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Review

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Upright, gantry-less treatments for particle therapy: a potential paradigm shift

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Abstract

Particle therapy can offer physical and biological advantages over conventional photon radiotherapy, yet its widespread adoption remains limited by the cost, scale, and complexity of the accelerators and rotating gantries involved. Upright patient positioning with fixed-beam delivery has re-emerged as a potential alternative that may simplify particle therapy systems. Here we consider upright, gantry-less particle therapy through the lens of philosopher Thomas Kuhn's 5 criteria for scientific change: (1) simplicity, (2) scope, (3) fruitfulness, (4) consistency, and (5) accuracy. Eliminating rotating gantries stands to improve simplicity by reducing mechanical complexity, weight, and maintenance requirements. This in turn should enable more robust and modular treatment rooms. Early studies also suggest that upright positioning has broad scope: it can reproduce most beam geometries achieved using gantries and appears feasible across multiple anatomical sites. Upright treatments may be fruitful in terms of reducing capital, construction, and operational costs. They will also bring opportunities for technological innovation and potentially for improved patient throughput due to faster ingress and egress. Regarding consistency, upright treatment postures more closely match normal, everyday physiology and are often associated with greater comfort for certain patient groups. Finally, in terms of accuracy, preliminary studies suggest suitable setup reproducibility and comparable treatment planning quality. Upright particle therapy, therefore, represents a promising alternative delivery model. Further treatment-planning studies, health-economic analyses, and prospective clinical trials are warranted to determine the role of upright systems alongside or in place of gantry-based systems.

Key words upright, upRT, gantry-less, particle therapy, seated, proton therapy, PBT, ion therapy

Introduction

Particle therapy—typically using protons or carbon ions—can offer both physical and biological advantages over conventional photon-based radiotherapy.[1] Its key physical advantage stems from the Bragg Peak, which enables conformal dose distributions with minimal exit dose, sparing healthy tissues. Particle therapy is typically delivered with patients in the supine position, a paradigm inherited from photon radiotherapy and supported by established immobilization and imaging systems (particularly supine CT scanners). However, the supine paradigm necessitates large and complex gantries to deliver particle beams from multiple angles around the patient. Fully rotating proton gantries often weigh over 100 tons.[2] Carbon ion gantries are even more expansive; consequently in 2026 only 4 centers worldwide treat patients using this technology.[3] The first carbon ion gantry to be built (Heidelberg, Germany) used conventional magnets and weighs over 600 tons (including 135 tons of magnets).[2] Carbon ion gantries constructed later in Chiba (Japan), Seoul (Korea) and Yamagata (Japan) employed superconducting magnets, reducing weights to approximately 300 tons in Chiba and around 200 tons in Seoul and Yamagata.[4,5] Nonetheless, the scale, complexity, and cost of such gantry systems has been acknowledged as a key barrier to the broader adoption of particle therapy.[6]

Upright positioning is well established and widely accepted in ocular proton therapy, where it has become the standard approach and has been successfully implemented with fixed beamlines around the world.[7] Seated proton therapy treatments have also been delivered for other anatomical sites[8] (primarily intracranial and head-and-neck indications) at several early centers, including the Harvard Cyclotron[9] (∼1980s, Boston, United States), iThemba labs (∼1990s, Cape Town, South Africa),[10] the Center de protonthérapie d' Orsay (∼1990s Orsay, France,

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United States),[11] the Midwest Proton Radiotherapy Institute (~2000s, Bloomington Indiana, United States),[12] and the ProCure Proton Therapy Center (~2000s, Oklahoma City, Oklahoma, United States). In recent years, there has been renewed interest in upright patient positioning, in which a seated or perched upright patient is rotated through a fixed treatment beam.[13,14] Since 2010, several additional in-house and commercial systems have further demonstrated the clinical feasibility of this approach for both proton and carbon ion therapy, as outlined in Table 1. Multiple vertical CT scanners, upright patient positioners and gantry-free beamlines are now entering the market, including from P-Cure (Israel), Leo Cancer Care (United States/United Kingdom), Mevion Medical Systems (United States) and Canon Medical Systems (Japan, in this case a diagnostic upright CT scanner, rather than one specifically for radiotherapy). Developments are also extending into the conventional, photon radiotherapy domain: in Melbourne (Peter MacCallum Cancer Center, Melbourne, Australia) a chair developed in-house is being combined with a conventional gantry-based photon linac, to explore the possibility of upright treatments using photons.[25] Leo Cancer Care is also developing a fixed-beamline linac, for upright photon radiotherapy.[26]

Although both commercial and research efforts in this area are accelerating, upright radiotherapy currently remains a niche technique, challenging long-established clinical workflows. Nonetheless, in a 2024 meeting of 81 international particle

Table 1 Centers delivering upright proton or ion radiotherapy for indications beyond ocular treatments, active since approximately 2010; data sought and confirmed via personal correspondence.

Center	Brief details of beamline, patient positioning system and upright imaging system	Treatment dates	Number of patients and clinical indications treated upright
Centre de protonthérapie d'Orsay, Orsay France	IBA proton cyclotron with: one full gantry, one fixed beam room dedicated to ocular tumors with a custom robotic chair, one fixed beam room dedicated to skull and brain tumors with a custom robotic chair and couch. X-ray radiography for positioning.	1991-present	>9000 eye treatments. >1000 patients treated for intracranial or head and neck indications, upright (upright alone or combined upright and couch treatments).
Northwestern Medical Proton Center, Chicago, USA	4 IBA proton therapy treatment rooms: one full gantry, two rooms with multiple inclined beam lines (30° and 90°), and one room with a single fixed beamline (90°). One chair designed for cranial treatment, one chair designed for thorax treatments. An IBA KUKA robot transports the chair. Upright treatment uses an upright CT scanner from P-Cure.	2012-present	>825 patients treated. 60% ocular, 27% brain, 6% head and neck, 4% Lung, 3% other.
Protvino City Hospital, Protvino, Russia	Proton Therapy Complex Prometheus (Gen 1; JSC Protom, Protvino, Russia)[15,16]: a proton synchrotron with a single fixed beamline. A fixed treatment chair with 360° rotation and vertical height adjustment. In-beamline X-ray CBCT imaging.	2015-2019	~75 patients treated. Head and neck, brain.
A. Tsyb Medical Radiological Research Centre (MRRC), Obninsk, Russia	Proton Therapy Complex Prometheus[17,18] (Gen 2; JSC Protom, Protvino, Russia): a proton synchrotron with a fixed beamline in a single treatment room; hexapod-based (6D + height adjustment) chair and horizontal patient deck; robotic C-arm X-ray CBCT imaging.	2016-present	>1300 patients treated. Head and neck, brain.
Shanghai Proton and Heavy Ion Centre, Shanghai, China	Fixed horizontal proton and carbon ion beamline from Siemens. 360° rotating chair manufactured in-house with 6 degrees of freedom and X-ray radiography for positioning.[19,20]	2019-present	>370 patients treated. 84% head and neck, 11% ocular (macular degeneration), 5% brain.
Hadassah Medical Center, Jerusalem, Israel	P-Cure Proton Therapy System (P-Cure Ltd., Shilat, Israel): proton synchrotron with a fixed beamline; robotic-based 6-DoF patient positioning system (chair-based and horizontal configurations); vertical treatment-planning CT with X-ray radiography/fluoroscopy for positioning.[21-24]	2023-present	>100 patients treated. 43% head and neck, 20% thoracic, 18% brain, 14% pediatric, 4% abdominal, 1% pelvic.

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therapy leaders, upright positioning was noted as a "desired clinical technological development," for some but not all patients.[27] Further, in a recent debate held at the 2026 ESTRO congress, nearly 70% of the audience backing upright proton therapy as a mainstream treatment option by 2035.[28] The growing momentum within both expert and broader scientific communities, therefore, begs the question: will upright patient positioning constitute a paradigm shift in particle therapy?

The concept of a paradigm shift was originally characterized by the philosopher Thomas Kuhn in his 1962 book "*The Structure of Scientific Revolutions*."[29] Throughout his career, Kuhn continued to explore the factors that lead to established scientific paradigms being abandoned in favor of new ones. In his essay "*Objectivity, Value Judgment, and Theory Choice*" Kuhn proposed 5 criteria which, when applied to a new scientific theory, influence whether that theory is adopted. The criteria were: simplicity, scope, fruitfulness, consistency and accuracy.[30] Kuhn noted "I select five, not because they are exhaustive, but because they are individually important and collectively sufficiently varied to indicate what is at stake."[30] In this editorial, we examine upright, gantry-less particle therapy through the lens of Kuhn's 5 criteria.

Simplicity

Kuhn's criterion of "simplicity" relates to elegance and reduction of unnecessary complexity. Particle therapy accelerator and beam delivery systems are complex systems. Steering a proton (let alone a carbon ion) beam at clinical energies requires strong, fast ramping magnets. Consequently, particle therapy gantries require the coordinated rotation of highly complex and massive subsystems, such as magnets, accelerator waveguides, high-voltage power supplies, water-cooling infrastructure and extensive cabling.[31] Rotating all these mechanical and electrical components not only drives the high weight, size and cost of particle therapy gantries, but also introduces additional potential points of failure. The gantry-based approach also requires rotation of the final beam-shaping and control elements within the "nozzle," making it especially challenging to integrate new components, such as additional detectors or beam modulating devices. Gantry sag is a known issue, whereby the isocenter shifts slightly at different gantry angles as a result of the gantry weight.[32] Accurate commissioning and quality assurance, therefore, necessitates quantifying mechanical inaccuracies and their effects on treatment fields across gantry angles. The heavy-ion gantry at Heidelberg Ion Beam Therapy (HIT) Center has only 20 different beam angles commissioned for clinical use.[33] Finally, rotating the beam around the patient also limits the space around the isocenter available for introducing new devices, such as proton imaging or beam monitoring systems measuring secondary radiation.

Fixed-beam approaches eliminate the requirement to rotate the components needed for beam shaping and delivery, offering a mechanically simpler system. Fixed beamlines may, therefore, be made more robust and modular, meaning that they are easier to maintain and upgrade. Improved upgradability is particularly attractive, as many emerging modalities such as FLASH or minibeams would require beamline modifications.[34,35] This modularity also aligns with broader efforts to improve the environmental sustainability of radiotherapy equipment: as the first commercial proton gantries reach the end of their useful life, it has been acknowledged that upgrading proton gantries is extremely challenging.[36] Eliminating gravitational variation associated with different beam-line orientations represents a further simplification, as the challenge of maintaining beam stability under changing gravitational loads is absent in fixed-beam systems. Commissioning and quality assurance can likewise be streamlined for upright, gantry-less systems, since dosimetric data and quality assurance are required for only a single beam angle. The fixed beam direction also simplifies the integration of additional beam monitoring systems. For example, a beam stop distal to the patient could incorporate a fixed particle detector to enable treatment verification with shoot-through beams.[37] Compared with gantry-based proton/particle imaging, that would be a substantial simplification, eliminating the need to rotate the detector equipment around the patient. Similarly, fixed beam lines enable the realization of at-isocenter, diagnostic quality fan-beam CT imaging, whereas CT-imaging within particle gantry rooms has previously been limited to the "fan-based CT on rails" concept, or gantry-based cone-beam CT. It can be argued that, in terms of adaptive radiotherapy, it will be a simplification for repeat/daily imaging to exactly match the pretreatment CT. From a computational treatment planning perspective, there is no fundamental increase/decrease in complexity. A simple coordinate transformation can be introduced to optimize the treatment plan for an upright, rather than a supine patient position.[38]

To date, studies of upright treatment workflows tentatively suggest the potential for simplification, largely related to easier patient ingress and egress compared with a supine couch, an aspect also relevant to upright radiology.[39] However, studies that explicitly report set-up and treatment times remain sparse for both upright and conventional supine radiotherapy. Direct comparison between studies is further limited by heterogeneity in treatment protocols, patient cohorts, disease sites, immobilization strategies, and definitions of workflow timepoints. A study from Protvino (Russia) reported that patients spent an average of 10 min 12 s (~50 patients, 1464 fractions) in the treatment room, for upright proton therapy for head and neck tumors (using thermoplastic masks, as standard for supine treatments).[18] In Miami (United States), supine proton therapy for head and neck cancer was associated with an average treatment time of 37 min,[40] whereas in Sapporo (Japan) it was associated with a mean treatment time of 24 min.[41] When a team of 2 therapeutic radiographers conducted repeat set-up tests of upright positioning for pelvic radiotherapy, Boisbouvier et al reported an average repeat set-up time of 2.9 min (range 2-4 min).[42] For a pelvic cohort treated supine, Qubala et al[43] reported a mean supine set-up time of 5:57 ± 2:11 min and s (mm: ss) when utilizing skin marks, vs 04:54 ± 01:06 when utilizing surface guidance. These initial results, therefore, suggest that upright workflows can be streamlined, but further, robust research is required.

While the arguments above favor simplicity, it is important to acknowledge that upright positioning will introduce some new complexities of its own. Upright positioning will lead to anatomical configurations that differ from the current radiotherapy knowledge base. Modern radiotherapy has been developed predominantly around supine treatments, and translating clinical

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protocols to upright treatments will involve a steep learning curve. For example, initial optimization of patient set-up positions and immobilization will be required, upright motion and other uncertainties will need to be characterized and considered in margin recipes, supine dose optimization objectives and constraints may need to be re-assessed. Exactly which aspects of clinical workflow require adaptation to support upright particle therapy, and how complex the necessary changes will be, remains a question of contemporary interest.[13] Over the coming months and years, we anticipate growing clinical experience with upright radiotherapy will shed further light on the necessary adaptations.

Fruitfulness

Kuhn's "fruitfulness" criterion emphasizes the potential of a new scientific framework to generate opportunities and advantages beyond those achievable within the existing paradigm. For upright particle therapy, fruitfulness stems from (1) economic aspects and (2) technological opportunities.

From a financial perspective, upright systems are anticipated to reduce costs throughout the facility lifecycle.[44] Fixed beam systems are lighter, smaller, and composed of fewer physical parts than gantry-based installations, lowering equipment costs and reducing mechanical complexity. Operational costs should also decrease, as simpler and more modular systems should lower expertise thresholds, potentially reducing a clinic/company's reliance on highly specialized staff. Power consumption might reasonably be expected to fall when (1) the need to rotate a heavy gantry is eliminated and (2) the 3D volume of the vault which requires heating/cooling is dramatically reduced.

For new treatment centers, construction and deployment costs should be reduced. Smaller system footprints decrease bunker shielding and structural requirements. They may even allow compact proton systems to be installed within existing hospital infrastructure, such as conventional linear accelerator vaults. This integration could embed particle therapy within standard radiotherapy departments rather than necessitating purpose-built centers. Installation and commissioning is likely to be faster: at McClaren Proton Center (Michigan, Flint), the mechanical installation of the upright treatment patient positioner and CT scanner took 21 days to the point of powering on (rather than calibration), whereas for the proton gantries within the center, installation took months. Maintenance burdens may decrease: fewer moving components should lead to reduced wear and tear, and it should be more straightforward to replacement failed parts within fixed beamlines. Improved patient ingress and egress may further increase throughput, enhancing daily treatment capacity.

Despite these promising prospects, economic fruitfulness remains to be fully demonstrated. Data on service records, operational efficiency and clinical performance are still limited and largely unpublished. The economics of upright treatments will clearly require full consideration across various upright system designs and healthcare systems around the world. As a counter argument to expected reductions in installation cost, transitional costs associated with making a paradigm change, for example, duplicating equipment and training, if working with both upright and supine treatment rooms, must also be considered.

Beyond possible economic and operational advantages, upright positioning clearly creates opportunities for technical innovation and fruitfulness, by freeing space and simplifying engineering around the room isocenter. One of the most critical challenges faced by particle therapy resides in uncertainties in the beam range within the patient. Range uncertainties necessitate the use of treatment margins and robust plan optimization, somewhat counteracting particle therapy's intrinsic potential for sharp dose conformation to the clinical target volume. Better imaging prior to treatment, such as dual-energy CT,[45,46] could reduce range uncertainty while also enabling plans tailored more closely to the anatomy of the day. Further, the possibility of integrating diagnostic-quality CT within the treatment room could aid adaptive RT workflows[47] and accelerated "straight-to-treatment" or "simulation free" pathways,[48,49] both of which are important areas for development within supine radiotherapy.

The simplified nature of gantry-less geometries should also lower barriers to the implementation of techniques long explored in research settings. In-beam MRI-guided proton therapy, for example, using ultra-low field scanners[50] or open-bore MRI systems,[51] should be far easier to realize without a large, metallic rotating gantry whose ferromagnetic and conductive components would perturb the magnetic field, degrade image quality, and introduce substantial engineering challenges associated with magnetic compatibility, shielding, and system integration. Following on from MR-linac experiences, it might be expected that live MR-guidance for particle therapy should be fruitful in terms of improved soft-tissue contrast, the possibility of tumor tracking/beam gating and margin reduction. The use of fixed detectors placed behind a rotating chair has also been proposed as a substantially simpler engineering solution (than gantry-mounted systems) for proton radiography, and potentially proton CT. If successfully implemented, these techniques could enable setup verification,[52] improved CT calibration[53] or even direct planning on proton CT-derived relative stopping power maps.[54] Similarly, the additional space around the patient could also facilitate easier incorporation of prompt gamma or other secondary-particle monitoring systems, some of which have already seen clinical deployment.[55,56]

Upright configurations may also support new hybrid treatment environments, such as combined photon-proton treatments within a single room.[57] Boron Neutron Capture Therapy is one emerging particle therapy approach which is essentially incompatible with gantry-based deliveries, but has been used together with upright positioning.[58] The therapeutic potential application of charged particles even heavier than carbon, such as neon[59] is currently also under investigation, but the utility of these beams would be very limited without the range of beam-angles afforded by rotating an upright patient. In this sense, upright positioning should function as a more modular and adaptable platform for innovation.

Broad scope

Kuhn's criterion of "broad scope" concerns the breadth of phenomena that a framework can accommodate and, in this case, the diversity of applications it can support. Here this translates to a key question: can upright positioning treat the same range

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of patients and indications as gantry-based particle therapy, or even extend that range further?

In part, this question was addressed in the work by Yan et al[60] who reassessed the need for a gantry across more than 4000 patient treatments at the Francis Burr Proton Therapy Center at Massachusetts General Hospital (Boston, MA, United States). They showed that, in principle, moving the patient should enable replication of the vast majority of beam angles typically delivered by a proton gantry. Although it cannot yet be stated conclusively that upright positioning is feasible for every patient group, largely due to ongoing technical developments and limited clinical experience in some subgroups, no indication has been definitively ruled out from upright treatment to date.

The clinical feasibility of upright radiotherapy has already been demonstrated across multiple disease sites (Table 1). Patients requiring head and neck radiotherapy have been treated in an upright position at several centers, including the Center de protonthérapie d' Orsay (Orsay, France),[61] the Northwestern Medicine Chicago Proton Center (Chicago, IL, United States), the Shanghai Proton and Heavy Ion Center (Shanghai, China), [19] the A. Tsyb Medical Radiological Research Center (Obninsk, Russia),[18,62] the Protvino City Hospital, (Protvino, Russia), and the Hadassah Medical Center (Hadassah, Israel).[22,23] Thoracic cases have also been treated in Chicago[63] and Hadassah. Although published evidence for abdominal and pelvic treatments remains limited, such treatments appear technically feasible.[64] Notably, even pediatric craniospinal irradiation has been delivered under anesthesia in an upright position, as recently reported from Hadassah Medical Center.[24] These results suggest that upright positioning can at least replicate much of the clinical scope currently achieved with gantry-based systems.

Due to preexisting comorbidities such as cardiac insufficiency, pulmonary disease, and orthopnea (shortness of breath when lying flat), some patients are unable to tolerate conventional supine positioning for radiotherapy.[65] Upright positioning has, therefore, been explored as a practical alternative. In Maastricht, seated photon radiotherapy was successfully used for a cohort of patients with advanced lung cancer who required palliative radiotherapy, but could not lie down because of dyspnoea.[66] Similarly, semi- or fully upright techniques have been described in several photon radiotherapy case reports in which supine positioning was not feasible, including patients with bilateral phrenic nerve injury and diaphragmatic paralysis,[67] excessive salivation associated with head and neck cancer,[65] severe respiratory compromise,[2] or musculoskeletal limitations such as limited mobility and kyphosis.[68] Even relatively common conditions, such as frozen shoulder, restrict compliance with "arms-up" supine setups, and upright approaches may provide more comfortable and tolerable arms-down alternatives.[5] Moreover, as the demographic profile of radiotherapy patients shifts toward older age groups[69] with higher burdens of comorbidity, limitations in positioning tolerance and performance status will become increasingly relevant. Upright positioning in general may expand access to radiotherapy, by enabling treatment for patients who would otherwise struggle to tolerate or complete a supine course of treatment. However, its feasibility in patients with orthostatic intolerance, autonomic dysfunction, severe frailty, or impaired postural control is, as yet, poorly characterized.

Upright positioning could also broaden the scope of existing treatment infrastructure, particularly for carbon ion therapy. Only 4 clinical centers worldwide operate carbon ion gantries, whereas thirteen additional centers operate with fixed carbon ion beam-lines (PTCOG registry,[3] January 2026). Consequently, carbon ion radiotherapy is typically delivered with supine postures, with limited beam angles, achieved either by couch rotation,[70] and/or by supplementary vertical or oblique beamlines.[3] A recent study from the Shanghai Proton and Heavy Ion Center demonstrated that, upright positioning improved beam angle optimization and organ sparing for head and neck treatments delivered using a fixed beamline.[71] Upright positioning, therefore, has the potential to expand the clinical capability of these existing facilities without requiring gantry installation.

Certain particle therapy delivery strategies are likely to benefit from upright geometries. Particle arc therapy has recently entered clinical application[72] and shows promise for improving treatment efficacy,[73] including through LET optimization.[74,75] Although proton/ion arc delivery can be performed with gantries it will likely be simplified by rotating the patient instead of the beam (the requirement to change gantry magnet parameters during rotation will be eliminated). This streamlining is especially relevant for heavy ions. A recent study reported a total delivery time of 27 min for a static arc delivered on the carbon ion therapy gantry at Heidelberg Ion Beam Therapy Center (Heidelberg, Germany).[33] In part this long arc time is due to the large gantry inertia, whereas upright patient positioners typically rotate at speeds of 1 rpm.

Besides these examples, through technological fruitfulness (as discussed above), upright positioning may ultimately broaden the list of clinical indications where particle therapy is indicated. For example, if the implementation of proton imaging/MR-guidance is realized more easily upright, and this in turn permits more aggressive margin reduction, it could improve the treatment of targets close to critical structures. This could lead to new therapeutic advantages relative to conventional photon radiotherapy and could broaden the list of indications where clear Normal Tissue Complication Probability/and Tumor Complication Probability benefits from proton/particle therapy are anticipated. Last but not least, upright treatments are likely to broaden the scope of particle therapy through the economic points discussed in the section above: cost-savings associated with upright radiotherapy could help to "democratise" particle therapy, making it more widely available.[44]

Consistency

Kuhn's "consistency" criterion requires that any novel conceptual framework remains concordant with established empirical knowledge. For upright radiotherapy, this consideration perhaps centers on whether treatment delivered in the upright posture is consistent with normal anatomy, physiology and patient experience.

From a physiological perspective, upright positioning is more congruent with patients' habitual daily posture, as most waking hours are spent seated or standing rather than supine. Immediately following adoption of a supine treatment position, internal anatomy will continue to evolve due to a combination

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of (1) redistribution of abdominal contents under gravity, (2) tissue relaxation, and (3) ongoing physiological processes such as bladder filling and bowel motion. An MRI study performed for a single male volunteer (in the context of automotive safety modelling) demonstrated that, relative to bony anatomy, the liver and right kidney were displaced caudally when the participant transitioned from a supine to an upright posture, whereas the spleen and the left kidney were displaced cranially.[76] In the context of radiotherapy, Reiff reported caudal kidney shifts (for both left and right kidneys) when 15 patients transitioned from supine to upright, with greater shifts being observed for the right kidney[77] (the right kidney is ipsilateral with the liver, the heaviest internal organ). Similarly, a time-resolved 4D MRI study from von Siebenthal et al. demonstrated baseline drift of abdominal organs after patients adopted a recumbent position, with progressive cranial liver drifts of up to 20 mm over 30 min ($n = 15$).[78] In a CT-based study involving 51 healthy volunteers, it was noted that, relative to supine positioning, upright positioning pushes the prostate, bladder, and rectum downward under gravity, and stretches these organs in the left-right and anterior-posterior directions,[79] findings supported by a further MRI study, which considered anatomical landmarks for 15 healthy volunteers.[64] A CBCT-based study of online adaptive supine SABR for pancreatic tumors ($n = 26$) reported reductions in bowel gas artifact following adaptation, which the authors attributed to bowel settling during prolonged supine positioning.[80] These findings suggest that posture changes themselves introduce anatomical variability, and that maintaining patients in an upright position—closer to their natural pretreatment state—may mitigate some gravity-driven organ drift. However, additional physiological factors, such as gastric emptying and other time-dependent visceral processes, may also impact posture-related organ motion and this needs to be further evaluated in the future clinical studies.

Respiratory motion represents an additional challenge for accurate particle therapy delivery. While the effects of upright posture on the respiratory-driven motion are not yet fully characterized, available data suggest that the magnitude of such motion may be reduced upright. Movements of the heart, lungs, liver, and diaphragm have been reported to be smaller in the upright position compared with supine,[81] and lung volumes typically increase.[82] Despite these potentially favorable trends, further studies are required to characterize motion patterns comprehensively and to determine their impact on delivery accuracy.

Consistency must also be considered from the patient's experiential perspective. Several studies have reported that conventional supine radiotherapy can be associated with emotional vulnerability and physical discomfort.[83,84] In one small study conducted in France, 7/9 women treated with conventional photon radiotherapy for breast cancer indicated a preference for upright positioning.[85] This was followed by another study in France for patients with breast and lung cancer treated with conventional radiotherapy, where 9/15 preferred upright positioning for physical comfort, whereas only 1/15 preferred supine positioning (the remaining 5/15 had no preference).[86] Similarly, in another study conducted in the United Kingdom, 7/9 former breast radiotherapy patients again reported greater comfort during a trial of upright positioning.[84] In the latter study, 6/9 former patients described the supine position as making them feel vulnerable, compared with only 1/9 for upright set-up, and 9/9 participants reported that they anticipated a stronger sense of social connection with therapists, when treated upright.[84] These findings suggest that upright positioning may align more closely with patients' perceptions of comfort, dignity, and engagement during treatment.[84]

Practical considerations further support this alignment with everyday experience. Many patients with reduced mobility find it easier to transfer into and out of a chair than onto a supine treatment couch. In a small-scale study of 11 prostate cancer patients treated with radiotherapy, 4/11 participants reported they had difficulties lying down or getting up from the supine treatment position, and 9/11 participants indicated that it would be easier to get in/out of the treatment chair.[87] In the same study, 6/11 of the participants who received supine prostate radiotherapy preferred the upright positioning they trialed, 3/11 were "not sure" and 2/11 preferred "lying down."[87] Similarly, in another study which investigated upright positioning in men and women who received pelvic radiotherapy 14/16 of participants reported being more comfortable upright, and once again participants generally described easier ingress and egress with upright positioning.[42] Such factors may improve tolerability and facilitate clinical workflows, particularly for frail or elderly patients.

For certain subgroups, the potential comfort benefits of upright positioning are likely to be particularly pronounced. For example, airway obstruction is typically reduced with erect postures,[88] a factor likely to make it easier for patients with pre-existing respiratory conditions to tolerate upright treatments. In patients with head and neck cancer, excessive salivation is frequently reported and can contribute to discomfort during treatment. Maintaining an elevated posture may reduce pooling of secretions within the pharynx, thereby lowering the risk of choking and facilitating airway clearance.[65] Clinically, it has been reported that patients undergoing treatment for head and neck cancer who are otherwise fit—and who tolerate radiotherapy lying flat—often report distress related to mucus accumulation, choking sensations, or orthopnea when treated in the supine position.[65] Consistent with these observations, additional conference presentations have indicated a strong preference for upright positioning among patients who received radiotherapy for head and neck cancer,[89,90] and the clinical evidence base for upright radiotherapy is currently most developed for this cohort (Table 1).

Despite these promising observations, consistency with patient experience is not universal. Preferences for treatment posture are heterogeneous,[87] and upright positioning may be less suitable for certain subgroups (such as patients with sacral chordoma tumors, who sometimes experience pain when seated). Moreover, the initial data on patient perspectives derives from small, exploratory studies, and enthusiasm for novel technology may influence subjective assessments. Larger, systematic investigations are, therefore, required to determine whether upright positioning reliably improves comfort, reduces perceived vulnerability, and supports routine clinical practice across diverse patient populations.

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Accuracy

Kuhn's criterion of "accuracy" requires a new paradigm to reproduce or improve upon the empirical performance of the existing standard of care. For upright radiotherapy, one might expect this criterion to concern whether geometric precision, dose delivery, anatomical reproducibility, and clinical outcomes are comparable to those achieved with conventional supine, gantry-based treatments.

Pre-clinical studies evaluating set-up accuracy indicate that upright positioning can deliver promising results in terms of inter- and intrafraction displacement, for the pelvic,[42] breast,[85,91] and head and neck regions.[92,93] Similarly, published clinical data on upright radiotherapy displacements is growing for the head and neck treatments,[18,19,22] and clinical outcome data reports are starting to emerge.[62] Collectively, these findings suggest that accurate and reproducible treatment delivery is feasible in the upright position, but further data is needed to make solid conclusions regarding the relative set-up and treatment accuracy of supine vs upright treatments.

A practical impediment worth acknowledging is the current scarcity of upright imaging infrastructure. Vertical CT scanning has been explored at Keio University (for many different radiology applications) using a prototype multi-position system from Canon.[94-97] but only relatively recently have vertical CT capabilities directly relevant to radiotherapy planning been described.[21,98] Dosimetric comparisons between upright and supine positioning remain limited. The first large-scale upright vs supine treatment planning study[79] considered photon (VMAT) treatments of the prostate, based on CT scans for 51 asymptomatic volunteers, scanned using the Keio University CT scanner. Dose distributions for the upright and supine plans were clinically comparable with respect to target coverage and organ-at-risk sparing, despite substantial anatomical differences. Although further studies are warranted, particularly for proton therapy, this current evidence suggests that upright positioning can achieve prostate treatment plans of similar quality to the supine standard.[79] For carbon ion therapy of the pancreas, a smaller treatment planning study ($n = 14$) reported several key anatomical and dosimetric advantages of the for the upright posture (vs supine positioning), including reduced dose to the bowel.[99]

Advances in image-guided and adaptive radiotherapy provide additional safeguards to maintain geometric and dosimetric accuracy in the upright setting. Current upright particle therapy systems incorporate daily upright fan-beam CT-based image guidance for treatment verification, [100] enabling detection of day-to-day anatomical variation. Offline replanning between fractions and online adaptive workflows then further allow correction for anatomical changes during treatment,[101] and these can be streamlined within upright workflows compared to conventional gantry-based approaches (where typically cone beam CT is employed). On the other hand, upright MRI scanners are currently low-field and limited in availability; consequently, supine MRI will likely remain an important component of the upright radiotherapy workflow for target and OAR definition. While methods for supine MR to upright CT registration have been proposed,[102] software tools required for this purpose are yet to be fully validated, a gap that still needs to be addressed.

At present, claims that upright radiotherapy may improve clinical accuracy typically derive from small-scale clinical or pre-clinical studies. Larger, prospective, and ideally harmonized datasets—if not formal clinical trials—will be necessary to establish the accuracy of upright radiotherapy more definitively. It should be noted that upright workflows adopted around the world are likely to be diverse, particularly in terms of immobilization, where various options will be available,[92] which may affect clinical results. Many of these factors are of course relevant to particle therapy more broadly, and to supine radiotherapy in general, but the roll-out of upright positioning presents an opportunity to consider multi-center harmonization from the start. Finally, a distinction must be made between "upright" and "compact" particle therapy systems: although upright configurations may enable smaller facilities, design choices made to minimize size may influence achievable plan quality. For example, compact accelerator designs employing passive energy switching close to the patient may necessitate collimators or shoot-through layers to achieve steep dose gradients.[37] Consequently, realized treatment accuracy is likely to remain partly vendor- and partly implementation-specific.

Conclusion

The evolution of science often involves subjective decisions as well as objective ones. As Kuhn observed: "the criteria of choice with which I began function not as rules, which determine choice, but as values, which influence it. TWO men deeply committed to the same values may nevertheless, in particular situations, make different choices as, in fact, they do. But that difference in outcome ought not to suggest that the values scientists share are less than critically important either to their decisions or to the development of the enterprise in which they participate. Values like accuracy, consistency, and scope may prove ambiguous in application, both individually and collectively; they may, i.e., be an insufficient basis for a shared algorithm of choice. But they do specify a great deal: what each scientist must consider in reaching a decision, what he may and may not consider relevant, and what he can legitimately be required to report as the basis for the choice he has made."[30]

In the authors' view, upright particle therapy offers clear advantages in simplicity, scope, and potential for further development (fruitfulness), while showing promising alignment with consistency and accuracy. Although it remains to be definitively established whether these gains extend across a broad range of clinical indications or are most pronounced in specific patient subgroups, the emerging evidence is encouraging. Clarifying the breadth of these benefits will be key to defining the future role of upright positioning. If confirmed across diverse indications, upright positioning has the potential to represent a genuine paradigm shift in particle therapy rather than merely a complementary alternative to the established supine model.

Addressing this uncertainty will require further rigorous investigation, including studies of patient set-up and experience, motion quantification, treatment planning comparisons, and ultimately prospective clinical trials, as well as health-economic analyses. Such evidence will clarify whether upright positioning's practical advantages translate into meaningful clinical benefit.

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We should also acknowledge the limitations of the framework we have applied in this manuscript. Kuhn's criteria were developed to describe revolutions in pure science—physics, chemistry, biology—where paradigms are often overturned by conceptual incompatibility. Radiotherapy is not so black and white. Upright and supine positioning for particle therapy can, and almost certainly will, coexist clinically in a way that, for example, phlogiston and oxygen could not,[103] to name just one example. In the case of particle therapy, a paradigm shift, if it comes, is more likely to be gradual and pragmatic rather than sudden and total.

Many of the same criteria-based considerations could also apply to conventional photon radiotherapy delivered upright. However, in particle therapy, the potential simplifications and cost savings are particularly substantial, given the complexity, size, and expense of rotating gantry systems and the large, shielded vaults required to house them. Consequently, the implications of upright delivery may be especially transformative in this domain.

We close by reflecting on Kuhn's words: "however incomprehensible the new theory may be to the proponents of tradition, the exhibit of impressive concrete results will persuade at least a few of them that they must discover how such results are achieved. For that purpose, they must learn to translate, perhaps by treating already published papers as a Rosetta stone, or, often more effective, by visiting the innovator, talking with him, watching him and his students at work. Those exposures may not result in the adoption of the theory; some advocates of the tradition may return home and attempt to adjust the old theory to produce equivalent results. But others, if the new theory is to survive, will find that at some point in the language-learning process they have ceased to translate and begun instead to speak the language like a native."[30]

This observation from Kuhn resonates with upright particle therapy's current status. The field is neither at the beginning—pre-clinical research has been performed, dosimetric comparisons are being made, clinical treatments are being delivered—nor near resolution. We are still in the translation phase: some colleagues are visiting the innovators, some are attempting to mirror upright developments within supine frameworks, and a few may already be speaking the new upright 'language' natively. It is hoped that manuscripts such as this one will aid the discussion and translation.

Ultimately, however, upright, gantry-less particle therapy may be judged not by its conceptual appeal, but by the clarity, robustness, and persuasiveness of its empirical results.

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Conflicts of interest

Dr T.S.A.U. is employed by Leo Cancer Care, a company who develop equipment for upright radiotherapy. Dr L.V. is a coordinator of the UPLIFT Marie Curie Doctoral Training Network on upright radiotherapy. Dr H.G. is Medical Director at McClaren Proton Therapy Center (Flint, Michigan), a clinic preparing to commence upright proton therapy. The views are the authors' own.

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