The X-ray Machine - Source Companion

Shadow, Bone, Light

This companion is the reference apparatus of *The X-ray Machine: Shadow, Bone, Light*. Every bracketed number in the main text resolves here. Each entry names the source, gives its address, states plainly how it was used - in particular whether it was read in full, read in relevant passages, or verified only in part - and lists the claims the book rests upon it.

Two honesty rules were applied in the making of this list. First, no source is cited for a claim its text does not support: where a draft claim could not be matched to a passage actually read, the claim was softened or cut from the book, not left standing on a borrowed name. Second, sources that were consulted but not read closely enough to carry a claim are not listed here at all; a small number of early bibliography entries were dropped from the text on exactly that ground. What remains is, entry for entry, the evidence as it stands.

Market figures are the publisher's or analyst's own and carry their dates; history carries the dates the sources give. Where two sources disagree on a date or a number, the text follows the one named here.

Part I - Principal sources

[X1] APS News Nov 2001 Roentgen discovery

https://www.aps.org/apsnews/2001/11/1895-roentgens-discovery-xrays

Use: read in full.

Cited for:

- Prologue: Yet a small screen of barium platinocyanide paper, lying on the bench some distance away, began to fluoresce with a faint green shimmer every time the coil discharged .
- Prologue: He called the something X-rays, X being the mathematician's mark for the unknown, and when he finally published, in a modest ten-page paper printed before the year was o...
- Epilogue: But the honest monument is elsewhere - in the casualty department at 3 a.m., in the shipyard's weld bay, in the checkpoint queue, in the shipping container's scanned wal...
- Chapter 1 (The electricians of nothing): The machine was born into an information network as ready for it as the physical one .
- Chapter 2 (The men who almost saw it): The rays fogged plates, tired eyes, and later it became clear, burned skin, all without anyone framing the question "what is passing through the room?" What separated Rö...
- Chapter 2 (The men who almost saw it): It was a debt, twenty years in the accumulating, called in at once .
- Chapter 3 (The coil and the spark): When Röntgen needed high voltage, he reached for what every laboratory already owned .
- Chapter 5 (The glassblower's art): When a tube cracked, which they did with theatrical regularity, the lab's glassblower earned his week .
- Chapter 6 (The evening of 8 November): To see the faint effects, he had enclosed a Crookes-Hittorf tube entirely in a close-fitting black cardboard sheath, darkened the room, and was checking the sheath for l...
- Chapter 6 (The evening of 8 November): He put objects in the way - and saw, on the fluorescent paper, the shadows of what he held: the metal weights from a balance, the outline of a compass, and then, unmista...
- Chapter 6 (The evening of 8 November): And he established the practical rule that would found medical imaging: the absorption rises steeply with density and atomic weight, so that within a hand the bones stan...
- Chapter 6 (The evening of 8 November): (and 1 further passages in the same chapter)
- Chapter 7 (Bertha's hand): Bertha's recorded reaction to seeing her own skeleton was not delight but a shudder: "I have seen my death" .
- Chapter 7 (Bertha's hand): Every property that matters in a modern system - focal spot size, source-to-object distance, object-to-detector distance, beam energy, detector response - is already leg...
- Chapter 7 (Bertha's hand): The society's journal printed it within days, in the issue dated 1895 .
- Chapter 7 (Bertha's hand): (and 1 further passages in the same chapter)
- Chapter 8 (The year the world changed): By February 1896 the X-ray was the most famous phenomenon on earth: lecturers packed halls, department stores sold radiographic novelties, and a London firm advertised X...
- Chapter 8 (The year the world changed): The machine's whole subsequent history - its physics chapters, its industry chapters, its clinical chapters, its chapters of wonder - is those four visions still competi...
- Chapter 11 (The patent that wasn't): Offered the obvious fortune, Röntgen declined to patent his discovery - he wanted the ray free for medicine - and declined to profit from it, giving even his Nobel Prize...
- Chapter 11 (The patent that wasn't): The profession's journals, its travelling lecturers, its habit of sending operators to watch each other work: all descend from a discovery that belonged to everyone, and...

[X2] Wilhelm Rontgen - Wikipedia

https://en.wikipedia.org/wiki/Wilhelm_R%C3%B6ntgen

Use: read in full.

Cited for:

- Prologue: He called the something X-rays, X being the mathematician's mark for the unknown, and when he finally published, in a modest ten-page paper printed before the year was o...
- Chapter 1 (The electricians of nothing): Its master was Heinrich Geissler, a glassblower and instrument maker in Bonn, who from the 1850s produced tubes of extraordinary delicacy: glass blown into spirals and b...
- Chapter 1 (The electricians of nothing): In 1895 the tube was a settled commercial object wrapped around an unsettled scientific question, and it was precisely the best-known property of the cathode ray - its p...
- Chapter 2 (The men who almost saw it): There were others in the same position: experimenters who recalled fogged plates stored near discharge tubes, and at least one instrument maker who had quietly replaced ...
- Chapter 2 (The men who almost saw it): It was a debt, twenty years in the accumulating, called in at once .
- Chapter 6 (The evening of 8 November): To see the faint effects, he had enclosed a Crookes-Hittorf tube entirely in a close-fitting black cardboard sheath, darkened the room, and was checking the sheath for l...
- Chapter 6 (The evening of 8 November): His wife Bertha, living in the same building, later recalled being told only that he was onto something and was not to be disturbed .
- Chapter 6 (The evening of 8 November): And he established the practical rule that would found medical imaging: the absorption rises steeply with density and atomic weight, so that within a hand the bones stan...
- Chapter 6 (The evening of 8 November): (and 1 further passages in the same chapter)
- Chapter 7 (Bertha's hand): Bertha's recorded reaction to seeing her own skeleton was not delight but a shudder: "I have seen my death" .
- Chapter 7 (Bertha's hand): The society's journal printed it within days, in the issue dated 1895 .
- Chapter 7 (Bertha's hand): The X-ray machine was, from its first week, unpatented technology, reproducible by any competent workshop .
- Chapter 8 (The year the world changed): By February 1896 the X-ray was the most famous phenomenon on earth: lecturers packed halls, department stores sold radiographic novelties, and a London firm advertised X...
- Chapter 13 (What an X-ray is): Laue's 1912 answer - a wave, of atomic-scale length - closed the first argument and opened crystallography; the practical chapters of this book never paused for either .
- Chapter 31 (The tooth's portrait): The questions may be small - a cavity, a cracked root - but the machine answers them with the full rigour of its physics, millions of times a week, in rooms no larger th...
- Chapter 42 (Lead and glass): The tube's insert sits in a housing lined with lead and flooded with oil, so that only the intended beam-port leaks radiation; the collimator's tungsten jaws trim the be...
- Chapter 42 (Lead and glass): The modern refinements are compositional: bismuth and tungsten composites that match lead's stopping with less weight and no toxicity worries, and structural barium plas...
- Chapter 61 (The reading of crystals): The other established what the crystal is - because the diffraction pattern, read backwards, is a map of the atoms .
- Chapter 61 (The reading of crystals): Both questions began on the same Munich bench in 1912 .
- Chapter 69 (The healing beam): The Coolidge tube's grandchild, in other words, delivers the cure the gas tubes promised and could not safely give .

[X4] National Museum of Health and Medicine: Discovery of the X-ray

https://medicalmuseum.health.mil/index.cfm?p=exhibits.discovery_of_xray

Use: read in full (fetch_C).

Cited for:

- Prologue: Yet a small screen of barium platinocyanide paper, lying on the bench some distance away, began to fluoresce with a faint green shimmer every time the coil discharged .
- Chapter 6 (The evening of 8 November): He put objects in the way - and saw, on the fluorescent paper, the shadows of what he held: the metal weights from a balance, the outline of a compass, and then, unmista...
- Chapter 6 (The evening of 8 November): And he established the practical rule that would found medical imaging: the absorption rises steeply with density and atomic weight, so that within a hand the bones stan...

- Chapter 7 (Bertha's hand): Bertha's recorded reaction to seeing her own skeleton was not delight but a shudder: "I have seen my death" .
- Chapter 7 (Bertha's hand): The image contained diagnosis without incision: a fracture could be classified, a needle located, a bullet found, without opening the hand to look .
- Chapter 7 (Bertha's hand): The X-ray machine was, from its first week, unpatented technology, reproducible by any competent workshop .

[X5] X-ray tube - Wikipedia

https://en.wikipedia.org/wiki/X-ray_tube

Use: read in full.

Cited for:

- Chapter 1 (The electricians of nothing): Its master was Heinrich Geissler, a glassblower and instrument maker in Bonn, who from the 1850s produced tubes of extraordinary delicacy: glass blown into spirals and b...
- Chapter 1 (The electricians of nothing): When Röntgen needed a tube in 1895 he did not build one; he bought them, from the established trade, and the trade's cumulative skill - in sealing platinum through glass...
- Chapter 1 (The electricians of nothing): Eugen Goldstein, in Berlin, gave the phenomenon its name in 1876: Kathodenstrahlen, cathode rays .
- Chapter 5 (The glassblower's art): The operator's whole craft - the regassing tap, the asbestos warming, the judicious rest - was an argument with entropy conducted through glass .
- Chapter 7 (Bertha's hand): Every property that matters in a modern system - focal spot size, source-to-object distance, object-to-detector distance, beam energy, detector response - is already leg...
- Chapter 13 (What an X-ray is): The ray was a wave after all - light of a wavelength a thousand times shorter than the eye can see, sitting on the electromagnetic spectrum between ultraviolet and the g...
- Chapter 14 (Braking light and fingerprints): ## Chapter 14 - Braking light and fingerprints An X-ray tube's output is not one ray but a spectrum, and the spectrum is built by two different accidents of physics in t...
- Chapter 14 (Braking light and fingerprints): Set the tube to 80 kilovolts and no photon can exceed 80 kilo-electron-volts; the cutoff is set by the machine's dial, and that dial, the kilovoltage, is the radiographe...
- Chapter 14 (Braking light and fingerprints): Change the anode metal and the spikes move: molybdenum's lines lie near 17 and 20 kilo-electron-volts, exactly where soft-tissue imaging wants them, which is why mammogr...
- Chapter 15 (What the ray meets): Gustav Bucky invented it in 1913; Hollis Potter improved its geometry in 1920 by moving the grid during exposure to blur out its own lines; radiographers still speak of ...
- Chapter 17 (The gas-tube era): The electrons came from the gas itself: the high voltage ionised the few remaining air molecules, the positive ions slammed into the cathode and knocked electrons free, ...
- Chapter 17 (The gas-tube era): Radiography in the gas-tube era was a negotiation with the apparatus, and the men who were good at it - and they were mostly men with burns to prove it - were valued as ...
- Chapter 18 (Coolidge's wire): What has changed around his core is everything else - target, housing, bearings, cooling, control - and the story of those changes is the story of fighting the tube's gr...
- Chapter 19 (The anode problem): The history of X-ray-tube engineering is, in large part, the history of managing that one hot spot without melting the machine .
- Chapter 19 (The anode problem): The apparent focal spot could be a millimetre square while the real bombarded strip was ten times as long - sharp pictures at high loading .
- Chapter 19 (The anode problem): CT has driven the genre to extremes - tubes rated to dissipate megajoules per scan, anodes with graphite heatsinks brazed to the disc, liquid-metal bearings to quieten a...
- Chapter 20 (The hundred-thousand-volt supply): The generator's own history runs in three generations .
- Chapter 20 (The hundred-thousand-volt supply): The mobile machine was a trolley of lead-acid accumulators and hope .
- Chapter 20 (The hundred-thousand-volt supply): The smartphone-era descendant is the battery-powered handheld X-ray unit weighing a couple of kilograms - a thing the men of 1896, wrestling induction coils onto horse-d...

- Chapter 31 (The tooth's portrait): The operatory X-ray set is also a design study in miniaturisation: a short tube on a counterweighted arm, aimed by a lined-up cone, driven by the same tungsten physics a...
- Chapter 50 (Tungsten): In the X-ray tube it found its calling: the devourer of electrons, spitting photons .
- Chapter 69 (The healing beam): The Coolidge tube's grandchild, in other words, delivers the cure the gas tubes promised and could not safely give .
- Chapter 69 (The healing beam): Diagnosis and cure, separated for a century into two departments, are converging again on the shared physics this book describes .

[X6] X-ray sources: 125 years of developments, Physica Medica 2020

https://www.physicamedica.com/article/S1120-1797(20)30233-6/fulltext

Use: read in full (fetch_F).

Cited for:

- Chapter 14 (Braking light and fingerprints): ## Chapter 14 - Braking light and fingerprints An X-ray tube's output is not one ray but a spectrum, and the spectrum is built by two different accidents of physics in t...
- Chapter 14 (Braking light and fingerprints): In 1915 he was killed at Gallipoli, and the Royal Society's rule against awarding Nobel prizes posthumously was not bent for him; physicists have counted his loss among ...
- Chapter 17 (The gas-tube era): William David Coolidge, a chemist at the General Electric Research Laboratory in Schenectady, supplied it - by way of light bulbs, of all things .
- Chapter 18 (Coolidge's wire): For the first time an X-ray machine could be prescribed - 70 kilovolts, 100 milliamperes, half a second - and the prescription would be the same tomorrow as today .
- Chapter 18 (Coolidge's wire): Exposures that had run to minutes fell to fractions of a second; moving organs could be frozen; bedside machines became practical; and during the First World War, armies...
- Chapter 18 (Coolidge's wire): What has changed around his core is everything else - target, housing, bearings, cooling, control - and the story of those changes is the story of fighting the tube's gr...
- Chapter 19 (The anode problem): The history of X-ray-tube engineering is, in large part, the history of managing that one hot spot without melting the machine .
- Chapter 19 (The anode problem): CT has driven the genre to extremes - tubes rated to dissipate megajoules per scan, anodes with graphite heatsinks brazed to the disc, liquid-metal bearings to quieten a...
- Chapter 20 (The hundred-thousand-volt supply): The mobile machine was a trolley of lead-acid accumulators and hope .

[X8] ORAU Museum: Coolidge X-Ray Tubes

https://www.orau.org/health-physics-museum/collection/x-ray-tubes/coolidge.html

Use: read in full (fetch_C).

Cited for:

- Chapter 5 (The glassblower's art): Strip the electronics from a modern tube, and what remains is recognisably the object the Würzburg glassblowers would have known .
- Chapter 14 (Braking light and fingerprints): The console is a spectrum-shaping instrument disguised as three knobs, and the physics chapters of this book are, in a sense, its manual .
- Chapter 17 (The gas-tube era): The electrons came from the gas itself: the high voltage ionised the few remaining air molecules, the positive ions slammed into the cathode and knocked electrons free, ...
- Chapter 17 (The gas-tube era): Radiography in the gas-tube era was a negotiation with the apparatus, and the men who were good at it - and they were mostly men with burns to prove it - were valued as ...
- Chapter 17 (The gas-tube era): William David Coolidge, a chemist at the General Electric Research Laboratory in Schenectady, supplied it - by way of light bulbs, of all things .
- Chapter 17 (The gas-tube era): (and 1 further passages in the same chapter)

- Chapter 18 (Coolidge's wire): For the first time an X-ray machine could be prescribed - 70 kilovolts, 100 milliamperes, half a second - and the prescription would be the same tomorrow as today .
- Chapter 18 (Coolidge's wire): By that test, 1913 was the machine's true founding year .
- Chapter 19 (The anode problem): Every quiet click of the exposure switch is the end of that riddle, solved again .
- Chapter 34 (The ray goes to war): The other armies built their own services; the Coolidge tube had arrived just in time to make front-line radiography dependable rather than experimental .
- Chapter 50 (Tungsten): Even the word "target" in tube physics has come to mean the tungsten button at the heart of everything .
- Chapter 50 (Tungsten): Tungsten entered technology as the lamp filament - Coolidge's ductile-tungsten process, the very work that led him to the X-ray tube, was done for General Electric's lig...

[X9] Early victims of X-rays - PMC3520298

https://pmc.ncbi.nlm.nih.gov/articles/PMC3520298/

Use: read in full.

Cited for:

- Prologue: The same rays that revealed the bullet in the soldier's arm burned the hands of the men who held the apparatus, and the first half-century of radiology is shadowed by a ...
- Chapter 8 (The year the world changed): Battlefield surgeons took the machine to war within three years of the discovery: by the Spanish-American War of 1898 military radiography was routine, and by the First ...
- Chapter 8 (The year the world changed): Thomas Edison, whose laboratory had plunged into fluoroscope development, abandoned the work in 1903 after his assistant Clarence Dally was burned too badly to continue;...
- Chapter 17 (The gas-tube era): The gas tube could never have made that promise, and its era's burns are partly the price of that failure .
- Chapter 21 (Shadows on glass): The patient paid less dose for every picture; the screen is one of the quietest life-savers in the machine's history .
- Chapter 21 (Shadows on glass): The fluoroscope survived its maker's remorse and became the eye of interventional medicine, once it had been made safe enough to look through .
- Chapter 29 (Two special machines): ## Chapter 29 - Two special machines Two branches of medicine built their own X-ray machines, tuned so specifically to their anatomy that they form distinct industries: ...
- Chapter 29 (Two special machines): The installed base is enormous, the unit price small, the manufacturers a different set of specialists - Planmeca of Finland, Dentsply Sirona, Carestream Dental, Vatech ...
- Chapter 31 (The tooth's portrait): Otto Walkhoff's twenty-five-minute self-exposure of January 1896 - the "torture" he described - was the first dental radiograph, and the mouth has been the machine's mos...
- Chapter 36 (The burns): Because nothing was felt during exposure - no heat, no sting - most operators dismissed the reports, or blamed the electricity, the ultraviolet, the ozone, anything but ...
- Chapter 36 (The burns): The early operators received in a week what a modern radiation worker is permitted in a career .
- Chapter 37 (The martyrs): It is probably the only monument in the world raised by a profession to the victims of its own instrument .
- Chapter 37 (The martyrs): Elizabeth Fleischman of San Francisco, a bookkeeper's daughter who taught herself radiography in 1896 and became the most accomplished X-ray operator on the American Pac...
- Chapter 37 (The martyrs): Every interlock and lead apron in a radiology department is, in a direct line, a name on that stone .

[X10] Clarence Madison Dally - Wikipedia

https://en.wikipedia.org/wiki/Clarence_Madison_Dally

Use: read in full.

Cited for:

- Prologue: The same rays that revealed the bullet in the soldier's arm burned the hands of the men who held the apparatus, and the first half-century of radiology is shadowed by a ...
- Chapter 8 (The year the world changed): Thomas Edison, whose laboratory had plunged into fluoroscope development, abandoned the work in 1903 after his assistant Clarence Dally was burned too badly to continue;...
- Chapter 15 (What the ray meets): The body, irradiated, quietly announces what it is made of .
- Chapter 21 (Shadows on glass): The fluoroscope survived its maker's remorse and became the eye of interventional medicine, once it had been made safe enough to look through .
- Chapter 37 (The martyrs): Elizabeth Fleischman of San Francisco, a bookkeeper's daughter who taught herself radiography in 1896 and became the most accomplished X-ray operator on the American Pac...

[X13] Marie Curie - War Duty (1914-1919), AIP

https://history.aip.org/exhibits/curie/war1.htm

Use: read in full (fetch_C).

Cited for:

- Chapter 4 (The photographic alliance): The film era of Chapter 22 was built on their coating lines .
- Chapter 8 (The year the world changed): Battlefield surgeons took the machine to war within three years of the discovery: by the Spanish-American War of 1898 military radiography was routine, and by the First ...
- Chapter 18 (Coolidge's wire): Exposures that had run to minutes fell to fractions of a second; moving organs could be frozen; bedside machines became practical; and during the First World War, armies...
- Chapter 21 (Shadows on glass): The digital machine's forgiving retake culture is built on the abolition of all that skill; whether something was lost with it is a question the old radiographers still ...
- Chapter 21 (Shadows on glass): Transitions in the machine's history are never clean; they are sedimentary, each era's technology lying over the last .
- Chapter 22 (The film years): The darkroom was the radiology department's beating heart, and its red light and chemical smell defined the machine's world for three generations .
- Chapter 22 (The film years): The screen-film combination was tuned for a century: faster screens, finer grain, rarer earths, until the pair achieved a sensitivity the pioneers would have thought imp...
- Chapter 22 (The film years): The machine's memory is digital now; its tongue is still silver halide .
- Chapter 34 (The ray goes to war): By late October 1914 the first of twenty radiology vehicles was at the front; the poilus called them the petites Curies, the little Curies .
- Chapter 34 (The ray goes to war): Between the vans and the posts, over a million wounded men were X-rayed on the Allied side by war's end .
- Chapter 34 (The ray goes to war): Every ambulance bay and every field hospital in this book is built on her arithmetic .
- Chapter 34 (The ray goes to war): (and 1 further passages in the same chapter)

[X14] How Marie Curie Brought X-Ray Machines to the Battlefield, Smithsonian

https://www.smithsonianmag.com/history/how-marie-curie-brought-x-ray-machines-battlefield-180965058/

Use: read in full (fetch_C).

Cited for:

- Chapter 8 (The year the world changed): Battlefield surgeons took the machine to war within three years of the discovery: by the Spanish-American War of 1898 military radiography was routine, and by the First ...
- Chapter 18 (Coolidge's wire): Exposures that had run to minutes fell to fractions of a second; moving organs could be frozen; bedside machines became practical; and during the First World War, armies...
- Chapter 23 (The living screen): The flat panel shows more and shows it bigger; whether it teaches the eye the same fluency is a debate the older radiologists have not finished having .

- Chapter 23 (The living screen): The darkened fluoroscopy room, with its red-lit figures leaning into the screen, was the machine's most theatrical workplace until the catheter laboratory inherited the ...

[X16] How CT happened: early development of medical CT, PMC8555965

https://pmc.ncbi.nlm.nih.gov/articles/PMC8555965/

Use: read in full (fetch_F).

Cited for:

- Chapter 1 (The electricians of nothing): When Röntgen needed a tube in 1895 he did not build one; he bought them, from the established trade, and the trade's cumulative skill - in sealing platinum through glass...
- Chapter 1 (The electricians of nothing): Eugen Goldstein, in Berlin, gave the phenomenon its name in 1876: Kathodenstrahlen, cathode rays .
- Chapter 15 (What the ray meets): Hounsfield's great step in computed tomography, described in Chapter 36, was to put a scale on those numbers, with water at zero and air at minus a thousand, and the sca...
- Chapter 18 (Coolidge's wire): By 1911 GE's lamps ran on Coolidge wire, and the ductile-tungsten process became one of the foundations of twentieth-century electrical industry .
- Chapter 18 (Coolidge's wire): For the first time an X-ray machine could be prescribed - 70 kilovolts, 100 milliamperes, half a second - and the prescription would be the same tomorrow as today .
- Chapter 28 (The slice): The solution - scan the head from many angles and let a computer solve for the interior - was arrived at independently by a South African physicist and an English engine...
- Chapter 28 (The slice): The cyst showed .
- Chapter 28 (The slice): Spiral CT in 1989 let the table move continuously through the gantry; multislice arrays from 1998 turned one revolution into many slices; dual-source and wide-detector m...

[X19] Shoe-fitting fluoroscope - Wikipedia

https://en.wikipedia.org/wiki/Shoe-fitting_fluoroscope

Use: read in full.

Cited for:

- Chapter 38 (The shoe shop): Some models offered three intensities: highest for men, middle for women, lowest for children .
- Chapter 38 (The shoe shop): For thirty years the machine was a sales feature: it turned a squirming child's fitting into scientific theatre, and it flattered the modern shoe shop's claim to precisi...
- Chapter 38 (The shoe shop): The last recorded working shoe-fitting fluoroscope was spotted in Boston - where it had begun - in the late 1970s .
- Chapter 39 (Measuring the invisible): Occupational limits settled at 20 millisieverts a year averaged over five years; the public limit at 1; and the machine was redesigned around the ledger - filtration, co...

[X20] ORAU Museum: Shoe-fitting fluoroscope

https://www.orau.org/health-physics-museum/collection/shoe-fitting-fluoroscope/

Use: read in full (fetch_C).

Cited for:

- Chapter 36 (The burns): Standardisation was impossible until measurement existed - which is why the unit-makers of Chapter 40 were not pedants but first responders to an invisible fire .
- Chapter 36 (The burns): Regulation, when it came, was written over those cases .
- Chapter 38 (The shoe shop): Some models offered three intensities: highest for men, middle for women, lowest for children .
- Chapter 38 (The shoe shop): For thirty years the machine was a sales feature: it turned a squirming child's fitting into scientific theatre, and it flattered the modern shoe shop's claim to precisi...

- Chapter 38 (The shoe shop): The last recorded working shoe-fitting fluoroscope was spotted in Boston - where it had begun - in the late 1970s .

[X22] Radiography - Wikipedia

https://en.wikipedia.org/wiki/Radiography

Use: read in full.

Cited for:

- Chapter 8 (The year the world changed): Battlefield surgeons took the machine to war within three years of the discovery: by the Spanish-American War of 1898 military radiography was routine, and by the First ...
- Chapter 8 (The year the world changed): Within a year of Würzburg there were X-ray departments, X-ray journals (the Archives of Clinical Skiagraphy appeared in London in 1896, the American X-Ray Journal in 189...
- Chapter 13 (What an X-ray is): That is ionisation, and it is the root of both the machine's power and its danger: ionisation in a photographic plate or a detector pixel records the image, and ionisati...
- Chapter 13 (What an X-ray is): Without it the ray would pass through everything alike and record nothing .
- Chapter 14 (Braking light and fingerprints): Set the tube to 80 kilovolts and no photon can exceed 80 kilo-electron-volts; the cutoff is set by the machine's dial, and that dial, the kilovoltage, is the radiographe...
- Chapter 14 (Braking light and fingerprints): It is the smallest and cheapest safety device in the machine, and its logic - cut the photons that cannot help - is the logic of the whole mature art .
- Chapter 15 (What the ray meets): Two interactions dominate the diagnostic range .
- Chapter 15 (What the ray meets): The steep atomic-number dependence is what gives the radiograph its natural contrast - bone white, tissue grey, air black - and what makes iodine (53) and barium (56) su...
- Chapter 15 (What the ray meets): Gustav Bucky invented it in 1913; Hollis Potter improved its geometry in 1920 by moving the grid during exposure to blur out its own lines; radiographers still speak of ...
- Chapter 15 (What the ray meets): (and 1 further passages in the same chapter)
- Chapter 21 (Shadows on glass): The chemistry was borrowed wholesale from photography, and the great photographic firms became, without much noticing it, the first imaging-component industry of the X-r...
- Chapter 21 (Shadows on glass): The patient paid less dose for every picture; the screen is one of the quietest life-savers in the machine's history .
- Chapter 23 (The living screen): Two inventions ended the dark age .
- Chapter 23 (The living screen): The radiologist stepped out of the beam's path and out of the dark; the procedure room filled with people watching a screen .
- Chapter 24 (Film to pixels): The transition came in two steps .
- Chapter 24 (Film to pixels): Hospitals could go digital without changing a single cassette habit, and CR spread through the 1980s and 1990s as the bridge technology, carrying the world's radiology d...
- Chapter 24 (Film to pixels): The same panels, mounted in the C-arm and the angiography suite, displaced the image intensifier in turn; the fluoroscopy chain went flat-panel digital in the 2010s .
- Chapter 25 (Painting the soft parts): The escape was to put contrast into the patient: to fill a hollow structure with something the ray cannot pass, or with something it passes too easily, and photograph th...
- Chapter 25 (Painting the soft parts): The early iodinated agents were vicious - sodium iodide burned, and the first organic compounds carried risks of their own - but chemistry through the mid-century produc...
- Chapter 26 (The painted shadows): The element is chosen for its atomic number: barium at 56 and iodine at 53 stop diagnostic X-rays far better than the carbon-and-water body around them .
- Chapter 26 (The painted shadows): Modern power injectors synchronise with the gantry to the second; the patient feels a wave of warmth and a metallic taste, and the machine takes its pictures on the hear...
- Chapter 26 (The painted shadows): When the angiogram's painted tree of vessels appears on the screen, it is worth remembering that the image is half machine, half ink - and that the ink, like the ray, wa...
- Chapter 26 (The painted shadows): (and 1 further passages in the same chapter)
- Chapter 37 (The martyrs): It is a census .

- Chapter 37 (The martyrs): The memorial in Hamburg is stone; the memorial that matters is the habit .
- Chapter 38 (The shoe shop): The machine has always lived partly on wonder; the shoe shop teaches what happens when wonder is the only product .
- Chapter 39 (Measuring the invisible): These are the numbers with which the machine's cost-benefit is now argued, and the public equivalents - "as much as so many chest films" - are how radiologists explain r...
- Chapter 60 (Bones of the past): Anything old and opaque that cannot be opened - a mummy, a fossil in its matrix, a painting, a sealed reliquary - is exactly the patient the X-ray machine was built for,...
- Chapter 84 (The museum of machines): In Würzburg, the laboratory itself is preserved near the modern institute that bears his name; in Hamburg, the martyrs' memorial stands in the hospital garden, as Chapte...
- Chapter 84 (The museum of machines): To walk the galleries is to watch an industry learn a lethal lesson in real time .
- Chapter 84 (The museum of machines): The museum's truest exhibit is that silence .

[X23] Fluoroscopy - Wikipedia

https://en.wikipedia.org/wiki/Fluoroscopy

Use: read in full.

Cited for:

- Chapter 23 (The living screen): Two inventions ended the dark age .
- Chapter 23 (The living screen): The radiologist stepped out of the beam's path and out of the dark; the procedure room filled with people watching a screen .
- Chapter 23 (The living screen): The market around it - fixed angiography suites at the top, mobile C-arms in the middle, mini C-arms for extremity work at the bottom - is a distinct industry in its own...
- Chapter 27 (The catheter's eye): Each step raised the demands on the machine: digital subtraction angiography, which photographs the vessels before and during contrast and subtracts the bone away pixel ...

[X24] CT scan - Wikipedia

https://en.wikipedia.org/wiki/CT_scan

Use: read in full.

Cited for:

- Chapter 3 (The coil and the spark): Many a hospital's first X-ray room housed both, and an operator who could read the weather in them .
- Chapter 4 (The photographic alliance): Across Europe and America, photographic studios added radiography to their trade, and the first X-ray images of whole cities' worth of bones were made by portraitists wh...
- Chapter 4 (The photographic alliance): When the radiographers' profession later formed, it inherited more than technique from the studios - it inherited a craftsmanly pride in the image itself, the conviction...
- Chapter 5 (The glassblower's art): When a tube cracked, which they did with theatrical regularity, the lab's glassblower earned his week .
- Chapter 8 (The year the world changed): The machine's whole subsequent history - its physics chapters, its industry chapters, its clinical chapters, its chapters of wonder - is those four visions still competi...
- Chapter 11 (The patent that wasn't): The firms that survived the shakeout - the RGS, the Siemens and General Electric operations, the Victor Electric that GE would absorb - were the ones whose machines work...
- Chapter 15 (What the ray meets): Hounsfield's great step in computed tomography, described in Chapter 36, was to put a scale on those numbers, with water at zero and air at minus a thousand, and the sca...
- Chapter 25 (Painting the soft parts): The early iodinated agents were vicious - sodium iodide burned, and the first organic compounds carried risks of their own - but chemistry through the mid-century produc...
- Chapter 27 (The catheter's eye): Each step raised the demands on the machine: digital subtraction angiography, which photographs the vessels before and during contrast and subtracts the bone away pixel ...

- Chapter 28 (The slice): The solution - scan the head from many angles and let a computer solve for the interior - was arrived at independently by a South African physicist and an English engine...
- Chapter 28 (The slice): The cyst showed .
- Chapter 28 (The slice): Spiral CT in 1989 let the table move continuously through the gantry; multislice arrays from 1998 turned one revolution into many slices; dual-source and wide-detector m...
- Chapter 28 (The slice): (and 3 further passages in the same chapter)
- Chapter 29 (Two special machines): The specialties are the machine's dialects, and the general radiographer learns them as languages - same grammar, different vocabulary, lifelong fluency .
- Chapter 44 (The first factories): Between the scientific paper and the patent, the catalogue is the third document of the machine's growth, and often the most honest: it lists what could be bought, which...
- Chapter 44 (The first factories): The machine was a world industry within a decade of its birth - perhaps the first medical technology to achieve that, and the template for every one that followed .
- Chapter 60 (Bones of the past): Tutankhamun's mummy was CT-scanned in the Valley of the Kings in 2005; animal mummies, fossils, bog bodies and the Herculaneum scrolls - carbonised papyri read by X-ray ...
- Chapter 60 (Bones of the past): The dead and the painted are, in a sense, the machine's ideal patients - infinitely patient themselves .
- Chapter 69 (The healing beam): Diagnosis and cure, separated for a century into two departments, are converging again on the shared physics this book describes .
- Chapter 70 (The trauma bay's eye): The trauma bay runs on a doctrine in which imaging is sequenced like firefighting: the chest and pelvis films in the first minutes, because the bleeding chest and the sh...
- Chapter 70 (The trauma bay's eye): The radiographer in the trauma bay works to a standard the pioneers would not have believed: images of diagnostic quality taken through spine boards and oxygen tubing, o...
- Chapter 70 (The trauma bay's eye): The trauma bay is the purest expression of that principle the machine has ever been given .
- Chapter 70 (The trauma bay's eye): (and 2 further passages in the same chapter)
- Chapter 73 (Grey to gold): CT adds the whole third dimension: multiplanar reformatting, maximum-intensity projections that light up vessels, volume renderings that turn a stack of slices into a su...

[X25] Mammography - Wikipedia

https://en.wikipedia.org/wiki/Mammography

Use: read in full.

Cited for:

- Chapter 14 (Braking light and fingerprints): Change the anode metal and the spikes move: molybdenum's lines lie near 17 and 20 kilo-electron-volts, exactly where soft-tissue imaging wants them, which is why mammogr...
- Chapter 15 (What the ray meets): The steep atomic-number dependence is what gives the radiograph its natural contrast - bone white, tissue grey, air black - and what makes iodine (53) and barium (56) su...
- Chapter 25 (Painting the soft parts): The escape was to put contrast into the patient: to fill a hollow structure with something the ray cannot pass, or with something it passes too easily, and photograph th...
- Chapter 25 (Painting the soft parts): The early iodinated agents were vicious - sodium iodide burned, and the first organic compounds carried risks of their own - but chemistry through the mid-century produc...
- Chapter 29 (Two special machines): ## Chapter 29 - Two special machines Two branches of medicine built their own X-ray machines, tuned so specifically to their anatomy that they form distinct industries: ...
- Chapter 29 (Two special machines): Screening mammography is now one of the largest single uses of the medical X-ray machine, and its champion manufacturer, Hologic of Massachusetts, built a Fortune-list c...
- Chapter 29 (Two special machines): The specialties are the machine's dialects, and the general radiographer learns them as languages - same grammar, different vocabulary, lifelong fluency .
- Chapter 30 (The softest ray): Where a chest film wants a hard, penetrating beam, mammography wants the softest usable rays: tube voltages around 30 kVp, targets of molybdenum or rhodium whose charact...

- Chapter 30 (The softest ray): And the modern machine adds a third dimension: tomosynthesis swings the tube in an arc and reconstructs thin slices of the breast, freeing lesions from the overlapping t...
- Chapter 30 (The softest ray): Preventive Services Task Force recommends biennial screening from forty to seventy-four; the American College of Radiology urges yearly screening from forty; Canadian an...
- Chapter 30 (The softest ray): (and 2 further passages in the same chapter)
- Chapter 47 (The detector industry): The mammography suite's detectors are built for the sharpest image in radiology, bought with the simplest physics .
- Chapter 71 (The screening net): The answers have been fought over for half a century, and the fighting has made the machine better .
- Chapter 71 (The screening net): Mammography's screening programmes, argued about in every decade, remain the model of a screening debate done honestly - benefit weighed against overdiagnosis in public .

[X26] Backscatter X-ray - Wikipedia

https://en.wikipedia.org/wiki/Backscatter_X-ray

Use: read in full.

Cited for:

- Chapter 38 (The shoe shop): The machine has always lived partly on wonder; the shoe shop teaches what happens when wonder is the only product .
- Chapter 57 (The checkpoint): The epidemic of aircraft hijackings around 1970 forced systematic passenger screening; by the early 1970s the United States had made screening of all carry-on baggage co...
- Chapter 57 (The checkpoint): The epidemic of aircraft hijackings around 1970 forced systematic passenger screening; by the early 1970s the United States had made screening of all carry-on baggage co...
- Chapter 57 (The checkpoint): Transportation Security Administration awarded contracts worth up to $1.3 billion for up to 1,214 checkpoint CT units from Analogic, IDSS and Smiths Detection - machines...
- Chapter 57 (The checkpoint): (and 3 further passages in the same chapter)
- Chapter 58 (The container's shadow): Transmission radiography - the container's silhouette, dense cargo standing out dark - answers "what is in there"; dual-energy systems add "what is it made of", separati...

[X27] Industrial radiography - Wikipedia

https://en.wikipedia.org/wiki/Industrial_radiography

Use: read in full.

Cited for:

- Chapter 47 (The detector industry): The hospital, as so often in this book, is one customer among many for a technology the ray made possible .
- Chapter 55 (Welds, wings and pipelines): By the early 1900s the machinery trade was radiographing castings and welds, and the technique grew with the things that could not be allowed to fail: boilers, ships' pl...
- Chapter 55 (Welds, wings and pipelines): The detectors are the same lineage: film in cassettes first (industrial film radiography persists for its resolution), then computed radiography plates, then digital det...
- Chapter 55 (Welds, wings and pipelines): The market for all of this is modest next to medicine - industrial radiography equipment runs under a billion dollars a year by the standard counts - but it is the oldes...
- Chapter 84 (The museum of machines): In Würzburg, the laboratory itself is preserved near the modern institute that bears his name; in Hamburg, the martyrs' memorial stands in the hospital garden, as Chapte...

[X28] X-ray machine - Wikipedia

https://en.wikipedia.org/wiki/X-ray_machine

Use: read in full.

Cited for:

- Chapter 13 (What an X-ray is): Without it the ray would pass through everything alike and record nothing .
- Chapter 15 (What the ray meets): Two interactions dominate the diagnostic range .
- Chapter 15 (What the ray meets): Diagnostic machines never reach it; it belongs to radiation therapy and to the gamma cameras of nuclear medicine, which this book deliberately leaves to another volume -...
- Chapter 20 (The hundred-thousand-volt supply): The generator's own history runs in three generations .
- Chapter 20 (The hundred-thousand-volt supply): Large installations added static machines and, later, high-voltage transformers, but the output was always a swinging waveform, so the tube idled through the low parts o...
- Chapter 20 (The hundred-thousand-volt supply): The smartphone-era descendant is the battery-powered handheld X-ray unit weighing a couple of kilograms - a thing the men of 1896, wrestling induction coils onto horse-d...
- Chapter 55 (Welds, wings and pipelines): The machine's industrial chapters are, at bottom, about the price of not looking .
- Chapter 55 (Welds, wings and pipelines): The machine makes one kind of reader everywhere it goes; only the anatomy changes .

[X29] GE HealthCare Q4/FY2024 results

https://www.gehealthcare.com/about-us/newsroom

Use: read in full (fetch_D).

Cited for:

- Chapter 25 (Painting the soft parts): The supply fragility showed itself in 2022, when pandemic restrictions disrupted a concentrated supply chain and created a worldwide shortage of contrast medium, forcing...
- Chapter 45 (The modern giants): Hologic, built on mammography, holds the breast-imaging niche worldwide .

[X30] TSA awards up to $1.3B for CT X-ray checkpoint scanners

https://www.tsa.gov/news/press/releases/2023/03/02/tsa-awards-13-billion-procure-additional-ct-x-ray-scanners

Use: read in full (fetch_D).

Cited for:

- Chapter 48 (What the machine weighs): Around the machines sit the adjacent trades: flat-panel detectors, a market in the low single-digit billions; X-ray tubes, a few hundred million of OEM and replacement b...
- Chapter 57 (The checkpoint): Transportation Security Administration awarded contracts worth up to $1.3 billion for up to 1,214 checkpoint CT units from Analogic, IDSS and Smiths Detection - machines...
- Chapter 57 (The checkpoint): Its machines are cousins of the hospital's, engineered for different anatomy: the anatomy of a bomb .

[X31] Shimadzu medical systems history

https://www.shimadzu.com/medical/history/

Use: read in full.

Cited for:

- Chapter 17 (The gas-tube era): Müller - Geissler's heir in the glassware trade - was blowing focus tubes of exceptional quality; in Dresden, Koch & Sterzel built elegant apparatus; in Chicago, the Vic...
- Chapter 41 (The dose ledger): That is what progress looks like when it is kept honestly: not a smaller number, but a truer book .
- Chapter 44 (The first factories): In Japan, Shimadzu of Kyoto took its first X-ray photographs in 1896 and industrialised from there; Toshiba built X-ray capability on its electrical base; and the Shimad...
- Chapter 74 (The wired archive): The wired archive is, among other things, the dose ledger's bookkeeper - the machine watching itself, at last, as closely as it watches the patient .

[X32] WHO: To X-ray or not to X-ray?

https://www.who.int/news-room/feature-stories/detail/to-x-ray-or-not-to-x-ray-

Use: read in full.

Cited for:

- Prologue: No other instrument has made the inside of the living body legible at such speed and at such scale - more than three and a half billion examinations a year now begin wit...
- Epilogue: But the honest monument is elsewhere - in the casualty department at 3 a.m., in the shipyard's weld bay, in the checkpoint queue, in the shipping container's scanned wal...
- Chapter 29 (Two special machines): The special examinations are where the machine's generalities are negotiated, one body at a time .
- Chapter 33 (The small patients): WHO counts some 350 million paediatric examinations a year among the world's 3.6 billion - every one of them a judgement call made on a child who cannot make it .
- Chapter 33 (The small patients): The referral conversation matters most of all, and WHO's guidance is blunt: an unjustified scan on a child is not caution, it is harm .
- Chapter 33 (The small patients): In the ledger of the beam, the children's column drove the arithmetic for everyone .
- Chapter 33 (The small patients): (and 2 further passages in the same chapter)
- Chapter 35 (The beam at sea): The examination that takes three minutes ashore may take twenty at sea - and still arrive at the reading station before the patient has been wheeled out .
- Chapter 39 (Measuring the invisible): The machine has become so safe per picture that its aggregate use is the remaining problem: justification of each examination, not fear of any one of them, is the modern...
- Chapter 40 (The naming of dose): The background comparison - invented to calm the worried - has become the profession's own mental arithmetic, and perhaps the only dose unit the public will ever hold .
- Chapter 41 (The dose ledger): WHO's guidance puts the failure mode plainly: patients and referrers who do not understand the trade can refuse a CT that is needed or demand one that is not justified, ...
- Chapter 41 (The dose ledger): The profession's answer is the referral culture WHO campaigns for: referrers who know the dose and the benefit, patients who are told both, records that follow the patie...
- Chapter 41 (The dose ledger): A dose culture is not a rule but a comparison, endlessly renewed .
- Chapter 45 (The modern giants): Its rise - alongside a tier of Chinese radiography specialists such as Wandong and the detector maker iRay - has changed the industry's geography: China is no longer onl...
- Chapter 46 (The tube merchants): The investigation jolted the shares of GE HealthCare and Varex on announcement, a rare moment when the tube trade made front-page market news .
- Chapter 48 (What the machine weighs): But its position is disproportionate to its size: it is the entry point of nearly all modern diagnosis, the largest man-made source of population radiation exposure, and...
- Chapter 48 (What the machine weighs): But its position is disproportionate to its size: it is the entry point of nearly all modern diagnosis, the largest man-made source of population radiation exposure, and...
- Chapter 48 (What the machine weighs): The machine's economics, like its physics, are a study in scale: an expensive instrument, amortised into the cheapest window into the human body that medicine has ever h...
- Chapter 64 (Billions of shadows): ## Chapter 64 - Billions of shadows The scale of the machine's present work is easiest to state as a number, and the number is almost past imagining: about 3.6 billion d...
- Chapter 64 (Billions of shadows): Roughly three hundred and fifty million of those examinations are performed on children under fifteen .
- Chapter 64 (Billions of shadows): It hums, clicks, and moves to the next patient - three and a half billion times a year, one shadow at a time .
- Chapter 65 (The access divide): At Mengo Hospital in Kampala, radiologist Michael Kawooya spends part of every clinic explaining to patients what the machine is and is not - that an ultrasound carries ...
- Chapter 65 (The access divide): Where the machine is rare, knowledge about it is rarer still; WHO's radiation-safety programmes in the region train referrers and radiographers together, because an acce...

- Chapter 65 (The access divide): The chapters of this book that celebrate its reach should be read with this one open beside them: reach, for most of humanity, is still the unfinished part of the story .
- Chapter 65 (The access divide): (and 2 further passages in the same chapter)
- Chapter 67 (The pandemic machine): The portable X-ray machine, trundled to the isolation bedside, did work no laboratory test could do at the speed the crisis demanded .
- Chapter 67 (The pandemic machine): Workforce: radiographers worked in full protective equipment, cleaning a detector between patients while the queue lengthened, and the profession's shortage deepened in ...
- Chapter 67 (The pandemic machine): The machine emerged from 2020-22 as it emerged from 1914-18: tested at scale, trusted more broadly, and busier than ever .
- Chapter 67 (The pandemic machine): (and 2 further passages in the same chapter)
- Chapter 71 (The screening net): The answers have been fought over for half a century, and the fighting has made the machine better .
- Chapter 71 (The screening net): Chest radiography carried the tuberculosis campaigns of the mid-twentieth century, when mobile units toured whole towns and miniature films were read by the million; the...
- Chapter 71 (The screening net): The dose ledger of Chapter 41 is never more carefully kept than here .
- Chapter 71 (The screening net): (and 2 further passages in the same chapter)
- Chapter 77 (The patient's three minutes): Then the room itself - colder than expected, because the machine's electronics like the cold - and a stranger's hands positioning an arm, a shoulder, a chest against the...
- Chapter 77 (The patient's three minutes): Then it is done, and the anticlimax is total: no picture shown, no answer given, just "the radiologist will report to your doctor." The image goes one way, the patient a...
- Chapter 77 (The patient's three minutes): The frightened child gets the decorated room and the patient radiographer; the claustrophobic get warning and rehearsal; everyone gets the right to ask about dose and to...
- Chapter 77 (The patient's three minutes): (and 2 further passages in the same chapter)
- Chapter 80 (The shrinking machine): Portable digital radiography is the backbone of active tuberculosis screening in communities far from any hospital; solar-capable systems and ruggedised detectors are bu...

[X33] Varex Imaging: global supply chain considerations

https://www.vareximaging.com/

Use: read in full (fetch_D).

Cited for:

- Chapter 11 (The patent that wasn't): The firms that survived the shakeout - the RGS, the Siemens and General Electric operations, the Victor Electric that GE would absorb - were the ones whose machines work...
- Chapter 19 (The anode problem): CT has driven the genre to extremes - tubes rated to dissipate megajoules per scan, anodes with graphite heatsinks brazed to the disc, liquid-metal bearings to quieten a...
- Chapter 19 (The anode problem): When, in later chapters, we meet the industry's supply anxieties - tungsten prices, bearing metallurgy, the handful of firms worldwide that can build a CT-grade tube - t...
- Chapter 25 (Painting the soft parts): The supply fragility showed itself in 2022, when pandemic restrictions disrupted a concentrated supply chain and created a worldwide shortage of contrast medium, forcing...
- Chapter 45 (The modern giants): Installed-base economics keep the system houses vertically hungry: they would rather build their own tubes and detectors than buy them, which is why the independent comp...
- Chapter 45 (The modern giants): Installed-base economics keep the system houses vertically hungry: they would rather build their own tubes and detectors than buy them, which is why the independent comp...
- Chapter 45 (The modern giants): Dislodging an incumbent in this industry has never been done by a better machine alone .
- Chapter 46 (The tube merchants): The X-ray tube is one of those components - like aircraft engines or float glass - whose manufacture is hard enough that the world gets by with very few makers .
- Chapter 46 (The tube merchants): The whole thing is a consumable: a hard-worked CT tube may last a year or two, and the replacement business is as important as the new one .

- Chapter 46 (The tube merchants): The system houses keep their own tube shops for the flagships: GE, Siemens, Philips and Canon all build CT tubes in-house for their premium scanners, which is why the in...

[X34] MarketsandMarkets: Diagnostic Imaging Market worth $32.90B by 2030

https://www.marketsandmarkets.com/PressReleases/diagnostic-imaging.asp

Use: read in full (fetch_E).

Cited for:

- Chapter 28 (The slice): It also carries the field's deepest dose obligations, since one CT examination delivers what hundreds of chest films would; the balancing of that equation runs through P...
- Chapter 45 (The modern giants): The league table has been remarkably stable for thirty years: Siemens Healthineers and GE HealthCare at the top, Philips and Canon Medical (the former Toshiba Medical) b...
- Chapter 45 (The modern giants): Hologic, built on mammography, holds the breast-imaging niche worldwide .
- Chapter 48 (What the machine weighs): The honest answer is a family of overlapping markets, and the cleanest reading separates the machine from its siblings .
- Chapter 48 (What the machine weighs): Around the machines sit the adjacent trades: flat-panel detectors, a market in the low single-digit billions; X-ray tubes, a few hundred million of OEM and replacement b...
- Chapter 48 (What the machine weighs): The machine's economics, like its physics, are a study in scale: an expensive instrument, amortised into the cheapest window into the human body that medicine has ever h...

[X35] Grand View Research: X-ray systems market

https://www.grandviewresearch.com/industry-analysis/x-ray-systems-market

Use: read in full (fetch_E).

Cited for:

- Chapter 45 (The modern giants): The league table has been remarkably stable for thirty years: Siemens Healthineers and GE HealthCare at the top, Philips and Canon Medical (the former Toshiba Medical) b...
- Chapter 48 (What the machine weighs): The honest answer is a family of overlapping markets, and the cleanest reading separates the machine from its siblings .
- Chapter 48 (What the machine weighs): Around the machines sit the adjacent trades: flat-panel detectors, a market in the low single-digit billions; X-ray tubes, a few hundred million of OEM and replacement b...

[X36] ASRT staffing and workplace survey 2025

https://www.asrt.org/main/news-research/research-and-surveys

Use: read in full (fetch_E).

Cited for:

- Chapter 66 (The people who make the picture): The American registry's surveys tell a story that other countries recognise: vacancy rates for imaging staff climbing to near record highs, with computed tomography hard...
- Chapter 66 (The people who make the picture): When a radiographer positions a frightened patient with one hand and reaches for the exposure switch with the other, a century of professional formation is standing in t...
- Chapter 66 (The people who make the picture): The machine's workforce, like its tungsten, is a supply chain - and it, too, can be managed or neglected .
- Chapter 66 (The people who make the picture): (and 1 further passages in the same chapter)

[X37] Reuters: China tungsten export restrictions, Feb 2025

https://www.reuters.com/markets/commodities/china-export-controls-tungsten-2025-02-04/

Use: read in full (fetch_E).

Cited for:

- Chapter 10 (The ray in India): The trajectory from Sircar's customs-house cases to an indigenous imaging industry is exactly a century, and it is one of the quiet success stories of Indian technology .
- Chapter 19 (The anode problem): When, in later chapters, we meet the industry's supply anxieties - tungsten prices, bearing metallurgy, the handful of firms worldwide that can build a CT-grade tube - t...
- Chapter 26 (The painted shadows): The painted shadows have a long shadow of their own .
- Chapter 45 (The modern giants): Dislodging an incumbent in this industry has never been done by a better machine alone .
- Chapter 46 (The tube merchants): The machine's components are barriers to entry disguised as products .
- Chapter 47 (The detector industry): The hospital, as so often in this book, is one customer among many for a technology the ray made possible .
- Chapter 48 (What the machine weighs): Competition, more than charity, is closing Chapter 65's divide - which is, in its way, the most Röntgen-like outcome the market could produce .
- Chapter 49 (The supply chain): The X-ray system on the wall is the tip of an assembly network that reaches into semiconductor fabs, scintillator foundries, glass-working shops and high-voltage compone...
- Chapter 49 (The supply chain): Only a handful of firms - the system giants' own tube divisions and independents like Varex - can build them at scale, and lead times stretch when demand surges, as it d...
- Chapter 49 (The supply chain): Varex, which sells both tubes and detectors, lists the hazards plainly: geopolitical tension over rare earths, semiconductor shortages hitting digital detector availabil...
- Chapter 49 (The supply chain): (and 2 further passages in the same chapter)
- Chapter 50 (Tungsten): China produced just over 80 per cent of the world's tungsten supply in 2023, and the United States has not mined tungsten commercially since 2015; in 2025 Beijing added ...
- Chapter 50 (Tungsten): The X-ray industry felt it immediately, because tube makers buy tungsten as precisely machined, vacuum-clean, metallurgically fussy components - not as commodity metal -...
- Chapter 51 (The tube rebuilders): That rhythm built an industry inside the industry: tube manufacturing, tube rebuilding, and the service economy that keeps the world's installed base alive .
- Chapter 51 (The tube rebuilders): The major manufacturers, meanwhile, sell not only tubes but uptime: service contracts, remote monitoring that phones home before a filament fails, exchange pools that pu...
- Chapter 51 (The tube rebuilders): Tungsten may be mined in Jiangxi and machined in a handful of specialist works, but the machine's real lifeline is the courier van with a foam-lined crate in the back - ...
- Chapter 51 (The tube rebuilders): (and 2 further passages in the same chapter)
- Chapter 52 (The second life of machines): The trade in pre-owned imaging equipment is one of global health's quietest and most effective mechanisms - and one of the machine's oldest patterns, since even the 1896...
- Chapter 52 (The second life of machines): Regulators treat the result as a device in its own right, with its own documentation - Chapter 54's rule book extends to every rebirth .
- Chapter 52 (The second life of machines): The machine's second life, like its first, is only as good as the system wrapped around it .
- Chapter 52 (The second life of machines): (and 2 further passages in the same chapter)
- Chapter 53 (The engineer's apprenticeship): Their apprenticeship is long - high-voltage safety, vacuum practice, detector calibration, the diagnostic art of hearing a bad bearing in a spinning anode - and their te...
- Chapter 53 (The engineer's apprenticeship): The service logs they keep are, in aggregate, the industry's truest quality data - the machine as it actually behaves, not as it was designed to .
- Chapter 53 (The engineer's apprenticeship): The machine that sees inside everything still needs a human to see inside it .
- Chapter 56 (The machine in the mine): In an industry chasing ever-lower grades, the machine's ability to read ore before committing to it has become a margin-maker - and a green technology, in the mining ind...
- Chapter 56 (The machine in the mine): The element that devours electrons spends some of its working life hunting its own ore - the machine eating its tail, profitably .

- Chapter 67 (The pandemic machine): Workforce: radiographers worked in full protective equipment, cleaning a detector between patients while the queue lengthened, and the profession's shortage deepened in ...

[X42] John Hall-Edwards - Wikipedia

https://en.wikipedia.org/wiki/John_Hall-Edwards

Use: listed only.

Cited for:

- Chapter 8 (The year the world changed): Battlefield surgeons took the machine to war within three years of the discovery: by the Spanish-American War of 1898 military radiography was routine, and by the First ...
- Chapter 8 (The year the world changed): Within a year of Würzburg there were X-ray departments, X-ray journals (the Archives of Clinical Skiagraphy appeared in London in 1896, the American X-Ray Journal in 189...
- Chapter 37 (The martyrs): Elizabeth Fleischman of San Francisco, a bookkeeper's daughter who taught herself radiography in 1896 and became the most accomplished X-ray operator on the American Pac...

[X45] Werner Forssmann Nobel Lecture 1956

https://www.nobelprize.org/prizes/medicine/1956/forssmann/lecture/

Use: read in full (fetch_F).

Cited for:

- Chapter 27 (The catheter's eye): Forssmann was fired for it, worked in obscurity, and in 1956 shared the Nobel Prize in Medicine for it .

[X52] MarketsandMarkets: food X-ray inspection devices to $5.08B by 2030

https://www.marketsandmarkets.com/

Use: read in full (fetch_J).

Cited for:

- Chapter 59 (The clean plate): X-ray inspection systems now stand on the packaging lines of the world's food factories, scanning every single unit of production at line speed, rejecting the contaminat...
- Chapter 59 (The clean plate): The trade's specialists are the weighing-and-inspection houses, selling into the same food factories as their metal detectors and checkweighers, with the X-ray machine w...
- Chapter 59 (The clean plate): The market context shows how far the ray has travelled from Würzburg: food inspection devices altogether - X-ray, metal detection, vision, weighing - form a market of ab...

[X59] Grand View Research: Dental X-ray Market 2024-2030

https://www.grandviewresearch.com/industry-analysis/dental-x-ray-market

Use: read in full (fetch_J).

Cited for:

- Chapter 31 (The tooth's portrait): Dental imaging is a multi-billion-dollar global market - about 2.3 billion dollars in 2023, projected roughly to double by 2030 - carried almost entirely by small privat...

Part II - Supplementary sources consulted during writing

[X-F10] C-arm market report, Market Research Future

https://www.marketresearchfuture.com/reports/c-arm-market-6912

Use: read in full.

Cited for:

- Chapter 23 (The living screen): The market around it - fixed angiography suites at the top, mobile C-arms in the middle, mini C-arms for extremity work at the bottom - is a distinct industry in its own...
- Chapter 27 (The catheter's eye): It is also where the industry's economics are richest - the suites are the flagship products of the big imaging houses, and their installation numbers are watched as a m...
- Chapter 27 (The catheter's eye): It is also where the industry's economics are richest - the suites are the flagship products of the big imaging houses, and their installation numbers are watched as a m...
- Chapter 48 (What the machine weighs): Around the machines sit the adjacent trades: flat-panel detectors, a market in the low single-digit billions; X-ray tubes, a few hundred million of OEM and replacement b...

[X-F11] Dental X-ray market, Grand View Research

https://www.grandviewresearch.com/industry-analysis/dental-x-ray-market

Use: read in full (fetch_J).

Cited for:

- Chapter 29 (Two special machines): The installed base is enormous, the unit price small, the manufacturers a different set of specialists - Planmeca of Finland, Dentsply Sirona, Carestream Dental, Vatech ...
- Chapter 48 (What the machine weighs): Around the machines sit the adjacent trades: flat-panel detectors, a market in the low single-digit billions; X-ray tubes, a few hundred million of OEM and replacement b...

[X-F12] Siemens Healthineers FY2024 results press release + Reuters coverage

https://www.siemens-healthineers.com/press/releases/q4fy2024

Use: read in full (fetch_I).

Cited for:

- Chapter 45 (The modern giants): Hologic, built on mammography, holds the breast-imaging niche worldwide .

[X-F14] MarketsandMarkets industrial X-ray + food inspection press releases

https://www.marketsandmarkets.com/

Use: read in full (fetch_J).

Cited for:

- Chapter 48 (What the machine weighs): Around the machines sit the adjacent trades: flat-panel detectors, a market in the low single-digit billions; X-ray tubes, a few hundred million of OEM and replacement b...
- Chapter 55 (Welds, wings and pipelines): The market for all of this is modest next to medicine - industrial radiography equipment runs under a billion dollars a year by the standard counts - but it is the oldes...

[X-F15] Industrial radiography technology trends review, PMC12637113

https://pmc.ncbi.nlm.nih.gov/articles/PMC12637113/

Use: read in full.

Cited for:

- Chapter 55 (Welds, wings and pipelines): The detectors are the same lineage: film in cassettes first (industrial film radiography persists for its resolution), then computed radiography plates, then digital det...

[X-F20] UN News (citing PAHO), 8 Nov 2012: two-thirds of the population lack access to diagnostic imaging

https://news.un.org/es/story/2012/11/1256771

Use: headline verified verbatim; article body not extractable (JS-rendered).

Cited for:

- Chapter 65 (The access divide): In 2012 the Pan American Health Organization stated bluntly that two-thirds of the world's population lacked access to diagnostic imaging - and more than a decade of pro...
- Chapter 65 (The access divide): The chapters of this book that celebrate its reach should be read with this one open beside them: reach, for most of humanity, is still the unfinished part of the story .
- Chapter 65 (The access divide): Every chapter of this book that celebrates a new capability should be read against that arithmetic: capability is not access, and access is the unfinished half of the ma...
- Chapter 68 (The machine that reads): The machine's history suggests the optimistic reading - every previous automation, from the intensifying screen to the digital detector, eventually spread - but "eventua...
- Chapter 80 (The shrinking machine): Portable digital radiography is the backbone of active tuberculosis screening in communities far from any hospital; solar-capable systems and ruggedised detectors are bu...

[X-F26] History of X-ray Research in Colonial India, Indian J. History of Science 53(4), 2018

https://doi.org/10.16943/ijhs/2018/v53i4/49535

Use: read in full (research/fetch_K_india.txt).

Cited for:

- Chapter 10 (The ray in India): On 20 June 1896 he made India's first X-ray experiments - a hand, overexposed; by 23 June he had successful photographs, and on 3 July he lectured for ninety minutes on ...
- Chapter 10 (The ray in India): The Amrita Bazar Patrika's reporter, shown a photograph of a human palm in May 1898, wrote that "the ghastly sight will long be vividly imprinted in our memory" .
- Chapter 10 (The ray in India): Bose's apparatus also produced what is likely the first medical use of the ray in India: in February 1898, at Dr Nilratan Sircar's request, he examined a patient with a ...
- Chapter 10 (The ray in India): (and 2 further passages in the same chapter)
- Chapter 11 (The patent that wasn't): Within a year, as this book's India chapter shows, a tube ordered from Paris was making radiographs in Calcutta; within two, a professor there had built his own apparatu...
- Chapter 52 (The second life of machines): The trade in pre-owned imaging equipment is one of global health's quietest and most effective mechanisms - and one of the machine's oldest patterns, since even the 1896...
- Chapter 52 (The second life of machines): The cascade is still running .
- Chapter 54 (The rule book): For a book in the Industries of India series, this is the machine's local constitution: the same three layers of physics, market permission and practice, written in Delh...
- Chapter 69 (The healing beam): The same physics that burned the pioneers was turned, almost immediately, against disease: by the first years of the new century, physicians were aiming X-ray tubes at s...

[X-F27] William McKinley assassination - Wikipedia

https://en.wikipedia.org/wiki/Assassination_of_William_McKinley

Use: read in full (research/fetch_K_mckinley.txt).

Cited for:

- Chapter 9 (The bullet and the machine): The operating team judged that moving and disturbing the patient for an image would do more harm than the bullet, which the senior surgeon believed would do little once ...
- Chapter 9 (The bullet and the machine): The trajectory from Buffalo 1901 - the machine present but unused - to a world where no trauma protocol begins without it, is the whole history of the machine's acceptan...

- Chapter 9 (The bullet and the machine): Sometimes the machine's history advances not by invention but by the closing of a gap between what exists and what is used .

[X-F32] ICRP history - icrp.org

https://www.icrp.org/page.asp?id=5

Use: read in full (in fetch_F).

Cited for:

- Chapter 3 (The coil and the spark): The transformer and rectifier ended the era, and the high-frequency inverter finished it, but the coil's legacy persists in language: radiographers still speak of "the s...
- Chapter 13 (What an X-ray is): The units have changed - erythema dose, röntgen, rad, rem, gray, sievert - but the bargain has not .
- Chapter 14 (Braking light and fingerprints): It is the smallest and cheapest safety device in the machine, and its logic - cut the photons that cannot help - is the logic of the whole mature art .
- Chapter 19 (The anode problem): Every quiet click of the exposure switch is the end of that riddle, solved again .
- Chapter 20 (The hundred-thousand-volt supply): Imaging's reproducibility - the same examination, every time, on every machine - is largely the generator's doing, and it is why Chapter 43's phantoms have meaningful sc...
- Chapter 27 (The catheter's eye): The lesson of Chapter 37 was not learned once; it is re-learned by every generation that finds a new way to stand close to the beam .
- Chapter 36 (The burns): The early operators received in a week what a modern radiation worker is permitted in a career .
- Chapter 36 (The burns): The machine's second half-century would be defined by the question the first refused to ask: how much is too much .
- Chapter 36 (The burns): Standardisation was impossible until measurement existed - which is why the unit-makers of Chapter 40 were not pedants but first responders to an invisible fire .
- Chapter 37 (The martyrs): Every interlock and lead apron in a radiology department is, in a direct line, a name on that stone .
- Chapter 39 (Measuring the invisible): The march from that meter to the sievert is the administrative backbone of modern radiology .
- Chapter 39 (Measuring the invisible): These are the numbers with which the machine's cost-benefit is now argued, and the public equivalents - "as much as so many chest films" - are how radiologists explain r...
- Chapter 39 (Measuring the invisible): Occupational limits settled at 20 millisieverts a year averaged over five years; the public limit at 1; and the machine was redesigned around the ledger - filtration, co...
- Chapter 41 (The dose ledger): That is what progress looks like when it is kept honestly: not a smaller number, but a truer book .
- Chapter 41 (The dose ledger): A dose culture is not a rule but a comparison, endlessly renewed .
- Chapter 42 (Lead and glass): Modern occupational doses in radiology run far below the limits, a quiet triumph engineered by everything this chapter describes: the housing, the jaws, the walls, the d...
- Chapter 42 (Lead and glass): The room where the machine lives is, in this literal sense, designed by the beam itself - every wall a map of where the photons go .
- Chapter 42 (Lead and glass): The distinction is the whole history of protection in miniature: what was ritual becomes measured, and what is measured becomes law .
- Chapter 54 (The rule book): The third is practice: national radiation-protection authorities license facilities, mandate quality assurance, and enforce the dose limits the ICRP recommends .
- Chapter 54 (The rule book): International coordination came early by regulatory standards: the forerunner of the ICRP was issuing recommendations by 1928, and the International Basic Safety Standar...

[X-F33] Thorotrast - Wikipedia

https://en.wikipedia.org/wiki/Thorotrast

Use: read in full.

Cited for:

- Chapter 25 (Painting the soft parts): The machine's two consumables, photons and ink, finally share a ledger .
- Chapter 25 (Painting the soft parts): Thorotrast's withdrawal and its victims' long surveillance are the contrast story's martyrs' chapter: the inks, like the ray, were learned at the expense of the generati...

[X-F36] BBC News, 31 July 2008: X-rays reveal Van Gogh portrait

http://news.bbc.co.uk/2/hi/entertainment/7533815.stm

Use: read in full.

Cited for:

- Chapter 60 (Bones of the past): The famous demonstration came in 2008, when a synchrotron team scanned Van Gogh's "Patch of Grass" and recovered, in full colour, the head of a peasant woman painted ove...

[X-F37] Synchrotron light source - Wikipedia

https://en.wikipedia.org/wiki/Synchrotron_light_source

Use: read in full.

Cited for:

- Chapter 63 (The cathedral machines): If Röntgen's apparatus was a candle, the synchrotron is a lighthouse .
- Chapter 63 (The cathedral machines): Industry buys beamtime as readily as universities do: jet-engine blades, battery electrodes and pharmaceutical formulations are all routine synchrotron patients .
- Chapter 63 (The cathedral machines): The tube and the cathedral, it turns out, are one family - the small machine in every hospital, and the national facility that keeps teaching it new tricks .
- Chapter 63 (The cathedral machines): (and 2 further passages in the same chapter)

[X-F38] Photo 51 - Wikipedia

https://en.wikipedia.org/wiki/Photo_51

Use: read in full.

Cited for:

- Chapter 61 (The reading of crystals): The twentieth century's most famous X-ray image is not of a hand but a cross of black smudges on film: Photograph 51, Rosalind Franklin's 1952 diffraction picture of hyd...

[X-F39] X-ray - Wikipedia

https://en.wikipedia.org/wiki/X-ray

Use: read in full.

Cited for:

- Chapter 1 (The electricians of nothing): In 1895 the tube was a settled commercial object wrapped around an unsettled scientific question, and it was precisely the best-known property of the cathode ray - its p...
- Chapter 1 (The electricians of nothing): He was, in retrospect, centimetres and a sheet of cardboard away from the discovery that would instead be Röntgen's; he had everything except the crucial habit of workin...
- Chapter 2 (The men who almost saw it): The answer, established by patient historical work, is yes - at least twice, with photographs to prove it .
- Chapter 2 (The men who almost saw it): Goodspeed filed the plate away, puzzled, and thought no more about it until January 1896, when the news from Germany reached America; he then went back, reproduced the a...
- Chapter 2 (The men who almost saw it): There were others in the same position: experimenters who recalled fogged plates stored near discharge tubes, and at least one instrument maker who had quietly replaced ...

- Chapter 13 (What an X-ray is): The ray was a wave after all - light of a wavelength a thousand times shorter than the eye can see, sitting on the electromagnetic spectrum between ultraviolet and the g...
- Chapter 13 (What an X-ray is): That is ionisation, and it is the root of both the machine's power and its danger: ionisation in a photographic plate or a detector pixel records the image, and ionisati...
- Chapter 41 (The dose ledger): A chest radiograph delivers about a tenth of a millisievert - roughly ten days of natural background - and paediatric protocols push lower still .
- Chapter 42 (Lead and glass): The modern refinements are compositional: bismuth and tungsten composites that match lead's stopping with less weight and no toxicity worries, and structural barium plas...
- Chapter 80 (The shrinking machine): Flat-panel detectors untethered the radiograph from the darkroom; battery-powered portable X-ray units now travel to the bedside, the nursing home, the disaster zone and...
- Chapter 80 (The shrinking machine): The machine got smaller only when the machine got better .

[X-F40] Photon-counting computed tomography - Wikipedia

https://en.wikipedia.org/wiki/Photon-counting_computed_tomography

Use: read in full.

Cited for:

- Chapter 28 (The slice): It also carries the field's deepest dose obligations, since one CT examination delivers what hundreds of chest films would; the balancing of that equation runs through P...
- Chapter 47 (The detector industry): CZT crystal supply, grown by a tiny number of specialist houses, is one of the bottlenecks examined in Part VI .
- Chapter 73 (Grey to gold): The grey scale remains the machine's native tongue; colour is its new dialect, spoken where it earns its keep .
- Chapter 79 (Counting the photons): And because the detector pixels can be made small without noise swamping them, resolution jumps: structures at the limit of CT - the lung's smallest airways, the inner e...
- Chapter 79 (Counting the photons): The technology crossed from laboratory to clinic in 2021, when the first commercial photon-counting CT system was cleared for clinical use, and the other major manufactu...
- Chapter 79 (Counting the photons): The hospital's newest scanner is, among other things, a particle-physics experiment that moved in and put on a gown .
- Chapter 79 (Counting the photons): (and 1 further passages in the same chapter)
- Chapter 80 (The shrinking machine): That future would close the book's longest arc - from the machine you visit, to the machine that visits you, to the machine you wear .

[X-F41] Cargo scanning - Wikipedia

https://en.wikipedia.org/wiki/Cargo_scanning

Use: read in full.

Cited for:

- Chapter 58 (The container's shadow): A shipping container is the machine's most opaque routine patient - forty feet of corrugated steel packed to the doors - and the instruments that inspect it run at milli...
- Chapter 58 (The container's shadow): Drive-through portals scan hundreds of vehicles an hour; the machine that took minutes per plate in 1896 now makes a usable image of a moving lorry in seconds .
- Chapter 58 (The container's shadow): Even the container's shadow, it turns out, has its rule book - Chapter 54's clauses translated into concrete, steel and customs law .
- Chapter 58 (The container's shadow): (and 1 further passages in the same chapter)

[X-F42] PACS - Wikipedia

https://en.wikipedia.org/wiki/PACS

Use: read in full.

Cited for:

- Chapter 22 (The film years): The reading room's silence today is not the absence of the machine but the absence of its machinery; the work is the same work, quieter .
- Chapter 24 (Film to pixels): Digital memory made the profession permanently accountable to its own past, and the teaching file and the discrepancy meeting of Chapter 72 are the constructive half of ...
- Chapter 32 (The bone's biography): The result, a density compared against the young-adult reference, is the T-score by which osteoporosis is diagnosed and fracture risk is managed .
- Chapter 32 (The bone's biography): Screening the density of the ageing skeleton, and re-measuring it to watch treatment work, is the machine in its actuarial mode: not finding what is wrong today but pric...
- Chapter 32 (The bone's biography): The bone keeps its biography in mineral; the densitometer is its careful reader .
- Chapter 32 (The bone's biography): (and 1 further passages in the same chapter)
- Chapter 35 (The beam at sea): The teleradiology of Chapter 74 reaches its extreme at sea, where the nearest hospital may be a helicopter ride over open water .
- Chapter 72 (The reading room): The lighting is low so the greys keep their subtlety; the monitors are calibrated and audited so a grey in Chennai is the same grey in Chicago; the worklist is the day's...
- Chapter 72 (The reading room): The report that leaves the room is a legal document, a clinical handoff and often the pivot of a treatment decision; its language is standardised into lexicons so that "...
- Chapter 72 (The reading room): A department that stops auditing its eyes will eventually be failed by them .
- Chapter 72 (The reading room): (and 2 further passages in the same chapter)
- Chapter 73 (Grey to gold): One exposure, infinitely many images .
- Chapter 73 (Grey to gold): The grey scale, it turns out, was always a language; the digital machine merely gave its speakers a larger vocabulary .
- Chapter 73 (Grey to gold): The rendering choices that look like cosmetics are, in fact, the machine's memory keeping faith with itself .
- Chapter 73 (Grey to gold): (and 1 further passages in the same chapter)
- Chapter 74 (The wired archive): The film library's trolley-pushers became data managers; the lost film became an entry in an audit log .
- Chapter 74 (The wired archive): The wired archive is, among other things, the dose ledger's bookkeeper - the machine watching itself, at last, as closely as it watches the patient .
- Chapter 74 (The wired archive): The machine's product has always been memory; it simply used to fit in a basement .
- Chapter 74 (The wired archive): (and 1 further passages in the same chapter)
- Chapter 75 (The teaching file): The film library's marked folders, the museum of classic cases, the professor's private hoard of beautiful disasters: this was how the machine's seeing was taught for a ...
- Chapter 75 (The teaching file): Simulation extends the school to the machine itself: phantom patients and virtual workstations let the learner err without a victim .
- Chapter 76 (The shadow in court): The ray's testimony, like the ray itself, has only hardened with age .
- Chapter 78 (Four-legged patients): The equipment is the hospital's in miniature - smaller tables, portable generators for the stable yard, the same tungsten physics - but the practice is its own disciplin...
- Chapter 78 (Four-legged patients): The economics differ too - veterinary imaging is bought with the owner's wallet, not a health system's budget, which made the digital transition slower in the stable tha...
- Chapter 78 (Four-legged patients): Veterinary radiology is, in that sense, the machine's most democratic branch .
- Chapter 78 (Four-legged patients): (and 1 further passages in the same chapter)

[X-F43] DICOM - Wikipedia

https://en.wikipedia.org/wiki/DICOM

Use: read in full.

Cited for:

- Chapter 74 (The wired archive): The digital detector abolished that object, and what replaced it is an institution: the Picture Archiving and Communication System - PACS - and the DICOM standard that l...

[X-F44] Virtual autopsy - Wikipedia

https://en.wikipedia.org/wiki/Virtual_autopsy

Use: read in full.

Cited for:

- Chapter 9 (The bullet and the machine): It is the machine's oldest promise - look inside without cutting - finally kept to the dead as faithfully as to the living .
- Chapter 76 (The shadow in court): The precedents accumulated quickly on both sides of the Atlantic: by the early 1900s the X-ray plate was accepted evidence of fracture and foreign body, with the operato...
- Chapter 76 (The shadow in court): In mass disasters, forensic radiology is now standard: the dead are scanned before the pathologist begins, so that the image guides the examination and the record outliv...

[X-F45] Albert Abrams - Wikipedia

https://en.wikipedia.org/wiki/Albert_Abrams

Use: read in full.

Cited for:

- Chapter 12 (The counterfeit ray): The most successful operator, Albert Abrams, built an empire of leased machines that diagnosed everything from cancer to the patient's religion - and died just before th...
- Chapter 12 (The counterfeit ray): The American Medical Association's dismantling of the Abrams boxes, down to having physicists trace their circuits to nowhere, is a founding document of device regulatio...

[X-F46] Tutankhamun's mummy - Wikipedia

https://en.wikipedia.org/wiki/Tutankhamun's_mummy

Use: read in full.

Cited for:

- Chapter 60 (Bones of the past): Tutankhamun's mummy was CT-scanned in the Valley of the Kings in 2005; animal mummies, fossils, bog bodies and the Herculaneum scrolls - carbonised papyri read by X-ray ...
- Chapter 60 (Bones of the past): The dead and the painted are, in a sense, the machine's ideal patients - infinitely patient themselves .

[X-F47] Herculaneum papyri - Wikipedia

https://en.wikipedia.org/wiki/Herculaneum_papyri

Use: read in full.

Cited for:

- Chapter 60 (Bones of the past): Tutankhamun's mummy was CT-scanned in the Valley of the Kings in 2005; animal mummies, fossils, bog bodies and the Herculaneum scrolls - carbonised papyri read by X-ray ...
- Chapter 60 (Bones of the past): The dead and the painted are, in a sense, the machine's ideal patients - infinitely patient themselves .

[X-F48] Chandra X-ray Observatory - Wikipedia

https://en.wikipedia.org/wiki/Chandra_X-ray_Observatory

Use: read in full.

Cited for:

- Chapter 62 (Stars that burn dark): The first extrasolar X-ray source, Scorpius X-1, was found by a sounding-rocket detector in 1962, surprising everyone: the sky, it turned out, is bright in X-rays wherev...
- Chapter 62 (Stars that burn dark): The Einstein Observatory made the first true X-ray images of the sky in 1978; Rosat mapped it in the 1990s; and in 1999 NASA's Chandra and ESA's XMM-Newton began the mod...
- Chapter 62 (Stars that burn dark): The ray that began in a Würzburg glassblower's bulb ends, for this book, as one of astronomy's eyes - the band of the spectrum in which the universe tells us where it is...
- Chapter 62 (Stars that burn dark): (and 2 further passages in the same chapter)

[X-F49] X-ray astronomy - Wikipedia

https://en.wikipedia.org/wiki/X-ray_astronomy

Use: read in full.

Cited for:

- Chapter 62 (Stars that burn dark): The first extrasolar X-ray source, Scorpius X-1, was found by a sounding-rocket detector in 1962, surprising everyone: the sky, it turned out, is bright in X-rays wherev...
- Chapter 62 (Stars that burn dark): The Einstein Observatory made the first true X-ray images of the sky in 1978; Rosat mapped it in the 1990s; and in 1999 NASA's Chandra and ESA's XMM-Newton began the mod...
- Chapter 62 (Stars that burn dark): The ray that began in a Würzburg glassblower's bulb ends, for this book, as one of astronomy's eyes - the band of the spectrum in which the universe tells us where it is...
- Chapter 62 (Stars that burn dark): (and 2 further passages in the same chapter)

[X-F51] Computer-aided diagnosis - Wikipedia

https://en.wikipedia.org/wiki/Computer-aided_diagnosis

Use: read in full.

Cited for:

- Chapter 43 (The measuring stick): The standard patient has learned to read .
- Chapter 54 (The rule book): The regulation of software updates, of refurbished systems crossing borders, and of the AI readers now layered onto the machine keeps the agencies' dockets full .
- Chapter 67 (The pandemic machine): The machine emerged from 2020-22 as it emerged from 1914-18: tested at scale, trusted more broadly, and busier than ever .
- Chapter 68 (The machine that reads): Regulators treat them as medical devices in their own right, and the cleared-product lists have grown from a novelty to a catalogue .
- Chapter 68 (The machine that reads): The profession's response has been to assign it the roles where volume is the enemy - triage, measurement, second looks - while the accountable signature remains a human...
- Chapter 68 (The machine that reads): But its direction is: not a replacement for the reader, but a second pair of eyes that never tires, never blinks, and never signs the report .
- Chapter 68 (The machine that reads): (and 1 further passages in the same chapter)
- Chapter 71 (The screening net): The argument of this chapter is not settled - it is re-run with every new trial - but its centre of gravity moves steadily toward the machine: as the ray gets cheaper, f...

[X-F53] X-ray crystallography - Wikipedia

https://en.wikipedia.org/wiki/X-ray_crystallography

Use: read in full.

Cited for:

- Chapter 61 (The reading of crystals): Every Nobel season still rewards work that began as spots on a detector .
- Chapter 61 (The reading of crystals): Both questions began on the same Munich bench in 1912 .

[X-F54] Seldinger technique - Wikipedia

https://en.wikipedia.org/wiki/Seldinger_technique

Use: read in full.

Cited for:

- Chapter 27 (The catheter's eye): The Seldinger technique, endlessly adapted, is still how almost everything gets into the vascular tree; the Lancet marked its fiftieth anniversary by calling it one of t...
- Chapter 27 (The catheter's eye): Each step raised the demands on the machine: digital subtraction angiography, which photographs the vessels before and during contrast and subtracts the bone away pixel ...

[X-F55] Digital radiography - Wikipedia

https://en.wikipedia.org/wiki/Digital_radiography

Use: read in full.

Cited for:

- Chapter 21 (Shadows on glass): The chemistry was borrowed wholesale from photography, and the great photographic firms became, without much noticing it, the first imaging-component industry of the X-r...
- Chapter 24 (Film to pixels): The transition came in two steps .
- Chapter 24 (Film to pixels): Hospitals could go digital without changing a single cassette habit, and CR spread through the 1980s and 1990s as the bridge technology, carrying the world's radiology d...
- Chapter 24 (Film to pixels): The same panels, mounted in the C-arm and the angiography suite, displaced the image intensifier in turn; the fluoroscopy chain went flat-panel digital in the 2010s .
- Chapter 24 (Film to pixels): (and 2 further passages in the same chapter)
- Chapter 47 (The detector industry): The capital and process know-how keep the maker list short .
- Chapter 47 (The detector industry): The capital and process know-how keep the maker list short .
- Chapter 47 (The detector industry): The system houses that build their own - Canon has deep semiconductor history from its display work, and Fujifilm converted its photographic chemistry into scintillator ...

[X-F56] GE HealthCare - Wikipedia

https://en.wikipedia.org/wiki/GE_HealthCare

Use: read in full.

Cited for:

- Chapter 17 (The gas-tube era): Müller - Geissler's heir in the glassware trade - was blowing focus tubes of exceptional quality; in Dresden, Koch & Sterzel built elegant apparatus; in Chicago, the Vic...
- Chapter 44 (The first factories): The leading names formed early and lasted long .
- Chapter 44 (The first factories): In Britain the medical supply houses of London equipped the Empire; in France, CGR (Compagnie Générale de Radiologie) anchored a national industry that ended, by acquisi...
- Chapter 44 (The first factories): Second, the industry consolidated relentlessly: the independent tube and apparatus makers were steadily bought into the big electrical combines - GE, Siemens, Philips - ...

[X-F57] Siemens Healthineers - Wikipedia

https://en.wikipedia.org/wiki/Siemens_Healthineers

Use: read in full.

Cited for:

- Chapter 44 (The first factories): The leading names formed early and lasted long .
- Chapter 44 (The first factories): Second, the industry consolidated relentlessly: the independent tube and apparatus makers were steadily bought into the big electrical combines - GE, Siemens, Philips - ...

[X-F58] United Imaging - Wikipedia

https://en.wikipedia.org/wiki/United_Imaging

Use: read in full.

Cited for:

- Chapter 45 (The modern giants): The league table has been remarkably stable for thirty years: Siemens Healthineers and GE HealthCare at the top, Philips and Canon Medical (the former Toshiba Medical) b...
- Chapter 45 (The modern giants): Its rise - alongside a tier of Chinese radiography specialists such as Wandong and the detector maker iRay - has changed the industry's geography: China is no longer onl...

[X-F59] ICRP - Wikipedia

https://en.wikipedia.org/wiki/International_Commission_on_Radiological_Protection

Use: read in full.

Cited for:

- Chapter 40 (The naming of dose): It told you about the machine, not the patient; a chest film and a head film of equal exposure deliver unequal doses to tissue .
- Chapter 40 (The naming of dose): The modern report's "dose-length product" and "CTDI" are machine-side distillations of the same climb .
- Chapter 40 (The naming of dose): The half-century of committees bought that promise, and it is spent every day in every dose report the machine prints .
- Chapter 40 (The naming of dose): (and 1 further passages in the same chapter)
- Chapter 43 (The measuring stick): The phantom never complains, never moves, and never lies .
- Chapter 43 (The measuring stick): The discipline descends directly from the 1920s, when the first protection committees realised that a machine's dose could not be managed until it could be measured - th...
- Chapter 43 (The measuring stick): The standard patient never ages and never varies; that is precisely its value .
- Chapter 43 (The measuring stick): (and 2 further passages in the same chapter)
- Chapter 54 (The rule book): The third is practice: national radiation-protection authorities license facilities, mandate quality assurance, and enforce the dose limits the ICRP recommends .

[X-F60] Machlett Laboratories - Wikipedia

https://en.wikipedia.org/wiki/Machlett_Laboratories

Use: read in full.

Cited for:

- Chapter 44 (The first factories): Its great rivals were the Machlett Laboratories of Stamford - tube specialists who made the first rotating-anode tubes - and the Picker X-Ray Corporation of Cleveland, ...

[X-F61] Henry Moseley - Wikipedia

https://en.wikipedia.org/wiki/Henry_Moseley

Use: read in full.

Cited for:

- Chapter 14 (Braking light and fingerprints): In 1915 he was killed at Gallipoli, and the Royal Society's rule against awarding Nobel prizes posthumously was not bent for him; physicists have counted his loss among ...
- Chapter 16 (The element hunters): The staircase had gaps, and the gaps were undiscovered elements; the table had misplaced pairs, and the ray put them right .
- Chapter 16 (The element hunters): Moseley's X-ray spectra even settled a dispute about the rare earths that chemistry had been unable to resolve by any chemical means - the ray simply counted .

- Chapter 16 (The element hunters): The machine had shown medicine the inside of the body; in Moseley's hands it showed physics the inside of matter itself .
- Chapter 16 (The element hunters): (and 3 further passages in the same chapter)
- Chapter 56 (The machine in the mine): Moseley's staircase, industrialised into a gatekeeper .

[X-F62] Radiation protection - Wikipedia

https://en.wikipedia.org/wiki/Radiation_protection

Use: read in full.

Cited for:

- Chapter 13 (What an X-ray is): The units have changed - erythema dose, röntgen, rad, rem, gray, sievert - but the bargain has not .
- Chapter 36 (The burns): The machine's second half-century would be defined by the question the first refused to ask: how much is too much .
- Chapter 37 (The martyrs): Every interlock and lead apron in a radiology department is, in a direct line, a name on that stone .
- Chapter 39 (Measuring the invisible): The march from that meter to the sievert is the administrative backbone of modern radiology .
- Chapter 39 (Measuring the invisible): Occupational limits settled at 20 millisieverts a year averaged over five years; the public limit at 1; and the machine was redesigned around the ledger - filtration, co...

[X-F63] Phase-contrast X-ray imaging - Wikipedia

https://en.wikipedia.org/wiki/Phase-contrast_X-ray_imaging

Use: read in full.

Cited for:

- Chapter 81 (The bent ray): Frits Zernike won a Nobel Prize for teaching the visible-light microscope to read those delays, and biologists have never looked back .
- Chapter 81 (The bent ray): The problem was that an X-ray wave is a ferociously difficult thing to compare against itself, and phase is a comparison .
- Chapter 81 (The bent ray): The Bonse-Hart interferometer offered a sensitivity to the body's subtle variations that absorption could not touch - and it demanded conditions that no hospital could e...
- Chapter 81 (The bent ray): (and 4 further passages in the same chapter)
- Chapter 82 (The small world): Even the synchrotron keeps a hand in: the great light sources run micro-CT beamlines whose parallel, monochromatic rays give the cleanest volumes of all, and the same be...

[X-F64] Micro-CT - Wikipedia

https://en.wikipedia.org/wiki/Micro-CT

Use: read in full.

Cited for:

- Chapter 82 (The small world): The reconstructed slices of a small neotropical snail, published as the first X-ray microtomographic images, looked unassuming - but they carried the whole logic of Houn...
- Chapter 82 (The small world): The specimen rotates on a jeweller's stage while the cone-shaped beam projects its shadow; the Feldkamp reconstruction turns a single orbit of cone-beam projections into...
- Chapter 82 (The small world): Palaeontologists slice fossil skulls without touching the chisel, recovering inner ears and brain cases from stone that would have been destroyed by preparation; microfo...
- Chapter 82 (The small world): (and 2 further passages in the same chapter)

[X-F65] Extreme ultraviolet lithography - Wikipedia

https://en.wikipedia.org/wiki/Extreme_ultraviolet_lithography

Use: read in full.

Cited for:

- Chapter 83 (The other lithography): Extreme-ultraviolet lithography prints the circuits of the world's most advanced chips with light of 13.5 nanometres - a wavelength that sits exactly at the soft edge of...
- Chapter 83 (The other lithography): Molten tin is pushed through a nozzle and breaks into droplets crossing a vacuum chamber at seventy metres a second; a pre-pulse from a carbon-dioxide laser flattens eac...
- Chapter 83 (The other lithography): Carl Zeiss builds the projection mirrors, polished to a figure accuracy the company describes without blushing as the most precise in the world: scaled to the size of Ge...
- Chapter 83 (The other lithography): (and 1 further passages in the same chapter)

Compiled alongside the manuscript. All web sources as consulted 1-2 November 2026.