being explored as a treatment for wounds infected with antibiotic resistant microbes [31] and as a tool for controlling airborne microbial diseases [32]. UV light in the UVC wavelength range is used for disinfection in some medical settings [33], [34].

X-rays are familiar to anyone who has ever broken a bone as they allow us to 'see' organs inside the body, especially those made of dense tissue, such as bone. CT scans (computerised tomography) use X-rays to gather data in computer-simulated slices through the body. The images produced by CT scans allow 3D imaging whereas standard X-rays are 2D. These scans can be used for better targeting of radiation treatment for cancers. In 2018, a team of scientists at the University of Canterbury, New Zealand, developed a special type of 3D X-ray scanner to differentiate various materials or tissues, providing more diagnostic information than standard CT [35].

Radiation therapy uses high-energy ionising radiation to treat many types of cancer tumours. More than 50 percent of cancer patients will receive radiation therapy as part of their treatment. Radiation therapy can be delivered to the body by carefully directed beams from an external machine, or from inside the body via a treatment called brachytherapy. The vast majority of cancer patients who receive radiotherapy receive external beam radiation. Although the aim is to only irradiate the tumour, inevitably, some tissue immediately surrounding the tumour will also be irradiated, which can result in acute and chronic side effects. Acute side effects (such as skin reactions) develop immediately after exposure; chronic side effects (such as fibrosis) develop over a prolonged period.

Brachytherapy is only used for certain cancers and involves placing radioactive material directly inside or very close to the tumour. The type of radiation used in brachytherapy does not travel much beyond the tumour, so healthy tissue surrounding the tumour receives only a small dose, often resulting in fewer side effects [36].

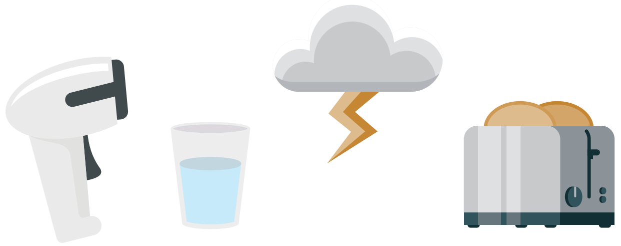
Other uses of radiation

There are many ways that we use radiation for our benefit. Some of the more familiar uses in industry, research, and around our homes are:

Lasers – produce a highly focussed, intense beam of light or infrared radiation. Lasers are used in many settings for cutting, including in clothes manufacturing and sheet metal work, and where other precision cutting is required. They are also used in laser printers in offices; barcode scanners in shops; laser pointers in various commercial and personal settings; and in optical fibre communication, or 'fibre broadband', that connects us to the internet.

Lighting and visual displays – our eyes use visible light for vision. We light our homes and streets using electric lights. It is used in digital screens and photography.

Remote controls and thermal imaging – infrared radiation is used in some TV remote controls and security lights. Search and rescue personnel use infrared cameras for thermal imaging to find those lost by detecting body heat. Radiant heaters in our homes keep us warm and comfortable.



Water treatment and disinfection – UV light is used in some water treatment systems to produce clean drinking water [37], [38]. It can also be used as a disinfection method as part of wastewater treatment processes [39].

Radar and weather forecasting – various radio waves, such as microwaves and millimetre waves, are used for radar, which has applications for air and sea navigation, as well as in speed detection systems. We can use microwaves for these applications by understanding patterns of scattering, interference, and reflection off objects such as cars and aeroplanes. One of the most common uses of radar that affects our everyday lives is its use in weather forecasting. In this case, the objects scattering and reflecting the microwaves are water droplets. New Zealand currently has nine rain radar sites spread around the country. These radars tell us the location and intensity of rainfall and in which direction a rain band is moving, allowing warnings to be issued if necessary [40].

Cooking – we use microwaves to cook our food, and radiant heat (mainly infrared radiation) in toasters, conventional ovens, and stove tops.

Applications in agriculture – following the discovery that exposure to ionising radiation causes chromosomal rearrangement and genome mutations, purposefully exposing reproductive cells to ionising radiation (called induced mutagenesis) has become an important research tool in genetics. A major application has involved plant breeders adopting radiation-induced mutations to change plant traits. More than 3,200 officially released cultivars from more than 200 plant species, including many fruit, grain, and ornamental crops, have been derived directly from radiation-induced mutations [41]. The Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, based in Austria, coordinates global applications of ionising radiation in agriculture, including the development and release of sterile insect pests, and the use of radiation in animal health and biosecurity, as well as in soil, water, and food security.

Scanning – dual-energy X-ray absorption scanners are used in medicine, aviation security, and industry. This technology is used for bone density measurements in hospitals; for distinguishing explosives and drugs from other items in airport security settings; and accurately measuring fat content on meat-processing conveyor belts at production speed [42]. The latter was designed in New Zealand and is now used around the world.

Energy generation and warfare – the high energy released by the decay of radioactive materials (nuclear energy) can be used in many ways, including for electricity generation and nuclear weapons, and as fuel for ships and submarines. Under New Zealand laws passed in 1987, some of these activities are not permitted [43]. We do, however, use radioactive material for beneficial activities, including medical diagnostics and treatments and some industrial sensors, where the risks of harmful exposure can be safely managed.

Industrial gauges – radioactive sources are used in many different types of industrial gauge. Examples include thickness gauges, gauges that check the levels of materials in storage tanks, and meters to check the density and moisture content of soils in civil engineering projects.

Sterilisation of medical and other products – very high doses of ionising radiation can be used to sterilise medical and other products. An advantage of this approach over others is that it allows for the sterilisation of pre-packaged products.

Radiocarbon dating – the radioactive decay of natural materials can be used to accurately date ancient objects made from stone, wood, plants, or animals. For example, radiocarbon dating carried out on a waka found at Anaweka, Tasman District, provided researchers with important information about ocean-going vessels in early Polynesia [44].

Ture ārahi me te whakahaerenga
Regulation and management of radiation

Monitoring and ongoing research informs international recommendations on acceptable levels of radiation and its safe use. At present, there is little evidence that the way we typically use and encounter radiation in our daily lives poses much risk to our health. We have also learned how to mitigate many of the potentially harmful effects of radiation. International and national organisations provide us with safety guidance on the use of radiation. We can also take individual action, such as covering our skin, to reduce our exposure to the Sun.

Non-ionising radiation

Radio waves – the effects of exposure to radio waves are well understood, and there are well established practices for safe use. At sufficiently high exposures, energy in radio waves absorbed into the human body causes temperature to increase. Extremely intense, brief pulses can affect cell membranes. Lower frequency radio waves (below 10 MHz) can also generate weak electric currents in the body, and at sufficiently high exposures, these may stimulate and interfere with the body's nervous system.

Much research has been done to investigate whether exposures at levels below those needed to heat the body or stimulate the nervous system could cause other effects [45], [46], [47]. Further research is required into other areas, such as the prolonged and heavy use of mobile phones [48], [49], although there is currently no substantiated evidence of harm.

In New Zealand, exposure limits are in place to protect people from the non-ionising radiation emitted by cellphone towers and other infrastructure, and sites are monitored independently on a regular basis [50], [51]. These limits also cover the frequencies that are currently used by 5G, and those that might be used in the future. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) provides guidelines on limiting exposure to radiofrequency radiation and ensuring public protection [52]. The guidelines are based on reviews of the research into health effects. The limits recommended by ICNIRP have been incorporated into a New Zealand exposure standard [53].

Light – looking directly at the Sun or other very bright light sources can damage the eyes, but normally we are protected by our natural response to look away. A particular property of laser light, however, means that even a low-powered laser can be focussed on to a spot small enough to damage the eye. High-power lasers can also burn skin. Standards have been developed internationally that classify lasers according to the risks they pose and the safety precautions that should be taken [54].

UV – this radiation from the Sun remains one of the most dangerous forms of radiation in our daily lives, and skin cancer rates in New Zealand are amongst the highest in the world [55]. UVA can penetrate our skin deeply and cause cancers such as melanoma. It is also responsible for some tanning and contributes to the ageing effect of the Sun on our skin. UVB cannot penetrate beyond the superficial skin layers. It is responsible for delayed tanning and burning and is the wavelength that causes most of the ageing effects of sun exposure, and skin cancer. It is important to take precautions – covering up exposed skin and protecting the eyes by using hats and sunglasses [56].

Ionising radiation

Damage to cells by ionising radiation is considered to be a chance event, and the likelihood of damage increases with increased exposure. Sufficiently high doses could cause acute health effects, including nausea, vomiting, burns, and impaired immune responses that appear within hours, days, or weeks of exposure [57]. Extremely high doses can cause death within a few days of exposure. Acute health effects can be completely avoided at lower doses. Delayed chronic health effects, such as radiation-induced cancer, can occur years or decades after exposure. The probability of a cancer-forming mutation occurring depends on the radiation dose received, age at exposure, and the type of body tissue or organ exposed to radiation [2]. In theory, even a very low dose could subsequently have health consequences, although the chance that this would happen is very small.

Principles for protection against the health effects of ionising radiation have been developed over several decades by organisations like the International Commission on Radiation Protection (ICRP). Protection against harm from ionising radiation follows three main principles: justification, optimisation, and dose limit. Justification means that any exposures to ionising radiation should do more good than harm. The diagnostic benefits from having an X-ray or CT scan, for example, should outweigh the potential risk from the X-ray dose. Optimisation requires that whatever doses are necessary to achieve a desired outcome (such as taking an X-ray) should be kept as low as reasonably achievable. Dose limits provide a final backstop in the protection scheme.

Some occupations will regularly involve the use of ionising radiation [58]. These workers are trained in using ionising radiation and are aware of the risks in their profession. For example, radiologists may receive higher than the average population dose of radiation [2]. They take extra measures to monitor their exposure and apply risk mitigation practices, such as wearing badges that record the personal dose of radiation received throughout their workday. New Zealand legislates codes of practice for professions that use high-energy ionising radiation [59].

Air travel at high altitude exposes travellers to higher levels of cosmic radiation than are found at the Earth's surface, as there is less protection from the atmosphere at higher altitudes. However, the levels of radiation exposure for most travellers is sufficiently low that the ICRP does not recommend any specific protection measures to be taken [60].

International guidelines make recommendations on the safe handling of generated sources of ionising radiation, according to the risks they pose to people and the environment. Our exposure from generated sources of ionising radiation in New Zealand is regulated by the Radiation Safety Act 2016 [61], which aims to protect the population and our environment, while allowing for its safe and beneficial use.

Whakaotinga
Conclusion

We are surrounded by radiation from many different sources, both naturally occurring and human generated, in our everyday lives. Radiation has been studied for many years and we now understand its various forms, their different amounts of energy and other characteristics that determine how radiation interacts with us and our environment.

We have learned how to use radiation safely for many applications, from communication technology to healthcare. This knowledge informs the setting of regulations for use and exposure limits to minimise risk.

We can also take precautions ourselves, for example, by limiting our exposure to harmful ultraviolet (UV) radiation from the Sun.

Ngā mātanga pūtaiao
Our experts

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He rārangi pukapuka
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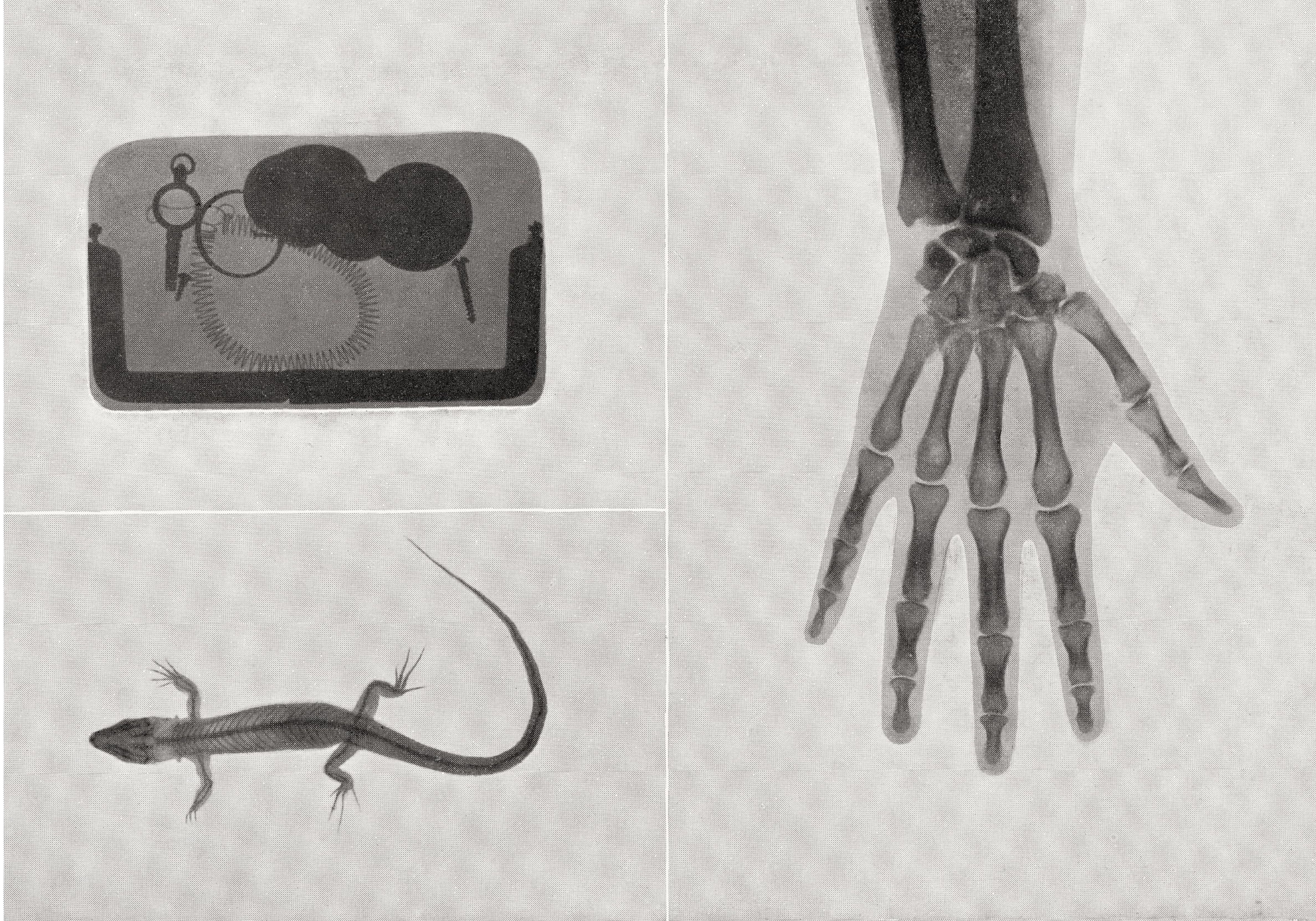

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