Beginner's Guide to x-ray imaging

3DX-RAY

Beginner's Guide to X-ray Imaging

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1. Introduction

X-rays have been used for medical and industrial imaging for many decades and tremendous progress has been made in the performance of the equipment. This has enabled a wider and growing range of applications to be addressed resulting in the use of x-rays in many new areas. This document is designed to help those new to x-ray imaging to understand the basic principles used, the capabilities and limitations of performance, and the safety issues of working with x-rays.

This document discusses the production of x-rays using x-ray generators. X-rays are also emitted from many radioactive materials (called radioactive sources). Issues relating to the management of radioactive sources are not covered in this document as they are not used in the industrial or security applications covered by this guide.

There are also extensive regulations, clinical and good practice guides for the use of x-rays on patients in clinical applications which are not included.

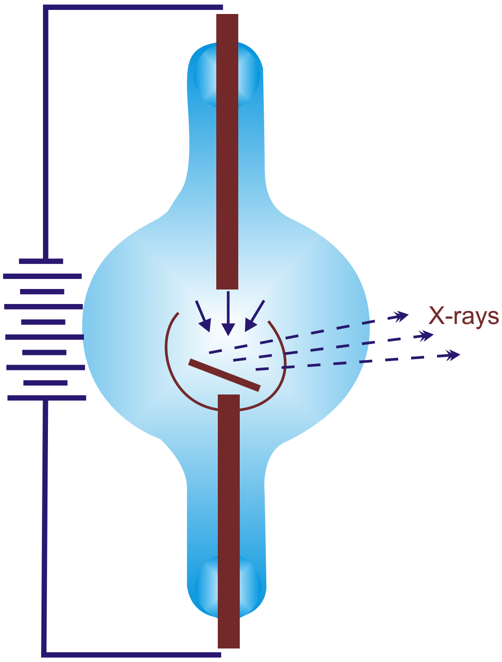
X-ray equipment designed for industrial and security applications should never be used on live humans or animals.

The first published X-ray taken of Roentgen's wife's hand and wedding ring.

X-rays were first observed and documented in 1895 by Wilhelm Conrad Roentgen, a German scientist who found them quite by accident when experimenting with vacuum tubes.

2. What are x-rays and how are they generated?

2.1 What are x-rays?



X-rays are part of the electromagnetic radiation spectrum. This spectrum includes radio waves, microwaves, infrared, the visible spectrum, ultra violet and gamma radiation. X-rays have a wavelength of the order of 10^{-10} metres, which is much shorter (or inversely a much higher frequency) than visible light. X-rays are also called ionizing radiation because of the way they interact with matter.

2.2 How are x-ray generated?

X-rays are produced by means of a cathode ray tube, which is similar to the tube of a television. Electrons are accelerated from a cathode at high speed towards a metal anode. As they hit the metal anode, they release energy. Over 95% of this energy is released as heat and less than 5% of the electrons' energy is converted into x-rays.

The principle constituents of an x-ray tube are:

Glass Envelope Provides a vacuum for the electron beam.

Electron Source A filament, which operates at a high temperature. The current through the filament provides control on the quantity of the electrons emitted.

High Voltage Applied between the filament (the cathode) and the anode. This high voltage controls the x-ray energy, and the force of the penetration of the x-rays.

Anode A piece of metal (typically tungsten) that is hit by the electrons, (sometimes called the "target").

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There are various ways of removing the heat from an x-ray tube.

Oil Filled The entire tube is immersed in oil, shielded in lead, and contained in a tank. The oil is there to cool the tube and help insulate the high voltage supply within the tank.

Gas Filled The tube is filled with gas and shielded with lead. As heat transfer in gas is much lower, the voltage levels are limited because of insulation issues. The energy of the x-rays produced by this type of tube is restricted to approximately 200 KeV.

Rotating Anode An alternative method of dissipating the heat is to rotate the anode so that the heat load is spread evenly over a larger area. The whole assembly is then immersed in oil. This enables higher powered generators to be designed as a much higher heat load can be dissipated.

X-rays can be produced by other methods, particularly from cyclotron-style equipment using the Bremsstrahlung effect. Additionally some radioactive sources produce x-rays. However, these are not generally suitable for security or industrial applications.

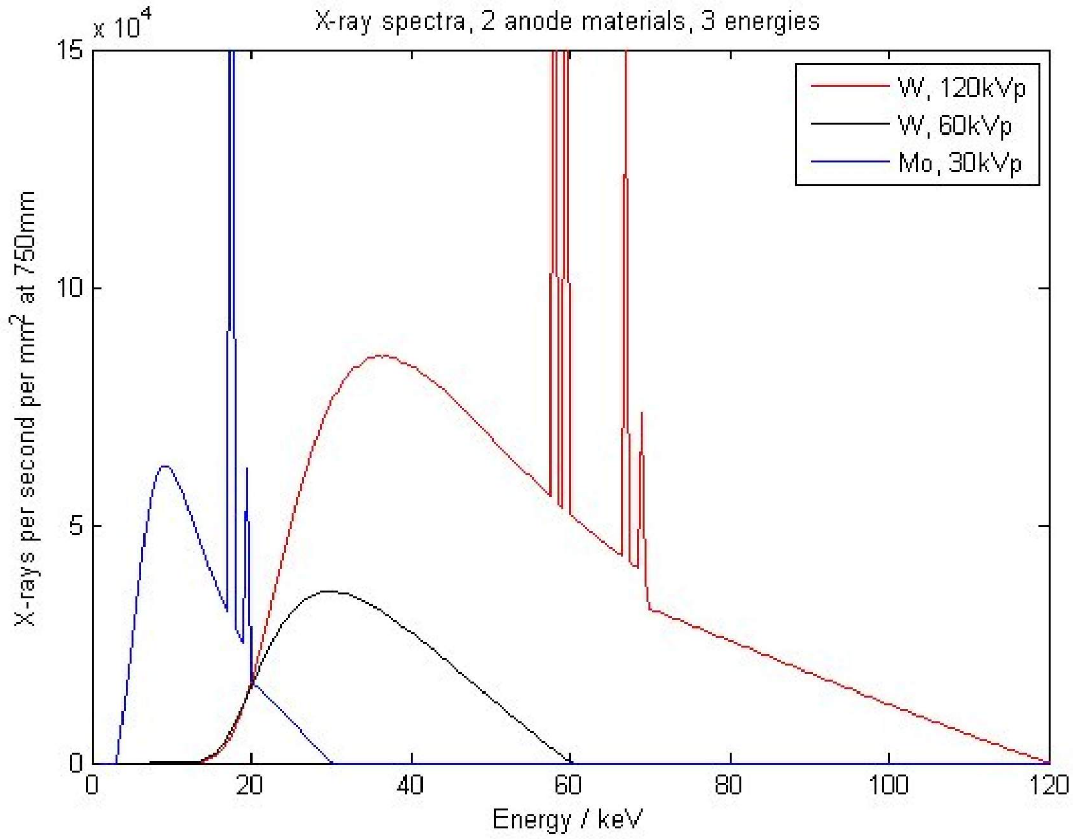
2.3 What affects the characteristics of the x-rays?

A number of parameters affect the characteristics of the x-rays produced by an x-ray tube and determine the spectrum. The characteristics affected are:

X-ray energy This is determined by the KV across the x-ray tube. Increasing KV leads to increasing x-ray energy and results in x-rays that are more penetrating.

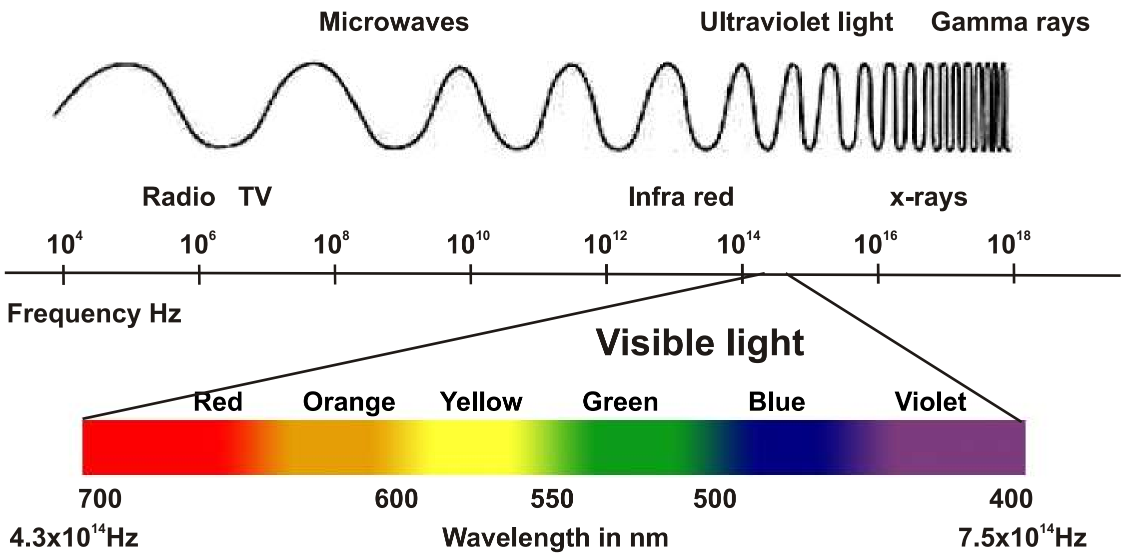
Flux density The number of x-ray photons produced is determined by the current (amps) through the x-ray tube.

X-ray spectrum When electrons hit the anode, the energy is absorbed. 95% is dissipated as heat, but the remaining 5% produces x-rays from the anode material. The material from which the anode is made will determine the spectrum, or distribution, of x-ray energies emitted. Anode materials typically used in x-ray tubes are copper, tungsten, molybdenum and silver.



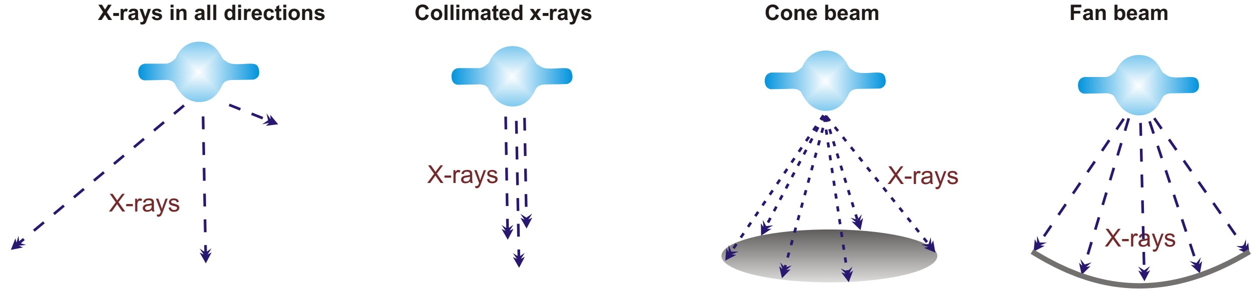
X-rays range in wavelength from10 to 0.01 nanometres, corresponding to frequencies in the range 30 to 30 000 PHz (1015Hz)

Electromagnetic spectrum

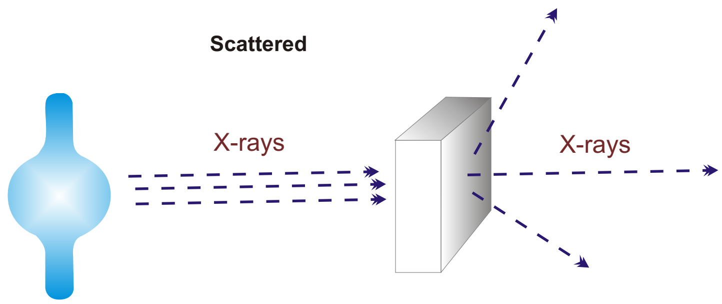


2.4 X-ray beams and how they are created

When x-rays are produced in an x-ray tube they travel in many directions depending on the shape of the anode (sometimes called the target, but not to be mistaken with the intended subject to be inspected by the x-ray, which can also be termed "target"). The x-ray tube is put in a steel or lead container to stop the x-rays escaping, in random directions, and a small hole (aperture or collimator) is introduced which releases them (collimates) in the required direction to form the primary beam. The shape of this aperture will determine the shape of the primary beam. Many different types of shape can be created, but the ones most commonly used in security and industrial applications are cone beams and fan beams.



When the x-ray beam enters an object it will interact with the material in one of three basic ways. It could pass through it completely unhindered, it may become totally absorbed or it may in some way interact with the material and be scattered, that is leave the material at a different angle and energy to that of the incident primary beam. The proportion of x-rays that pass through, are absorbed or are scattered will be dependent on the energy of the x-rays and the material they pass through.



In general scattered x-rays are created by any material that the x-ray beam hits, the target, air, x-ray shielding such as steel or lead, and travel in all directions. As a result, any x-ray system will produce x-rays from a number of points and surfaces. These scattered x-rays are important, because they can affect the quality of the x-ray image. They are also a safety issue as they can cause significant exposure to personnel, therefore any system designed to screen items and personnel from exposure to the primary x-ray bema may also have to consider screening of these scattered x-rays.

2.5 Containing and stopping x-rays

Different materials absorb x-rays in different amounts at different energies. This principle is used in x-ray imaging. In general the denser a material the better it absorbs x-rays so materials such as lead which absorb x-rays very effectively are widely used to shield people against harmful effects.

X-rays with more energy (KV) will be harder to stop so require more lead to effectively stop them therefore the thickness of lead required is dependent on the x-ray energy.

3. How are x-rays detected?

3.1 Different types of x-ray detectors

Historically, photographic film was the most widely used detection medium in x-ray imaging applications. It has been used since the discovery of x-rays at the end of the nineteenth century. However, the principal disadvantage of x-ray film is its low sensitivity due to poor absorption. Only about 1 % of the incoming x-rays are absorbed in the film and hence imaged. In addition the film needs to be chemically developed before it can be viewed. A major advantage of film, of course is the fact that the detection area can be comparatively large.

Over the last 30 years a wide range of electronic (digital) x-ray detection devices have been developed which are now steadily taking over from film in many applications. The advantages of digital x-ray imaging systems compared to the photographic film are the higher sensitivity due to increased absorption and the avoidance of time and material consumed in chemical processing. The image is immediately available in digital systems which allows real-time operation of equipment. Because the image is available digitally, it can be processed on the computer, for example, adding colour to identify areas of interest, or measure specific features.

There are many ways to detect x-rays, all of which detect incoming photons by their interaction with the detector material. That interaction produces a signal which can be in the form of an electric current, a low-energy photon (typically visible light) or heat. The most widely used types of detectors are described below.

Proportional counter arrays

Proportional counters are large area detectors. They are filled with gas that produces an electrical charge when an x-ray passes through. The photon's energy is determined from the strength of the electrical signal; its time from the arrival of the x-rays and the shape of the electrical signal.

Microchannel plates

Microchannel plate detectors are also large-area detectors. They are basically x-ray photomultipliers (a device which detects dim light by producing a cascade of electrons). They are composed of layers of reactive material divided into narrow channels. The energy and location of incoming x-ray photons are determined by the strength, channel location and time of the electrical signal produced by the photon's interaction with the detector.

Charged coupled devices (CCDs)

In contrast to proportional counters and microchannel plates, CCDs are small-area detectors and require the photons to be focussed onto the detector plane. CCDs are made of silicon doped with impurities to create sites with different conductivities. Incoming x-rays then interact with the silicon and impurities to create a "cloud" of electrons. A voltage is applied across the CCD, and this cloud of electrons follows that voltage to the end of the CCD chip. From the charge of the electron cloud, the photon's energy is determined. Since regular readouts are performed, the timing can also be determined.

Properties of common x-rays detectors

Detector	Energy range (keV)	Δ E/E at 5.9 keV (%)	Deat time/event (μs)	Maximum count rate (s^{-1})
Gas ionization (current mode)	0.2 - 50	n/a	n/a	10^{11*}
Gas proportional	0.2 - 50	15	0.2	10^6
Multiwire & microstrip proportional	3 - 50	20	0.2	10^6 mm^{-2}
Scintillation [NaI(T1)]	3 - 10,000	40	0.25	2×10^6
Energy - resolving	1 - 10,000	3	0.5 - 30	12×10^5
Surface barrier (current mode)	0.1 - 20	n/a	0.2	10^8
Avalanche photodiode	0.1 - 50	20	0.001	10^8
CCD	0.1 - 70	n/a	n/a	n/a
Superconducting	0.1 - 4	<0.5	100	5×10^3
Image plate	8 - 80	n/a	n/a	n/a

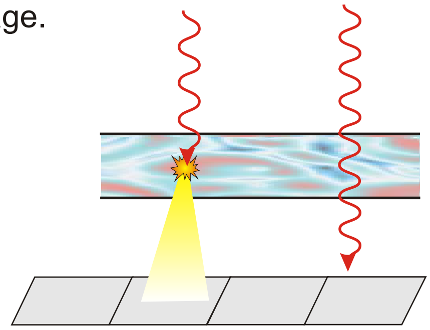
** Maximum count rate is limited by space - charge effect to around 10^{11} photons s^{-1} cm^3*

Semiconductor detectors
Several types of semiconductor detector exist, and more are under development. The main types include energy-resolving semiconductor detectors made from silicon or germanium detectors which are good as energy-resolving detectors of single photons (about 150 eV at 5.9 keV), and current-mode semiconductor detectors - semiconductor diodes used in current mode to measure x-ray flux, they offer very linear responses and thin entrance windows.

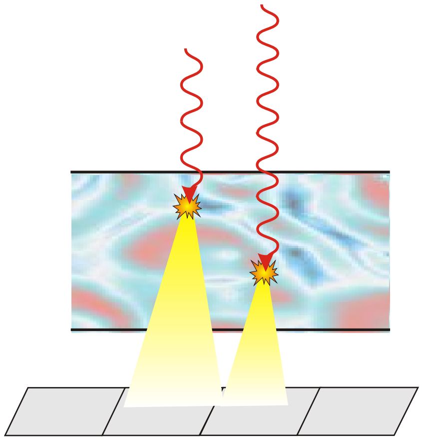
Amorphous silicon flat panel detectors
A further development of the CCD technology is large area flat panel image sensors based on amorphous silicon. These were originally developed for x-ray imaging in medical applications. As they provide both high resolution and high dynamic range, these expensive image sensors are well suited to certain high-end of industrial applications.

3.2 Scintillators - improving detector effectiveness

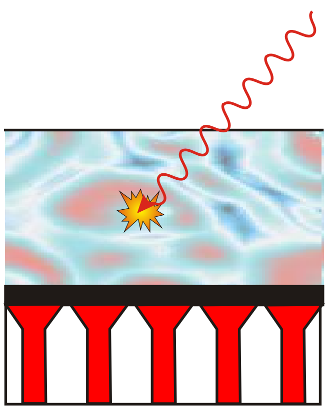
Several of the detectors above, such as amorphous silicon flat panels and CCDs, incorporate a scintillator screen in order to increase their efficiency in capturing x-rays. Scintillators are far more efficient at stopping x-rays than the semi-conductor or CCD which are far more efficient at absorbing light than x-rays. When an x-ray strikes the scintillator, it is converted to light. The light emitted (via a process called fluorescence) is then absorbed by the detector and converted to an electronic image.



Thin scintillator low sensitivity



Thick scintillator high sensitivity



Scintillator bonded to detector

Different types of scintillators are used depending on the energy of the x-rays to be detected. The scintillators can also be used in different configurations. In one possible configuration the scintillator is bonded directly onto the electronic device such as the CCD or amorphous silicon panel which increases the collection efficiency.

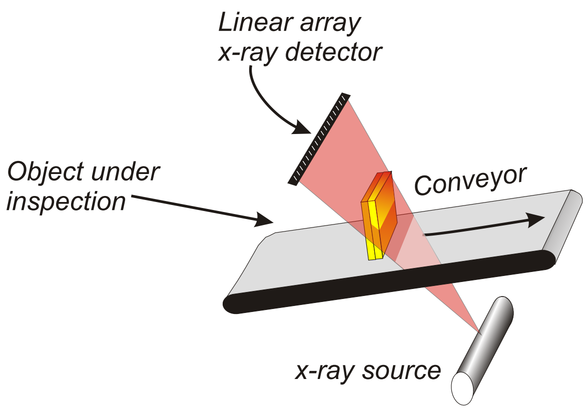
More traditionally, a fluoroscopic screen has been used. The x-rays are absorbed by the screen and turned into light creating an image, which can be captured using a standard 2D camera.

3.3 Different configurations of x-ray detectors

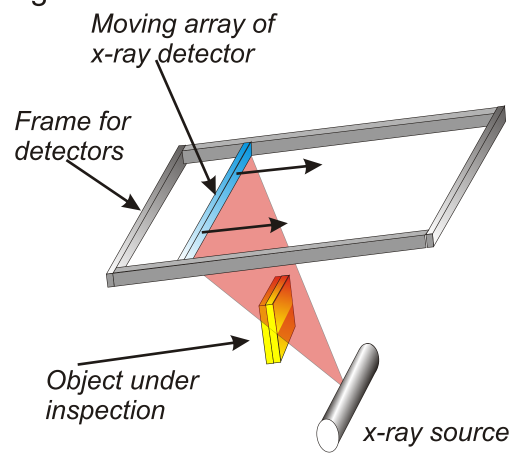
Detectors for digital x-ray imaging systems may either have linear (line scan) or area configurations.

Line scan x-ray systems

Line scan technology uses a thin linear array of semiconductor detectors to acquire the image line-by-line either as the object passes by on a conveyor, or, in the case of TPXi, as the detector is moved across the target.

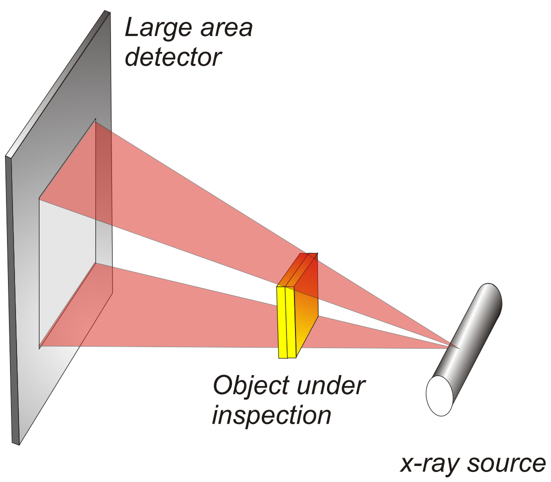


Schematic of a line scan x-ray imaging system with objects moving past on a conveyor



Schematic showing moving detector array, and stationary package

Producing an image using a line scan may use a thin curtain of x-rays to illuminate the detector array. As the object passes through the inspection area it is illuminated by the x-ray curtain and the resultant line image formed on the detectors is continuously read by the computer, building up a complete image of the object line-by-line. This technique also reduces the x-ray exposure to the object being inspected by around 98%.



Area detectors are two-dimensional and filled with rows and columns of detectors. They require no scanning procedure. They typically use large and expensive specialised “imaging” chips, similar to those used in conventional digital or movie camera.

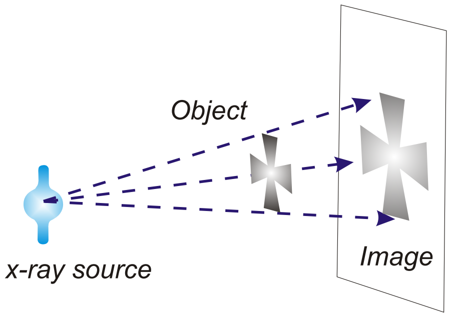
The different configurations are suitable for different applications. For example, in baggage inspection machines, linear detectors are used since the bags are transported past the detector on the conveyor belt. In medical applications, an area detector is normally used because a picture of an area of the body is required and the patient must remain still.

4. About x-ray images

4.1 How x-ray Images are created

The creation of x-ray images is based on the ability of x-ray energy to pass through matter. This ability varies with different substances; e.g., wood and flesh are easily penetrated, but denser substances such as lead and bone absorb more of the x-ray energy. The penetrating power of x-rays also depends on their energy. The more penetrating x-rays, known as hard x-rays, have a higher frequency and are thus more energetic, while the less penetrating x-rays, called soft x-rays, have lower energies. X-rays that have passed through an object provide a visual two dimensional image of its interior structure when they strike a photographic plate or x-ray detector; the darkness of the shadows produced on the plate or screen depends on the relative absorbtion of different parts of the object.

4.2 Image resolution



How a image is formed

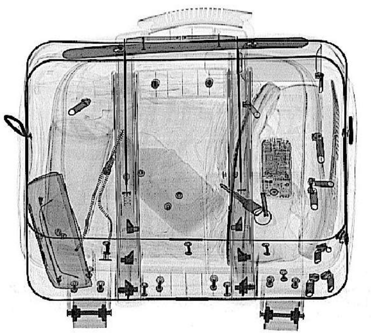
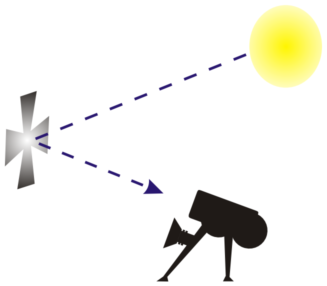


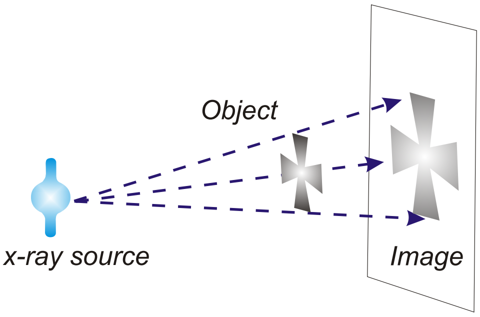
Image of a suitcase from an x-ray baggage screening machine



Light rays from object being collected by sensor.

In optical pictures the resolution of the image is determined by the resolution of the camera. This is because light rays are reflected from the object to fall on the detector and the resolution is determined by the pixel size of the detector.

In x-ray imaging, the object lies between the x-ray generator and the detector and the images are formed as shadowgraphs.

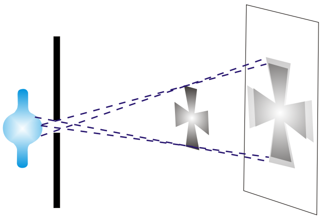


How an x-ray image is formed.

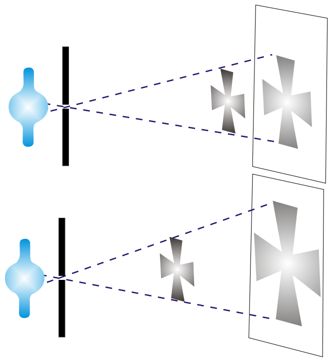
In such x-ray systems three factors determine the resolution:

- The size of the spot within the generator where the x-rays are produced
- The geometric magnification effect of the position of the target relative to the generator and detector
- Detector resolution

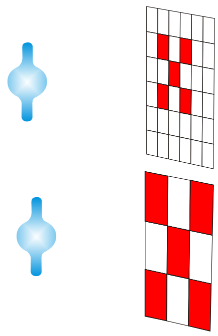
These three factors can be shown graphically as follows:



Effect of spot size



Effect of target position / image



Detector resolution

It is important that all three elements of the system are optimized if high resolution images are to be obtained. The benefits of a high resolution detector can be completely eliminated by the use of the wrong x-ray generator spot size and / or by the geometric positioning of the object between the x-ray generator and the detector.

Image clarity is at least as important as resolution and is affected, to a very large degree, by the image processing capabilities of the system. Although technical details are rarely published for commercial reasons a simple comparison of the images produced on different systems is easily sufficient to demonstrate the widely ranging options available.

4.3 3D x-ray images

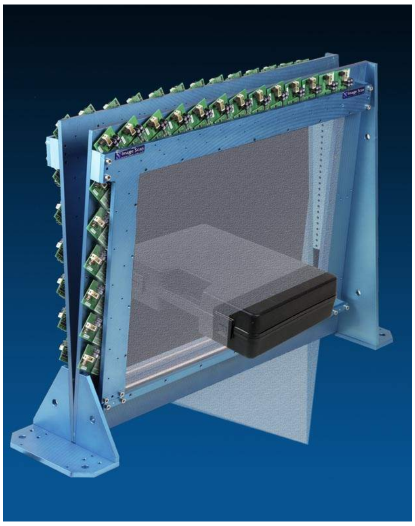
X-ray images are a convenient medium to look within objects however the resultant images contain absorption information from all objects along the beam path between the x-ray generator and the detector. This concatenation of target depth to a single plane can lead to difficulty in understanding the nature of the target and the objects that lie within it. It may be useful to understand this original depth information and there are a number of x-ray imaging techniques available to reveal this. We will consider two such techniques for the purposes of the discussion here, stereoscopy and computer aided tomography.

4.4 3D stereoscopic x-ray images

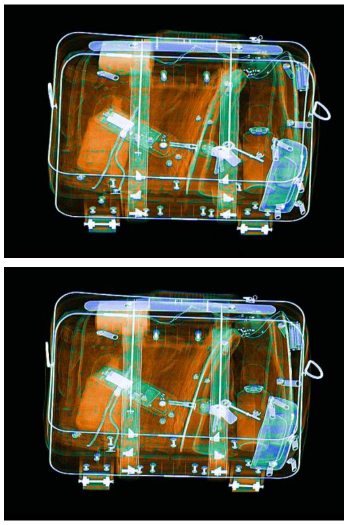
Stereoscopic pictures are produced in pairs with each member of the pair showing the same scene or object from a slightly different angle much in the same way as you view the real word with two eyes, each seeing a slightly different view of an object. If each eye of an observer is only shown one of the stereoscopic views then the brain interprets the differences in these views as depth or different distances to points and objects seen. Although an experienced observer of stereopairs with training may be able to achieve the proper focus and convergence without special viewing equipment (e.g., a stereoscope), ordinarily some device is used that allows each eye to see only the appropriate picture of the pair. Typically, either different colours, polarizations or specialised projection systems are used to ensure that the observer sees only the correct image with the correct eye and hence get the full dramatic effect of 3D images.

3D x-ray stereoscopic images can be created using a special camera which has a single x-ray generator and two x-ray detectors.

Graphic of stereo x-ray camera



3D Stereoscopic x-ray camera



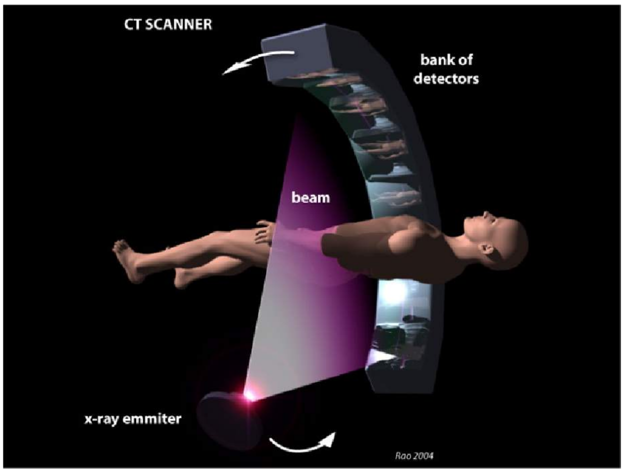
Stereoscopic pair of images

The stereoscopic pair of images are acquired at the same time and displayed on the monitor together with different polarizations. The images are viewed through spectacles with lenses of matched polarization which allow the observer to view real-time 3D images.

4.5 3D computed tomography (CT) x-ray images

Computed tomography (CT), originally known as computed axial tomography (CAT), was first developed for medical imaging and is now finding increasing uses within the industrial inspection field. It employs tomography (imaging by sections or sectioning) and uses digital processing to generate a 3D image of the internals of an object or person from a large series of two-dimensional x-ray images taken around a single axis of rotation. The word "tomography" is derived from the Greek tomos (slice) and graphia (describing).

CT produces a volume of data which can be manipulated, through a process known as windowing, in order to demonstrate various structures based on their ability to block the x-ray beam. Although historically (see below) the images generated were in the axial or transverse plane (at right angles to the long axis of the body), modern scanners allow this volume of data to be reformatted in various planes or even as volumetric (3D) representations of structures.

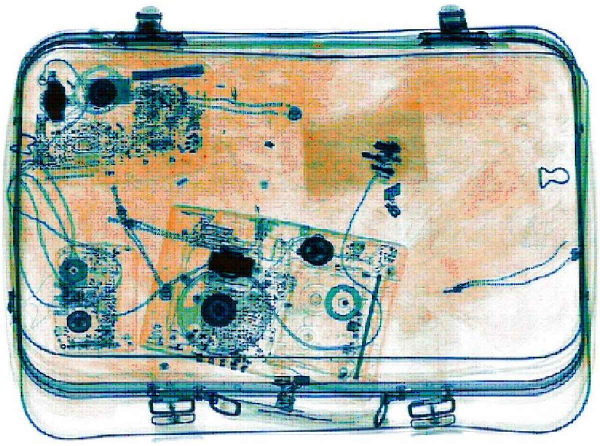


In recent years CT imaging has been widely adopted in a range of industrial applications for inspection of large industrial components such as automobile engine blocks. Although this technique is relatively slow (10 minutes to acquire and process image data) the resultant images can be very powerful in the laboratory analysis of faults and failure mechanisms within products.

4.6 Materials differentiation and dual energy

X-rays provide information on the density and position of items. However, by detecting and analysing the response of an object to two distinct x-ray energy bands it is possible make a broad determination of the type of material the x-rays have passed through. This technique is known as dual energy x-ray analysis or DEXA for short and relies on the way absorption varies with the atomic number of the material. Generally DEXA is used to classify, broadly, objects into 'organic', 'metallic' or a 'mixture' of the two. The results are usually displayed using false colour - typically orange is used for organic materials, blue for metallic and green for mixtures.

DEXA is performed in real-time and can be used in a variety of industrial and security applications: for example to show the difference between dense organic material, (such as explosives) and non-organic, (such as the metal in guns or knives). It can also discriminate between bone and tissue in meat products.



5. Applications of x-ray imaging

5.1 Applications overview

Over the past 30 years, a wide range of applications have developed for x-ray imaging. These include:

Industrial	Non Destructive Testing of welds Non Destructive Testing of castings Automated serial inspection in production lines including QC and SPC
Security	Baggage / parcel scanning in the transport industry Inspection of suspect packages
Space Science	Space Science radiology Earth observation Planetary observation X-ray astronomy
Clinical	General clinical imaging Mammography Dental Thoracic Nuclear Medicine
Other	Examination of paintings

5.2 Imaging inside containers

X-rays have been used to image inside of containers such as baggage for many years. Imaging of complex assemblies in industrial inspection or security forensics, however, present a number of additional problems, especially relating to the construction materials of the items being inspected. When the construction materials are similar or the same, such as plastic-in-plastic or metal-in-metal, identifying the different components can be difficult particularly when they overlap within a complex assembly. Where components made of low absorption materials are in a container or casing made of a high absorption material, then identifying the components can be a challenge due to the absorption of the casing. Improvements in x-ray generators, detectors and image processing have significantly improved the ability to image and analyze these complex objects.

5.3 Metrology

Metrology measuring and checking of dimensions, positions, angles, volumes and alignment (e.g. of needles) with x-rays has traditionally been difficult. Recent advances, particularly in 3D stereoscopic x-ray imaging techniques and image processing, have largely solved this problem. Inspection rates of greater than one item per second with accuracies of 100 µm are regularly achieved in production lines, and accuracies around the micron level are possible.

5.4 Quality control and SPC

X-ray imaging is an useful technology for both QC and SPC operations. Real-time databases can be produced representing a highly accurate 3D digital representation of each component as they flow by. These can be analysed, processed and enhanced as part of the equipment's own software suite or linked directly into a QC or SPC package.

6. X-rays and safety

X-ray equipment designed for industrial and security applications should never be used on any humans or animals.

6.1 Sources of radiation

Ionising radiation occurs as either electromagnetic rays (such as x-rays and gamma rays) or particles (such as alpha and beta particles). It occurs naturally (e.g. from the radioactive decay of natural radioactive substances such as radon gas and its decay products) but can also be produced artificially. Everyone receives some exposure to natural background radiation.

Natural radiation comes from atoms within the Earth, as well as from cosmic rays (invisible, high-energy particles that bombard Earth from space) and accounts for about 82 percent of a person's yearly radiation exposure. In the late 1980s radon, a colourless, odourless, and tasteless radioactive element produced by the radioactive decay of radium, thorium, or actinium was recognized as a significant source of natural radiation. Radon accounts for 55 percent of a person's natural radiation exposure, while human-made sources account for about 18 percent of a person's yearly radiation dose.

6.2 Measuring x-rays

The term or unit used to describe the radiation dose received is a Sievert. This is the SI unit of absorbed dose and is equal to one Joule/ per Kilogram or 100 rems.

In practice, fractions of Sieverts apply…

$\frac{1}{1000000}$ Sv = 1 µSv $\frac{1}{1000}$ Sv =1 mSv

There are two major methods of measuring x-rays as part of the safety procedures for operators. For people who regularly work with radiation sources, a film badge is worn; this measures the accumulated x-ray dose over time. This is sent to a central laboratory for analysis and monitoring.

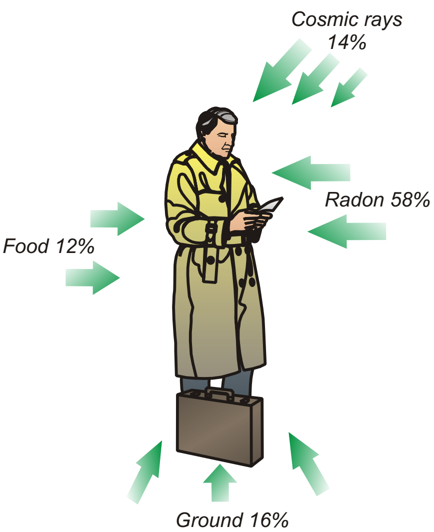
Most industrial x-ray systems are screened using lead to prevent x-rays from escaping. X-ray meters are used to inspect the system and check for any escaping x-rays. An example of a typical x-ray meter is shown here.

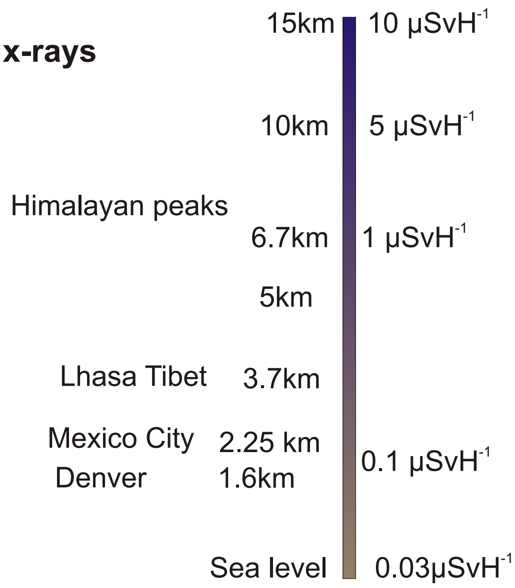
6.3 Typical exposure levels to x-rays and natural radiation

We are exposed to x-rays from natural sources and human activities. The table below shows the level of exposure that we normally receive and the levels that are dangerous.

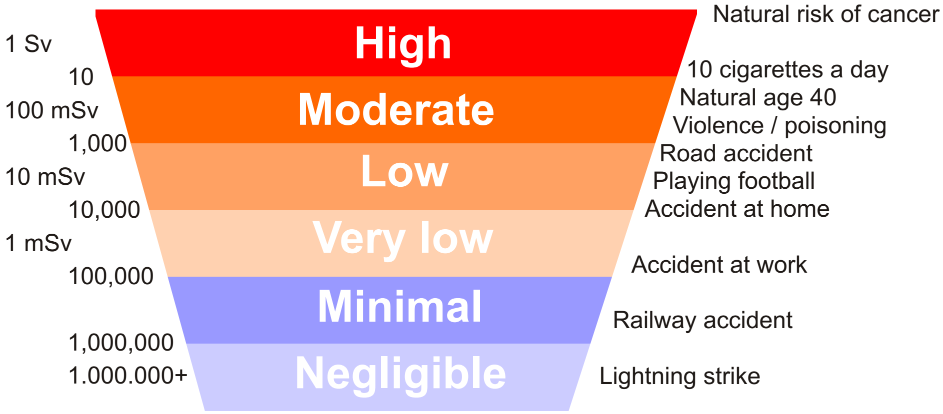
	mSv
chest x-ray	0.02
fluoroscopy	60
chromosome changes	100
radiation sickness	1000
possible death	3000
	mSv / y
average (UK) natural background	2.7
radiation worker	1.1
occupational dose limit	20

6.4 Comparative risks of exposure to x-rays





Increase of dose (per hour) received at altitude



Comparative Risks of Exposure to X-rays Source: Govt Chief MD

6.5 Shielding and penetration

Shielding from x-rays is usually in the form of a lead sheet, or lead apron/blanket. Most sources use shielding inside their case and baggage scanners are lead lined, with lead curtains at each end of the tunnel. Shielding reduces the amount of energy in the x-ray. The penetrating power of an x-ray is expressed in terms of the KeV of the x-ray source. Our standard x KeV source will penetrate x cm of solid steel and still produce a useable image.

6.6 Spreading the dose over time

At low doses and dose rates such as those normally experienced by workers, the general public or TPXi operators following normal operational procedures, the risks to health are assumed not to change with the time period over which dose is received. At high doses and rates, such as those used in radiotherapy, spreading the dose is used to reduce the effect on healthy tissues by allowing a period for cell repair and recovery.

6.7 Radiation regulations

X-rays and other forms of radiation can be dangerous to humans unless they are managed properly. Governments across the world have developed Radiation Regulations to ensure that such systems are safely installed and operated. These Regulations vary from country to country. It is essential to understand and obtain professional advice on the Radiation Regulations that apply to the country in which an x-ray system will be operated.

7. FAQs

Q: Will inspection by a typical x-ray baggage scanner make items such as clothes radioactive or leave any residual radiation?

A: No, imaging with x-rays leaves no trace of residual radiation.

Q: Should operators wear a "radiation badge"?

A: For people operating some types of x-ray inspection equipment this is not normally required - such equipment is designed to ensure that no x-rays can escape, and are regularly inspected to confirm this. When open x-ray generators are used, such as the TPXi-675 flat panel inspection system, again radiation badges are not normally required as the exclusion zone required of 50 metres will protect the operator. However, the radiation protection regulations, in the country that the equipment is being operated, should always be followed.

Q: Is it safe to eat my lunch if it has been exposed to the X-ray radiation?

A: Yes, - there are no known adverse effects from eating food that has been irradiated by this type of x-ray system. The radiation dose typically is around 0.1 mSv for a chest x-ray. The average dose rate from background radiation is 3.6 mSv per year.

Q: Will electronic equipment be harmed by exposure to x-rays from security or industrial products?

A: No, the x-ray dose is far to low to damage electronic equipment.

Q: Will photographic film be fogged?

A: It is unlikely, but possible. Our security equipment is safe for all but the fastest film speeds (speeds below 1000). However, multiple exposures of film to any x-ray source even "film safe" ones can eventually result in fogging or increased granularity.

Q: What do the words exposure and dose mean?

A: Exposure is the amount of ionizing radiation that strikes the material. In health physics, it is defined as a measure of ionisation in air caused by x-ray or gamma radiation only. Dose is the amount of radiation or energy absorbed and can be expressed either as an absorbed dose, (the amount of energy absorbed per unit mass), or as an equivalent dose, (which is adjusted for the relative biological effect of the type of radiation). Not all radiation has the same biological effect, even for the same amount of absorbed dose).

Q What units are used to measure x-rays?
A: Sv (Sievert) The SI unit of absorbed dose equivalent (1 Joule/ per Kilogram or 100 rems)

rem (Roentgen Equivalent Man) is the unit of equivalent dose, it relates the absorbed dose in human tissue to the biological effect it causes. 1 Sv = 100 rem

R (Roentgen) is the old unit of exposure of ionizing radiation, it indicates the strength of the ionizing radiation. One Roentgen is the amount needed to produce ions carrying 1 electrostatic unit of electrical charge in 1 cubic centimeter of dry air under standard conditions.

rad (Roentgen absorbed dose) is the old unit for absorbed radiation dose. 1 rad means each gram of the object received 100 ergs of energy or 1 rad = 100 ergs/gram.

Appendix 1- A background to x-rays

As the wavelengths of light decrease, they increase in energy. X-rays have smaller wavelengths and therefore higher energy than light waves. We usually talk about x-rays in terms of their energy rather than wavelength. This is partially because x-rays have very small wavelengths, but also because x-ray light tends to act more like a particle than a wave. X-ray detectors collect actual photons of x-ray light - which is very different from the radio telescopes that have large dishes designed to focus radio waves!

X-rays were first observed and documented in 1895 by Wilhelm Conrad Roentgen, a German scientist who found them quite by accident when experimenting with vacuum tubes.

A week later, he took an X-ray photograph of his wife's hand which clearly revealed her wedding ring and her bones. The photograph electrified the general public and aroused great scientific interest in the new form of radiation. Roentgen called it "X" to indicate it was an unknown type of radiation. The name stuck, although (over Roentgen's objections), many of his colleagues suggested calling them Roentgen rays. They are still occasionally referred to as Roentgen rays in German-speaking countries.

The Earth's atmosphere is thick enough that virtually no X-rays are able to penetrate from outer space all the way to the Earth's surface. This is good for us but also bad for astronomy - we have to put X-ray telescopes and detectors on satellites! We cannot do X-ray astronomy from the ground.

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