RADIOTHERAPY EQUIPMENT • ENGINEERING HISTORY

How therapeutic LINACs evolved

What X-ray tubes and cobalt machines could not do; how precision engineering, CT, imaging, collimators and software changed treatment; and why different designs still coexist.

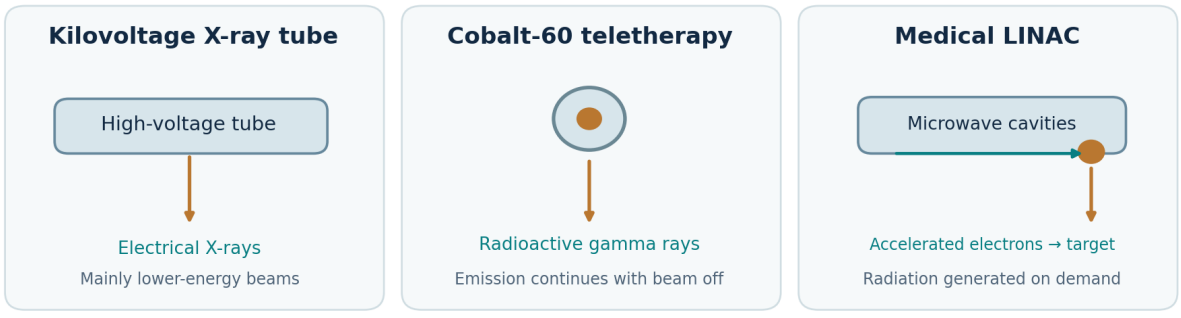
6 November 2026 | Technical review with numbered Vancouver references and source-linked photographs.

Before the LINAC: what had to change?

For much of the twentieth century, radiation oncology relied on three different methods: kilovoltage X-ray tubes for shallow and moderately deep targets, radioactive sources placed inside or near a tumour (brachytherapy), and external-beam radioactive-source machines such as cobalt-60 teletherapy units. These methods were useful, and some remain essential. The practical problem was how to deliver an adequately penetrating beam to deep tumours, shape it accurately, and reproduce the treatment safely day after day. [1, 2, 3]

An X-ray tube accelerates electrons across a high electrical potential and stops them in a metal target. With conventional kilovoltage therapy, dose falls rapidly with depth and surface or bone dose can be relatively high. That remains an advantage for selected superficial lesions, not a reason to use it for large deep pelvic targets. Brachytherapy is different: a sealed source is brought close to, or into, the treatment site. It offers very steep dose fall-off and has not been superseded by external-beam LINACs, notably in cervical and prostate cancer. [1, 2]

Cobalt-60 made deep teletherapy practical with a compact gamma-ray source. But its activity decreases continuously with a physical half-life of about 5.27 years: beam-on time lengthens as the source ages, and source replacement creates cost, logistics and security obligations. A LINAC generates radiation only when energized and can deliver higher-energy photon beams with finer electronic control. These were important advantages, although LINACs require much more power, maintenance and specialist expertise. [3, 4]



Three different ways of producing therapeutic radiation. The drawing shows the operating principle, not physical equipment dimensions.

Authentic photograph: Cobalt-60 teletherapy unit, Amsterdam, 1973. Rob Mieremet / ANEFO, CC BY 4.0. Open freely licensed photograph

Technology	What it solved	What remained difficult
Kilovoltage X-ray therapy	Controllable beam; useful for shallow	Limited penetration for deep targets;

	lesions	skin/bone dose
Brachytherapy	Very high local dose and rapid fall-off	Invasive placement, source handling and site-specific applicability
Cobalt-60 teletherapy	Compact, penetrating gamma-ray source	Continuous decay; source exchange, security and limited beam modulation
Medical LINAC	On-demand MV photons/electrons and electronic beam control	Electrical/RF complexity, scheduled QA and service requirements

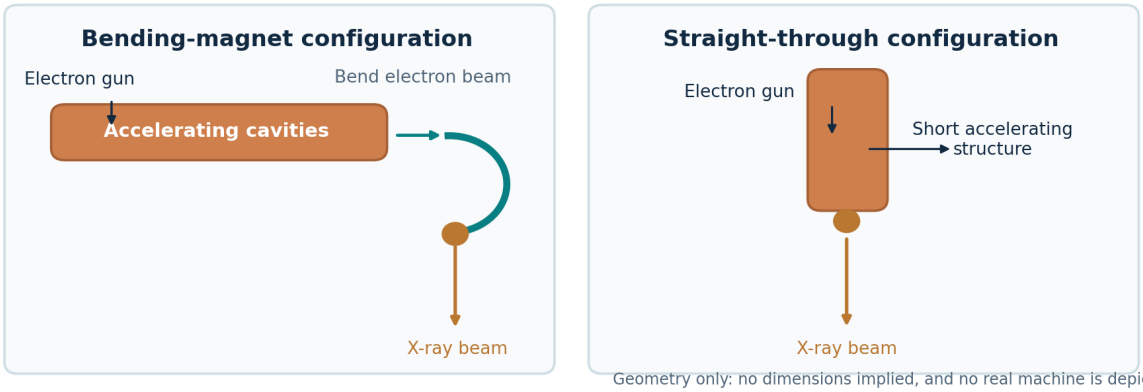
The technologies remain complementary in some indications rather than forming a simple sequence of total replacement.

1953–1970: microwave engineering brings radiation into the hospital

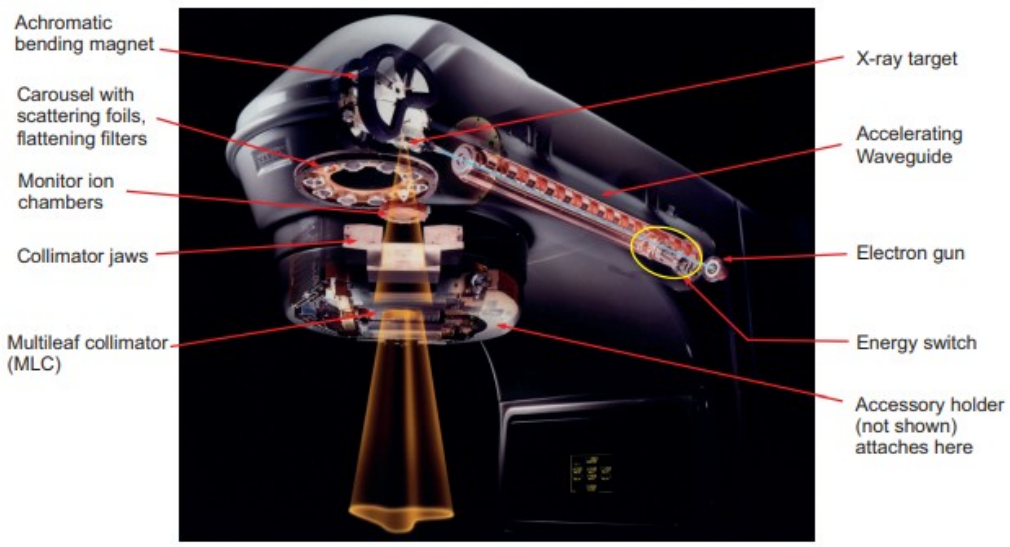
The crucial precondition was high-power microwave engineering. The magnetron and klystron were developed for radio and radar applications, and wartime advances made it possible to deliver intense microwave fields into carefully machined evacuated copper cavities. Electrons injected from an electron gun gain energy as they pass through those cavities. A target converts the electron beam into megavoltage X-rays. [1, 3, 5]

The first hospital medical LINAC treated patients at Hammersmith Hospital in London in 1953. Its accelerating waveguide was metres long, and the machine did not resemble the compact heads used today. The next decades brought rotating, isocentric machines, improved RF efficiency and smaller accelerating structures. A single source could be aimed from different angles while the patient stayed near a fixed point called the isocentre. [1, 2, 3, 6]

A genuine Clinac cutaway shows why “the accelerator” and “the treatment head” are not the same thing. In many conventional machines the electron gun and accelerating waveguide run along the gantry, away from the downward photon beam direction. A bending magnet turns the electrons toward the X-ray target. Other compact single-energy designs place a short structure in line with the target and need no large electron-bending assembly. The precise configuration depends on the machine. [1, 3]



Two legitimate accelerator layouts, simplified. The drawing deliberately does not claim to be a cutaway of any specified product.



Varian-supplied cutaway reproduced from the technical figure supplied with this discussion. The long accelerating structure, bending magnet, target, monitor chamber and MLC are visible.

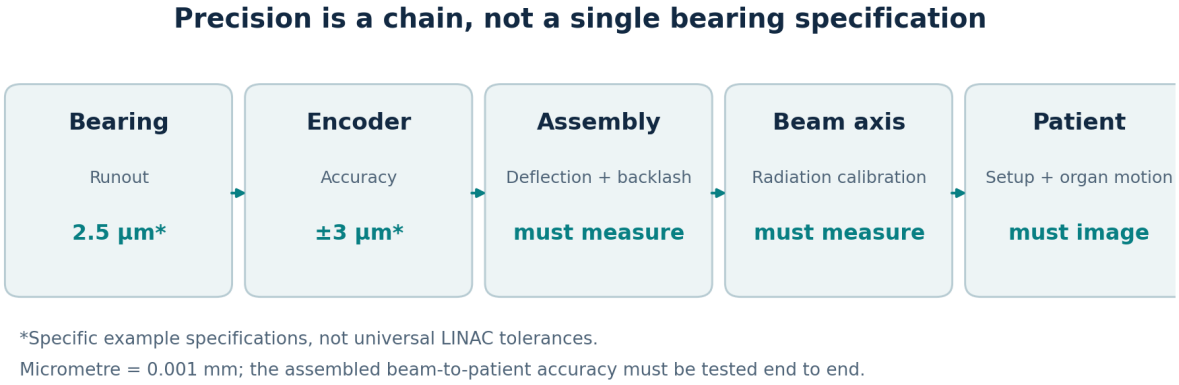
Authentic photograph: Varian Clinac 2100 C/D, photographed 2011. Guy Lebègue, CC BY-SA 3.0. Open freely licensed photograph

1970s onward: accurate motion became as important as accurate radiation

A rotating gantry sounds simple: move a heavy arm around a patient. The engineering problem is keeping the radiation axis aimed at the same point throughout rotation. Gravity pulls the head differently at each angle. Bearings have runout, gears have backlash, frames bend, and heat changes dimensions. A machine can stop its motor to a precise encoder reading and still have a displaced X-ray beam. [1, 7, 8]

Precision bearings carry a heavy rotating assembly while allowing low-friction motion. “Runout” means that a supposedly perfect circle of rotation wobbles slightly; axial runout refers to motion along the bearing axis, radial runout to motion perpendicular to it. Precision bearing sets used in machine tools can reach micrometre-scale runout. For one specific SKF precision bearing arrangement, correctly matched and mounted sets can achieve axial runout of about 2.5 µm. That is 0.0025 mm — not the accuracy of a whole LINAC. [7]

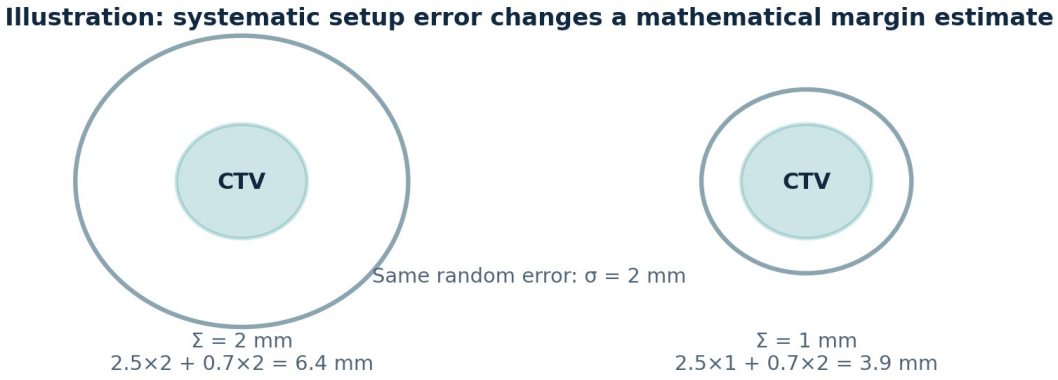
Absolute encoders measure position independently of the motor’s pulse count. One present-day HEIDENHAIN linear encoder specifies an accuracy grade of ±3 µm over a 1,240 mm measuring length, even though its finest electronic measuring step is far smaller. **Resolution is not accuracy:** displaying more decimal places does not make the machine more accurate. In decimal millimetres, 0.01 mm is 10 µm, 0.001 mm is 1 µm, and 0.0001 mm is one tenth of a micrometre. Final accuracy depends on calibration, mounting, thermal drift, stiffness and independent measurement. [8]



Five linked uncertainty sources. The first two figures are examples from manufacturer datasheets; they are not specifications of a particular radiotherapy machine.

The clinical payoff was not automatic millimetre-for-millimetre reduction of the PTV. The planning target volume is meant to accommodate geometric uncertainties from the entire process: patient setup, organ motion, contouring and delivery. Van Herk and colleagues showed why systematic error matters especially strongly for a course of treatment. A commonly used illustrative margin formula is $2.5\Sigma + 0.7\sigma$, where Σ describes systematic setup uncertainty and σ random uncertainty, under the original model assumptions. [9]

For example, reducing **one modelled systematic error component** from 2 mm to 1 mm while holding σ at 2 mm changes that formula from 6.4 mm to 3.9 mm. This is a mathematical illustration, not a recommended clinical margin. A better bearing cannot eliminate respiratory motion, deformation or delineation uncertainty. Smaller margins became realistic only when precise mechanics were combined with better imaging, positioning and motion management. [9, 10, 11]



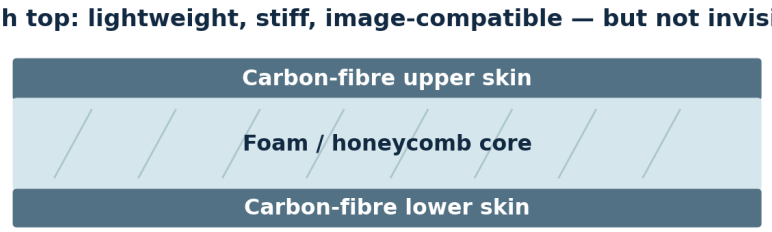
Worked illustration of the published margin formula, not a measured comparison of old and new machines.

Patient supports: why carbon fibre mattered

The patient table needs to do several things at once: carry a person, avoid sagging as far as practical, move reproducibly and allow imaging and posterior treatment beams to pass through. Early tables often relied on metal frames and removable open “tennis-racket” inserts. Composite construction made long, relatively stiff and light couch tops with fewer bulky metal obstructions possible. [12]

A common modern design is a sandwich: thin carbon-fibre skins separated by a lightweight foam or honeycomb core. The spacing increases bending stiffness without a solid block of material. But carbon fibre is only **relatively** radiolucent. It attenuates the beam and can increase skin dose; therefore the treatment planning system must model the couch and immobilization hardware. The

AAPM review documents examples of several percent attenuation, depending on energy and beam angle. [12]



A generic composite sandwich panel. Actual couch design, patient load limits, attenuation and deflection are manufacturer-specific.

1970s–1990s: CT changed what radiotherapy could plan

Before CT, radiation fields were usually designed around skin marks, plain radiographs and a small number of anatomical measurements. CT provided cross-sectional views of the patient, including the tumour and structures that should be spared. The first clinical CT scan was obtained in 1971; Hounsfield published the method in 1973. Three-dimensional planning and CT simulation developed over the following decades rather than appearing overnight. [13, 14]

Computer models could now calculate the path of each beam through different tissue densities and display the dose in three dimensions. Digitally reconstructed radiographs (DRRs) gave an image with which to compare treatment-room images. CT did not make anatomy perfectly visible, and later MRI and PET integration remained important. But it changed planning from drawing a field on a body outline to designing dose around a three-dimensional target. [13, 14, 15]

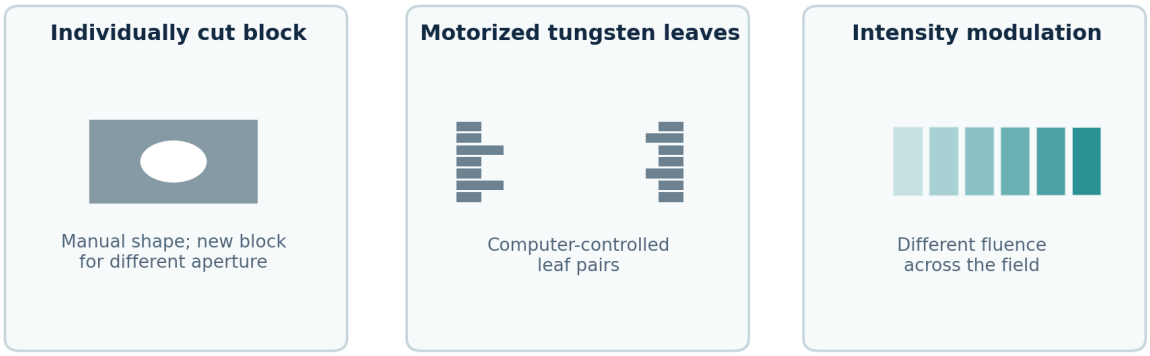
Authentic photograph: Early EMI CT scanner on display. Philip Cosson, public domain. Open freely licensed photograph

From lead blocks to computer-controlled leaves

For decades, technicians shaped fields using custom metal shielding blocks. This was effective but labour-intensive: a different opening meant a different block, mounted on a tray. Motorized jaws provided rectangular fields, wedges modified beam intensity, and compensators changed fluence with depth or position. These were practical precursors of modern modulation, not primitive ideas to be dismissed. [14, 15]

The multileaf collimator (MLC) replaced many custom blocks with rows of narrow tungsten leaves. Each leaf or leaf pair moves into the radiation field under computer control. The machine can make an irregular opening without a new manufactured block, or change the opening repeatedly during one fraction. Ideas appeared earlier, but commercially useful MLC systems emerged in the 1980s–1990s as motors, position feedback and control computers improved. The first commercial MLC realized by Scanditronix was reported in 1984. [14, 16]

The limitation is mechanical and dosimetric. More, thinner leaves improve geometric shaping but add motors, sensors, mass and maintenance points. Rounded leaf tips, interleaf leakage and motion errors need accurate modelling. An MLC is not a perfect opaque stencil. [16]



From a custom-cut block to movable leaves and fluence modulation. This is an explanatory geometry drawing, not a photograph.

Authentic photograph: Real multileaf collimator assembly. Jejecam, CC BY-SA 3.0. Open freely licensed photograph

Inverse planning: the decisive software change

Traditional forward planning asks: “If these beams are used, what dose will they produce?” Inverse planning reverses the problem: “What beam intensities will best satisfy these target and organ-at-risk objectives?” Anders Brahme and colleagues formalized influential approaches in the 1980s. Optimization algorithms then converted desired dose distributions into patterns that the MLC could deliver. [15, 16, 17]

The idea required computers capable of dose calculation and optimization, electronically controlled leaves, and reliable machine communication. Commercial IMRT reached patients in the 1990s, initially through specialized systems such as NOMOS MIMiC/Peacock and later on conventional LINACs. Continuous gantry motion with changing MLC leaves and dose rate led to volumetric modulated arc therapy (VMAT), typically reducing delivery time compared with many fixed IMRT fields for suitable cases. The planner must still check whether the plan is deliverable and safe. [15, 16, 17]

1990s–2000s: the machine learns to see where the patient is

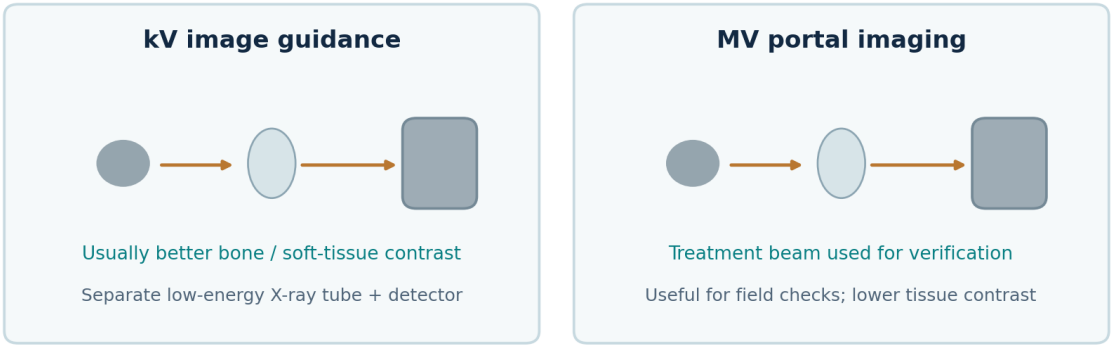
A planning CT is an image taken on a different day. The patient can be shifted, the bladder can fill differently and a lung tumour can move with breathing. Image-guided radiotherapy (IGRT) adds measurements made on or near the treatment machine and compares them with the planning reference. [10, 18, 19]

Why kilovoltage and megavoltage imaging are different

A kilovoltage (kV) imaging system usually uses a separate diagnostic-energy X-ray tube and flat-panel detector. It often gives better contrast between bone and surrounding tissue and can acquire projections for cone-beam CT. A megavoltage (MV) portal image uses the high-energy treatment beam and an electronic portal imaging device (EPID) on the opposite side. It is excellent for verifying treatment-field geometry, but its subject contrast is generally poorer because high-energy photons interact differently with tissue. [10, 18, 19]

Two real published comparisons: a prostate study provides side-by-side anteroposterior and lateral MV portal and kV images of implanted fiducial markers in clinical patients; a review illustrates MV portal alignment using skull and head-and-neck bony anatomy compared against

DRRs. These are actual published examples and are linked directly in the online article. They show what each method detects, rather than invented “before and after” pictures. [10, 19]



The two image-generation chains. See the linked original clinical images for the appearance of real kV and MV radiographs.

Real prostate kV/MV image comparison (Figure 1) — clinical images in the original publication.

Actual head-and-neck MV portal imaging examples (Figure 1) — clinical images in the original publication.

The next step was rotating the imaging tube and detector to reconstruct a three-dimensional image. Jaffray and colleagues demonstrated flat-panel cone-beam CT for image guidance in 2002. On-board CBCT helps detect changes in the location of the tumour and organs, but has its own limits in scatter, image artefacts and soft-tissue contrast. [10, 18]

2000s–2020s: movement introduces a fourth dimension

A tumour does not necessarily remain at one point throughout a fraction. Four-dimensional CT (4DCT) groups images by respiratory phase to show movement over a breathing cycle. It enables internal target volumes, gating windows and more informed motion management. Early practical methods were described around 2004; respiratory tracking, breath-hold methods and surface monitoring then became progressively integrated into clinical equipment. [11, 20]

The trade-off is important: imaging a moving target does not make it stationary. A 4DCT reflects breathing during that scan, while breathing may vary during treatment. Gating pauses irradiation outside a chosen window; tracking moves the beam or adjusts delivery; breath-hold asks the patient to adopt a repeatable respiratory position. Each works only when its correlation with the internal target has been validated. [11, 20]

Different geometries for different clinical problems

The conventional rotating C-arm

The familiar C-arm keeps a relatively large accelerator and MLC rotating around a fixed isocentre. It is a broadly useful architecture for conformal treatment, fixed-field IMRT, VMAT, electrons on equipped systems and many types of SBRT. Its strengths are generality and a mature maintenance ecosystem; its limits include the large moving mass, rotational radius and the finite range of collision-free noncoplanar directions. [1, 21, 22]

Authentic photograph: Varian TrueBeam medical LINAC. Michael Goodyear, CC BY-SA 4.0. Open freely licensed photograph

Authentic photograph: Elekta Versa HD in a treatment room. Chris Olszewski, CC BY-SA 4.0. Open freely licensed photograph

TomoTherapy: why a CT-scanner-like ring?

TomoTherapy places a LINAC on a ring and advances the patient couch through the bore while the source rotates, delivering narrow fan-beam radiation in a spiral. This suited complex and long targets and combined treatment with megavoltage CT imaging. The ring geometry reduces some possibilities for strongly noncoplanar beam directions and its narrow fan beam can make some plans slower than modern VMAT; delivery time depends strongly on target length and planning settings. Modern descendants include the commercial Radixact system. [16, 21, 23]

Authentic photograph: TomoTherapy Hi-Art system, Reggio Emilia, 2008. ASL Reggio Emilia, CC BY-SA 3.0. Open freely licensed photograph

CyberKnife: move the source instead of the patient

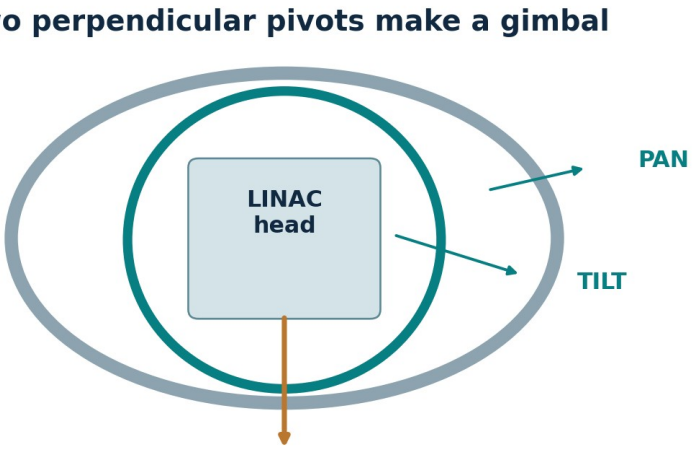
CyberKnife attaches a compact LINAC to an industrial robotic arm, providing many noncoplanar beam directions. It grew especially useful for stereotactic radiosurgery, body stereotactic radiotherapy and image-guided target tracking. The price is more moving joints, a specialized imaging and control system, and complex robot/path calibration. It is not simply a small version of a conventional C-arm. [21, 23]

Authentic photograph: CyberKnife robotic radiosurgery system, 2012. Minaforpresident, CC BY-SA 3.0. Open freely licensed photograph

Vero4DRT: what exactly is a gimbal?

A gimbal is a joint system with two perpendicular rotational axes: a cradle can **pan** left and right and **tilt** up and down independently. Gimbals were used in maritime compasses and nautical clocks long before radiotherapy: two hinged rings helped an instrument remain roughly level as the ship rolled. This is sometimes called a Cardanic suspension, although examples predate Girolamo Cardano. Cameras and telescopes later used related mechanisms. [24, 25, 26]

Vero4DRT used a compact C-band LINAC on an O-ring and a two-axis gimballed X-ray head. Each axis could rotate approximately ±2.5°, enough to shift the radiation beam by several centimetres at isocentre for fine real-time tracking. Larger angular access still came from the gantry/O-ring. Two orthogonal kV tubes and detectors observed internal anatomy; the gimbal then adjusted the MV radiation direction. A gimbal is therefore **fine beam steering**, not a six-axis robot. [24, 25]



Simplified two-axis gimbal. The diagram shows pan and tilt relationships, not the dimensions of a Vero mechanism.

MRI-LINACs and online adaptation

The MR-LINAC brought another kind of information to the treatment machine: high-quality soft-tissue imaging while the patient is positioned for irradiation. This meant developing accelerators compatible with strong magnetic fields, new shielding and imaging reconstruction, and new workflows. First patients were treated on a 1.5 T MR-LINAC in Utrecht in 2017. The equipment is expensive and clinically useful for selected targets that are poorly seen with ordinary kV imaging. [27]

CBCT-based online adaptive treatment took a related but different route. Systems such as Ethos use the day's images to update contours, calculate or select a plan, check it and deliver it while the patient stays on the couch. Better GPUs and automated contouring made this workflow practical, but adaptation adds review and QA work instead of magically removing the clinician. Auto-contouring of organs is increasingly useful; defining malignant extent remains a separate clinical judgment. [28, 29]

A practical comparison of recognisable machine families

These systems are not ranked by purchase price because comparable public, installed-and-supported quotations are generally unavailable. Clinical treatment time also varies with target size, fractionation, modality and planning. The table instead compares the engineering choices that determine strengths and trade-offs. Historical systems are marked clearly. [21, 22, 23, 27, 30, 31, 32]

Machine family	Geometry / imaging	Main strength	Principal limitation / burden
Conventional C-arm: TrueBeam, Versa HD	Rotating C-arm; kV CBCT and MV portal imaging	Most versatile general-purpose platform	Large gantry, shielding and service infrastructure
Halcyon / Ethos	Compact ring; integrated kV CBCT; Ethos adaptation	Efficient standardised workflow; daily anatomy-informed planning	Restricted noncoplanar access; adaptation adds staff time
TomoTherapy / Radixact	Helical ring; MVCT	Very long or complex target volumes	Narrow fan-beam geometry; less noncoplanar flexibility
CyberKnife S7	Six-axis robot; stereoscopic imaging / tracking	Many noncoplanar beam directions; moving-target stereotaxy	Specialised robotics, imaging and long-term maintenance
Vero4DRT (historic)	O-ring plus pan/tilt gimbal; paired kV imagers	Fine beam tracking plus noncoplanar access	Complex custom architecture; not a current mainstream product
Elekta Unity MR-LINAC	Ring LINAC coupled to 1.5 T MRI	Soft-tissue visibility and on-table adaptation	Magnet integration, workflow duration and infrastructure
ZAP-X	Dedicated self-shielded intracranial radiosurgery	Compact dedicated brain SRS footprint	Not a multipurpose whole-body workhorse
Siddharth-II	Compact ring with beam stopper; option-dependent MLC/IGRT	Marketed toward accessible general-purpose radiotherapy	Published performance and service footprint vary by model/region

A qualitative comparison of capabilities, not a numerical performance ranking or a claim of equivalent indications.

Access to radiotherapy: projects and marketed responses

Clinical access depends on more than the machine: staff, simulation, treatment planning, shielding, electrical reliability, spare parts and service contracts matter. Several responses are visible in the literature. The Indian-manufactured Siddharth-II is a **marketed medical LINAC**, with US FDA 510(k) clearance records. CERN's STELLA project, by contrast, has published work on a modular, serviceable system specification; it is a development and access initiative, not a finished commercial LINAC. [31, 33]

The Australian Nano-X project has investigated a fixed beam combined with patient rotation, in part to simplify the mechanical structure. Its published 2023 work describes a prototype and imaging feasibility programme. The associated clinical trial record was updated in May 2026 as **withdrawn because funding was unavailable**. This does not by itself establish that the underlying engineering concept failed, but it is important evidence about development maturity. [34, 35]

Patents: interesting mechanisms that did not become familiar products

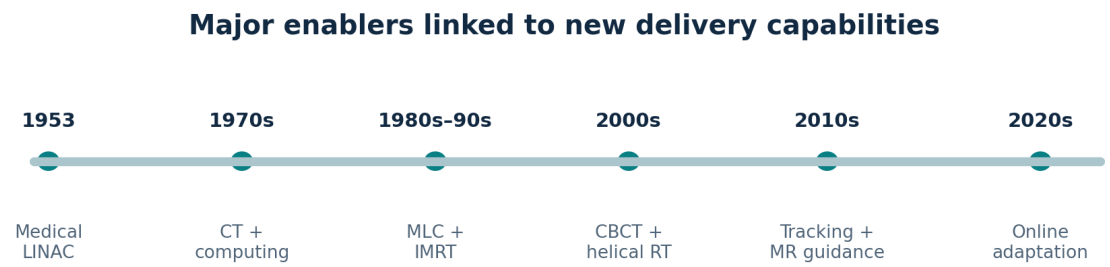
A patent records a proposed technical solution and the claims its inventors sought to protect. It does not prove that a complete medical device was built, qualified or commercially sold. Three instructive examples appeared after conventional C-arms and robotic systems were already established. The engineering challenges described below are plausible obstacles, **not documented explanations for each company's product decisions**. [36, 37, 38]

Proposal / earliest priority	Problem it addressed	Mechanical idea	Why integration would be demanding
Siemens, 2009: linear guides with rotating head	Fixed-radius gantry limits source positioning	Orthogonal straight rails plus one or more head rotations	Large moving frame, patient clearance, cable routing, multi-axis calibration
Accuray, 2011: inward-extending ring head	Fixed source distance limits geometry	Radial translation of entire head from a ring	Heavy moving payload, deflection at extension, collision and calibration
Accuray, 2010s: head that slides and pivots on a rotating beam	Broaden noncoplanar beam access	Head translation along beam plus two pivot axes and ring motion	Many coupled moving axes and a complex shielding/clearance envelope

Representative disclosed concepts. No commercial product matching these claimed combinations was established in the sources reviewed.

Their patent figures are worth studying precisely because they force the reader to ask where the heavy mass moves, how much additional travel is needed, and what the patient and couch obstruct. The diagrams and full claim sets can be inspected in the cited original patent records. A legal status such as "expired for fees" concerns a particular patent and jurisdiction, not all related intellectual property. [36, 37, 38]

What ultimately drove progress?



Each step depended on several complementary technologies; these are broad historical periods, not single invention dates.

The first decisive step was generating penetrating radiation electronically. The second was making the source move around a stable reference point. CT then provided three-dimensional anatomy to plan against. Motorized collimators made complex fields repeatable, while computing made inverse planning feasible. On-board imaging linked the plan to the patient in the treatment room. Finally,

fast imaging, more powerful computation and reliable motion control made respiratory tracking and online adaptation possible. [1, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 24, 25, 27, 28, 29]

No single bearing, patent or algorithm accounts for the gain. The history of therapeutic LINACs is best understood as the gradual removal of the largest uncertainty at each stage: energy, pointing, anatomy, beam shape, patient position and internal motion. New equipment succeeds when several of those problems are solved together, reliably enough to be used every day. [1, 9, 10, 20]

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39. National Cancer Institute. TomoTherapy treatment image; NCI public-domain media via Wikimedia Commons. Full source

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