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Review Article

Enabling gantry-less radiotherapy through upright patient positioning: Current consensus and future direction

Petra Trnkova [a,1], Tracy Underwood [b,c,1], Rasmus Bokrantz [d], Erik Engwall [d], Carri Glide-Hurst [e], Cristina Garibaldi [f], Lars Glimelius [d], Taku Inaniva [g], Oliver Jäkel [h,i], Simon Jolly [j], Tony Lomax [k,l], Maria Chiara Martire [m], Vincenzo Patera [n], Lorenzo Placidi [o], Alexander Pryanichnikov [p,q,r], Ilaria Rinaldi [s], Gordon Sands [b,c], Esther G.C. Troost [t,u,v], Alessandro Vai [w], Ye Zhang [k,2,*], Lennart Volz [m,2]

[a] NucleOn - Centre for Nuclear Research in Oncology, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[b] Research Department, Leo Cancer Care, Crawley, United Kingdom
[c] Department of Medical Physics and Biomedical Engineering, University College London, London, United Kingdom
[d] Research and Development, RaySearch Laboratories, Stockholm, Sweden
[e] Department of Human Oncology, University of Wisconsin Madison, Madison, USA
[f] Radiation Research Unit, European Institute of Oncology IRCCS, Milan, Italy
[g] Department of Accelerator and Medical Physics, National Institutes for Quantum and Radiological Science and Technology, Chiba, Japan
[h] Heidelberg Ion beam Therapy centre, Heidelberg University Hospital, Heidelberg, Germany
[i] Medical Physics in Radiation Oncology, German Cancer Research Centre (DKFZ), Heidelberg, Germany
[j] Dept of Physics & Astronomy, University College London, London, United Kingdom
[k] Centre for Proton Therapy, Paul Scherrer Institute, Villigen-PSI, Switzerland
[l] Department of Physics, ETH Zurich, Zurich, Switzerland
[m] Biophysics, GSI Helmholtz Center for Heavy Ion Research GmbH, Darmstadt, Germany
[n] Department of Basic and Applied Science for Engineering, Universita' di Roma "Sapienza", Roma, Italy
[o] Fondazione Policlinico Universitario Agostino Gemelli, IRCCS, Department of Diagnostic Imaging, Oncological Radiotherapy and Haematology, Rome, Italy
[p] Division of Biomedical Physics in Radiation Oncology, German Cancer Research Centre (DKFZ), Heidelberg, Germany
[q] Institute of Biomedical Engineering, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[r] Research and Development, P-Cure Ltd./Inc, Shilat, Israel
[s] Department of Radiation Oncology (Maastro), GROW School for Oncology, Maastricht University Medical Centre+, Maastricht, Netherlands
[t] OncoRay-National Centre for Radiation Research in Oncology, Dresden, Germany
[u] Department of Radiotherapy and Radiation Oncology, Faculty of Medicine and University Hospital Carl Gustav Carus, TUD Dresden University of Technology, Dresden, Germany
[v] Institute of Radiooncology - OncoRay, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
[w] Department of Radiation Oncology, National Centre for Oncological Hadrontherapy, Pavia, Italy

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ABSTRACT

Purpose: Gantry-less radiotherapy with a fixed treatment beam, in which an upright patient is slowly rotated, promises reductions in treatment room costs and could offer anatomical / comfort benefits for certain patients. Several radiotherapy centres worldwide have now designed or acquired upright patient immobilization systems; however, many aspects of the upright treatment workflow are yet to be fully addressed.
Materials & Methods: During the 2024 ESTRO physics workshop on "Gantry-less Radiotherapy: Challenges and Opportunities", 22 participants, including medical physicists, a radiation oncologist, academics and representatives from industry, discussed in-depth the open questions and existing solutions for clinical implementation. Clinical aspects, technical and implementation challenges, opportunities and a "wish-list for vendors" were addressed.

* Corresponding author.
E-mail address: ye.zhang@psi.ch (Y. Zhang).
[1] Shared first author.
[2] Share last author.

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Results: Imaging and immobilisation present crucial challenges, but ongoing research projects and industrial development are progressing in both areas. However, the lack of upright patient data, data sharing issues, and the limitations associated with data generation have been recognized as significant obstacles to achieving clinically meaningful evaluations. A priority-ranked wish-list for vendors, covering immediate clinical needs and future opportunities is presented as one result of the experts' discussion.
Conclusion: Gantry-less radiotherapy with upright patient positioning holds significant promise for simplifying treatment delivery, improving accessibility, reducing costs and providing a streamlined platform for innovative new technologies. However, many challenges remain. The most critical part is clinical and technical evidence. Realizing the potential of gantry-less treatments will require continued collaborative efforts from academia, hospitals, and industry, ideally supported by national and international societies.

1. Introduction / overview

Gantry-less radiotherapy (RT) with particles and photons offers compelling potential advantages over conventional gantry-based RT. The elimination of the rotating gantry significantly reduces the physical footprint and installation requirements of the equipment, making RT more compact and potentially cheaper. Simplifying the system should also permit improved RT availability, especially for particle therapy (PT) [1,2]. Without the mechanical constraints of a rotating gantry [3,4], gantry-less systems can achieve faster treatment delivery times. More open and modular beamline designs could also streamline maintenance, improve system reliability and offer easier commissioning and upgradability [2]. Current state-of-the-art beam delivery techniques enable comparable plan quality with both gantry-based and gantry-less systems [5].

Gantry-less radiotherapy approaches use either horizontal or upright patient positioning. Horizontal systems have been used for many years in PT with fixed beamlines and patient lying on treatment couch [6]. However, flexibility in beam angles selection is limited as it relies on rotating the couch. Several approaches for patient rotation around the longitudinal axis were investigated [7,8], but due compromised patient comfort and organ deformations under gravity, none has been implemented on a significant scale. In contrast, upright positioning systems with patients either seated or standing promise the same beam selection flexibility as gantry-based systems by rotation of an upright patient [2,9]. Moreover, several studies report on increased patient comfort and reduced anxiety with upright positioning [10,11].

As upright RT has emerged as a promising approach for gantry-less treatment paradigms, several commercial systems are currently in various stages of development and clinical implementation, but clinical experience remains limited. Single-institute studies have already demonstrated first clinical and pre-clinical experience with positioning accuracy [12,13], patient comfort [10,11,14,15] or impact on patient anatomy [16–19]. The expected benefits have also been reported in several reviews [2,9,20]. Ongoing research focuses on addressing challenges including motion management in the upright position [21], development of immobilization devices [22,23], optimization of image guidance workflows [24], expansion of the clinical evidence bases to exploit the anatomical benefits of upright posture [25–27] and investigating new treatment approaches that will be unlocked with upright positioning [28–30].

The momentum behind upright radiotherapy is increasing, but clinical implementation is lagging. Therefore, upright radiotherapy experts and interested parties gathered during the ESTRO 2024 physics workshop (18.-19.10.2024, Krakow, Poland) on *Gantry-less Radiotherapy: Challenges and opportunities* to derive pathways to clinical translation of the technology. In this work, the insights from the workshop are reported. The overview focuses on technical, implementation and workflow aspects. Additionally, considerations on potential clinical application, pre-clinical and clinical evidence are provided. The report is divided into following sections: (1) Clinical aspects, (2) Technical challenges, (3) Implementation challenges, (4) Opportunities, and (5) Wish-list for vendors.

1.1. Clinical aspects

To date, upright positioning has not been ruled out for any clinical indication treated with conventional radiotherapy. However, clinical evidence is sparse, and treatment parameters have not always been reported in a consistent manner [26,31,32]. A summary of published clinical evidence is provided in Table 1.

Small cohort studies on healthy or patient volunteers indicate that several treatment sites, including head and neck (H&N) [12], breast [11,14], lung [18], abdomen [17,36] and pelvic malignancies [16], may benefit from upright positioning as gravitational effects on anatomy and respiratory motion in the upright posture may offer dosimetric and/or physiological advantages. Additionally, expected improvements in patient comfort and potentially shorter set-up times, could expand RT access for patients who struggle to tolerate supine positioning due to orthopnoea, back pain, or other medical conditions. While initial findings are promising, more robust clinical data is needed for diverse patient groups, on: set-up repeatability and stability, motion management, internal anatomy, treatment plan quality, patient comfort, workflow timings and staffing requirements. In the future, the suitability and accuracy of upright positioning for complex applications such as reirradiation of patients previously treated in the supine position should also be considered.

Feasibility and possible benefits for paediatric patients remain to be addressed, particularly with regards to patient cooperation and the application of anaesthesia. A single case study has demonstrated the feasibility of upright cranio-spinal PT, with anaesthesia [31]. Additionally, it is challenging to deliver non-coplanar fields with current upright patient positioning systems, such that the suitability of upright positioning for intracranial tumours / stereotactic radiosurgery is yet to be determined.

Since clinical evidence is still limited, palliative treatments represent a particularly compelling early application. They could offer a practical pathway to evaluate positioning reliability and reproducibility, while allowing clinical teams to build confidence in workflows and system performance before broader adoption in curative settings.

2. Technical challenges

2.1. Imaging

Gantry-less RT with upright positioning introduces fundamental differences in imaging hardware, image acquisition [37] and posture-dependent anatomy and physiology [16–19] compared with recumbent workflows. Imaging therefore becomes a primary technical determinant of clinical feasibility of upright radiotherapy.

Currently, commercial solutions exist for upright CT [38–40] and upright MRI [41]. However, both are constrained by mechanical and bore clearance limitations around chair hardware, such as backrests and headrests as well as the need to accommodate immobilization accessories. For MRI, limited coil availability and patient comfort in even more restricted seated or semi-standing postures during longer scans can pose additional challenges. MRI scanners capable of upright imaging are

Table 1
Summary of current clinical evidence for upright radiation therapy. The presented studies are either prospective therapeutic trials or retrospective clinical reports or prospective imaging evaluation.

Author/ Year/ Ref	Imaging / RT Modality / Immobilization	Number of patients: Tumour site	Dose prescription / Fractionation schedule	Key Results- Geometric evaluations	Main findings/ Clinical outcome
Blumenfeld 2026 [31]	Vertical CT/ P-Cure PT System / thermoplastic mask	1 Paediatric: CNS relapse of neuroblastoma	18.0 Gy(RBE) in 12 fx with SIB of 21.6 Gy(RBE) to resection cavity followed by sequential boost to resection cavity in 5fx, (total dose of 30.6 Gy(RBE)	3D localization error Cranial isocentre x = 2.4 ± 2.5 mm y = 1.2 ± 1.9 mm z = 3.2 ± 4.5 mm φx = 0.5 ± 1.0 deg φy = 1.1 ± 1.0 deg φz = 1.7 ± 2.0 deg Spinal isocentre x = 2.1 ± 4.2 mm y = 0.1 ± 2.5 mm z = 1.2 ± 4.7 mm φ x = 0.0 ± 0.7 deg φ y = 0.0 ± 2.0 deg φ z = 0.2 ± 1.2 deg	The upright setup provided unobstructed airway access, enabling safe anaesthetic management. The patient tolerated daily anaesthesia well, maintained spontaneous respiration. No acute toxicities of grade ≥ 2.
Blumenfeld 2025 [26]	Vertical CT/ P-Cure PT System	20 Adults: Recurrent H&N (80 %), Brain (20 %)	H&N: 60–70 Gy(RBE) in 30–35 fx or 45–50 Gy(RBE) in 15–20 fx Brain: 54 Gy(RBE) in 30 fx or 35 Gy(RBE) in 10 fx	3D localization error χ = –1.4 ± 3.6 mm, Y = –2.6 ± 1.8 mm, Z = –0.1 ± 4.7 mm, φχ = –0.5 ± 1.1 deg, φy = –0.2 ± 0.9 deg, φz = –0.0 ± 1.0 deg	PT significantly reduced radiation exposure to OARs – Upright PT vs. supine IMRT: Follow-up 3 months (14 pts}: 9 CR, 3 PR, 2 SD. Most acute toxicities (grade 1–2): fatigue (45 %), mucositis (31.3 %, and skin dermatitis (55 %). • Spinal Cord D_{max} (14 pts) 12.5 Gy(RBE) vs. 18.3 Gy ($p < 0.006$) • Brainstem D_{max} (10 pts) 6 Gy (RBE) vs. 19.1 Gy ($p < 0.001$)
Sun 2025 [13]	In-house upright patient positioner with six degrees of freedom, used together with a supine couch, for proton and carbon ion therapy / thermoplastic masks	28 patients: H&N	A variety of fractionation schemes, e.g. 28 Gy(RBE) supine fractions using protons plus 5 upright fractions using carbon ions for the majority of patients.	Upright: > 78 % fractions within the 1 mm/° threshold, 94 % within the 2 mm/° threshold Supine: > 61 % fractions within the 1 mm/° threshold, 86 % within the 2 mm/° threshold.	Upright treatments demonstrated comparable residual setup errors to supine treatments, with most errors falling within clinically acceptable thresholds.
Gordon 2024 [33]	Built-in CBCT / thermoplastic mask	14 patients: Esthesioneuroblastoma	Mean total dose 63(48–70) Gy (RBE) with 2.0 Gy(RBE)/fx	NA	Median follow-up 28 months • 1y LC = 100 %; • 2y LC = 88.9 %; • 1y PFS = 92.9 %; • 2y PFS = 75.0 %; • 1y OS = 2.9 %; • 2y OS = 84.4 %
Lemaeva 2024 [34]	Upright patient-positioner with PT accelerator system "Prometheus"	51 patients: Chordoma (40pts) and chondrosarcoma (11 pts)	Sequential boost: (1) 50 Gy to CTV; (2) 70–74 Gy to the tumor bed or GTV. The median number of fractions was 35.	NA	1-, 2- and 3-year rates of OS reaching 98.0 % (95 % CI 86.9–99.7 %), 88.6 % (95 % CI 74.5–95.1 %) and 82.7 % (95 % CI 66.7– 91.5 %), respectively
Feldman 2024 [12]	P-Cure Proton Therapy Solution, IGAPT: daily 3DCT + kV-KV radiographs before treatment + weekly 3DCT after irradiation. 5-point thermoplastic masks.	10*H*&N,	35–18 fx	3D localization error X = -0.1 ± 3.9 mm; Y = 3.7 ± 3.5 mm; Z = 0.5 ± 6.2 mm; Residual errors X = -0.3 ± 1.4 mm; Y = 0.0 ± 1.3 mm; Z = 0.6 ± 1.6 mm; intra-fx localization error X = -0.2 ± 1.2 mm; Y = 0.0 ± 1.4 mm; Z = 2.3 ± 2.0 mm;	A small, systematic shift in the vertical direction was detected in the follow-up 3D/3D registration (intra-fx localization error).
Marano 2023 [19]	Vertical 4DCT, P-Cure Ltd Imaging	18 thoracic	NA, only imaging evaluation	Upright vs. supine (Average relative difference ± 95 % CI): Positioning (15pts): +29 % ± 6.6 %;	Potential benefits of upright from the heart position change and the lung volume change – Upright vs. supine (Average relative difference ± 95 % CI): • Heart's bottom to sternum's top distance + 4 mm (15pts): +2.6 ± 2.3 %;

(*continued on next page*)

currently low-field systems, resulting in reduced signal-to-noise ratio and a narrower range of imaging techniques compared to high-field recumbent MRI scanners.

Upright CT imaging will be integrated into many treatment solutions from start, whereas other modality images (e.g. MRI and PET) will still be acquired in the recumbent position. Therefore, both Deformable Image Registration (DIR) and Artificial Intelligence (AI) will play important role in transferring information from recumbent to upright position, e.g. for generation of AI-based upright synthetic images. However, synthetic images must be treated with caution as they may contain systematic biases in geometry and density [42]. The biases must be measured, uncertainties reported, and planning made robust to those uncertainties.

The validation of synthetic images will require a complimentary quality assurance (QA) program combining dedicated phantoms and numerical models: physical phantoms for geometry, density, and motion patterns checks [43]; numerical anatomies for variability and uncertainty in AI models [44]. Exact reproducibility and physiological realism are competing virtues. Beyond a point, phantoms cannot mimic posture-dependent organ support and soft-tissue mechanics. This motivates a distinct biomechanics effort (imaging and modelling) to predict organ motion/settling in seated postures.

2.2. Treatment planning

Experience from RT treatment planning in the recumbent position can, in most cases, be directly translated to the upright position. The visualization of the beams-eye-view and 3D patient model will reflect the upright patient position, and a rotation for the chair will be set instead of the gantry, along with other variable parameters such as backrest angle. All communication to and from the treatment planning system (TPS} will be transferred using the latest DICOM standard, which already supports upright position [36].

The different patient geometry associated with upright positioning may provide advantages or disadvantages in treatment planning, depending on the treatment site. In many cases, different magnitudes (both smaller and larger) of uncertainties will arise compared to the recumbent position, related to patient positioning and setup, inter- and intra-fractional organ motion and treatment delivery. While the magnitude of the uncertainties may vary, they can still be handled through the same robust optimization techniques or geometrical margins developed for RT treatment planning using gantries [45,46].

Potentially, the most challenging treatment scenario will be the use of non-coplanar fields. For extra-cranial cases at least, every non-coplanar field is likely to require a repeat CT at a different chair tilt, to reflect anatomical changes due to differences in gravity. Moreover, planning each field on different image sets will pose additional complexities in terms of dose optimization and dose accumulation.

As not all imaging modalities (e.g. PET and MR) are likely to be available upright, accurate DIR algorithms will be required to transfer information from one imaging position and modality to another. Moreover, reliable DIR will be required for dose accumulation between RT in different positions, should upright positioning be alongside supine positioning, for combined modality treatments or for re-irradiation.

2.3. Quality Assurance and phantoms for dosimetry

The QA of upright RT systems is yet to be fully addressed. The commissioning of one of the first upright PT centres was described by Feldman *et al* [47]. With only a fixed beamline, dosimetric QA for photon and particle RT remain the same [48,49] but the whole procedure will be simpler than for a gantry-based system. Beam QA devices can either be placed at isocentre or immediately in front of/within the nozzle. Modest development of bespoke mounting systems will be needed to change the fixation from a flat couch to chair system. Laser or in-room X-ray imaging will be used for referencing the QA device position.

As the large water tank cannot typically be placed on a treatment chair, due to its dimensions and weight, independent holding platforms to stand on the floor must be developed. Then, horizontal fixed beam data acquisition can only be performed through the water phantom entrance window, such that precise characterisation of the tank material will be crucial, especially for PT.

The mechanical testing of chair movement and comprehensive end-to-end validation of coordinate transformation between in-beam imaging, chair motion and beam delivery will be critical. Especially, in case of treatment planning on recumbent CT, validation of coordinate transformation between out-of-room recumbent planning CT and in-room upright image-guidance must be performed. Additionally, DIR QA between images of different anatomical position must be integrated.

Plan specific QA (PSQA) presents a greater challenge, since QA devices would need to either accommodate beams delivered from multiple directions during chair rotation or be nozzle mounted. Due to complexity in chair motion and coordinate transfer, angle-specific phantom-based dosimetric verification should be considered, especially for early adopters to gain confidence in the system. Independent secondary dose calculation, i.e. Monte Carlo-based dose reconstruction should be an integral part of the PSQA process as in standard radiotherapy.

For multi-institutional clinical trials or systematic data collection, technical credentialing is a critical process to ensure consistency, accuracy, and compliance across participating sites [48,50]. In the upright paradigm, modifications of clinical standards will be required, such as new geometry for beam output calibration and range verifications, standardization of treatment planning strategies, anthropomorphic and geometric phantoms that can be mounted vertically in upright immobilization, and image-guided quality assurance for, depending on the technology, imaging for dose calculation and end-to-end testing. In the instance that the upright image is to be used for primary treatment planning, the upright CT or validated surrogate (e.g., dual-energy CT,

Table 1 (*continued*)

Author/ Year/ Ref	Imaging / RT Modality / Immobilization	Number of patients: Tumour site	Dose prescription / Fractionation schedule	Key Results-Geometric evaluations	Main findings/ Clinical outcome
					• Left lung volume (N = 18) + 17 % ± 4.7 %; • Right lung volume (N = 18) + 9.9 % ± 5.8 %; • Lung Excursion (N = 14) + 13 % ± 26 %
Pryanichnikov 2018 [35]	Upright patient-positioner with PT accelerator system "Prometheus"	82 patients: Intracranial and H&N tumours	Mixed due to the broad range of patients.	NA	Treatment results presented for ~ 40 patients, no acute toxicities exceeding grade 2

Legend: IGAPT = image-guided adaptive proton therapy; LC = loco-regional control; PFS progression-free survival; OS = overall survival; CR = complete response, PR = partial responses, SD = stable disease; OAR = organ at risk; CI = confidence interval.

upright MRI generated into a synthetic CT) will also need to be verified. While many motion platforms exist, their use in the upright orientation is still under development and will also need to be addressed if respiratory gating or 4D imaging is to be employed.

2.4. Chair design

Upright radiotherapy chair design has evolved from multiple parallel engineering efforts worldwide, all converging on similar mechanical principles required for geometric reproducibility, patient comfort, and compatibility with modern image-guided RT. Despite differences between systems, including commercial systems from P-Cure (P-Cure Ltd, Israel) [47] and Leo Cancer Care (Leo Cancer Care, United Kingdom and USA) [11] (Fig. 1), alongside in-house systems from Protom / Prometheus, Shanghai Proton and Heavy Ion Centre (SPHIC) [13], Northwestern Medicine in Chicago [32] and Peter MacCallum Cancer Centre (PMCC) [24], their designs share structural logic (Table 2).

Across most systems, the backrest is the central structural element ensuring immobilization stability. P-Cure employs a curved, single-piece carbon-fibre backrest, which minimizes deformation during robotic manipulation [12,26,31,47]. In the LCC system, a flat carbon-fibre backrest [10,11] can also be interchanged with other options, including one specifically designed for head fixation using thermoplastic masks. Similarly, a similar rigid back panel in the Protom / Prometheus system supports thermoplastic mask fixation for skull base and sinonasal tumours [33,35,51]. Clinical data from SPHIC's carbon-fibre head and shoulder interface demonstrates sub-millimetric mechanical accuracy for their carbon-fibre backrest [32,52]. Rather than adopting a rigid backrest, the PMCC have adopted a forward leaning support system [24], also consistent with an earlier prototype presented by MD Anderson [22].

All upright radiotherapy chairs employ a multi-point lower-body stabilization system. P-Cure's ergonomic evaluations demonstrated that shin support prevents anterior sliding, while properly elevated knee supports distribute load and reduces thigh fatigue. LCC's pelvic cancer investigations, using a shin rest and heel stop, maintained displacements within a few millimetres throughout 20-minute sessions, confirming the utility of constraining leg motion [10]. Seat geometry affects pelvic stability: the P-Cure ergonomic tests showed the need for reduced seat depth for smaller individuals and contoured front edges for comfort. Similar refinements appear in other systems, emphasizing convergence toward e a suitable anthropometric fit.

H&N reproducibility depends on the rigid coupling between the immobilization mask and the backrest. P-Cure, Protom and LCC all mount thermoplastic masks directly to their carbon-fibre backrests, forming a closed geometric chain. Protom's more than 500 image-guided verifications confirm stable head alignment in seated skull-base treatments [33,51]. SPHIC uses a height-adjustable carbon interface plate integrated into the multi-axis positioning platform, again reinforcing the principle that mask fixation must be mechanically unified with the chair's rigid structure [52].

Systems using fixed beamlines depend on chair rotation. Leo Cancer Care use a slip ring which allows multiple consecutive 360° rotations in either direction. Protom/Prometheus employs a 360° rotating base, maintaining geometric stability during multiple beam-angle delivery. SPHIC couples rotation with hexapod fine adjustment, reporting deviations between beams well below 1 mm. The P-Cure chair, though rotated via a robotic system rather than an internal bearing, must remain

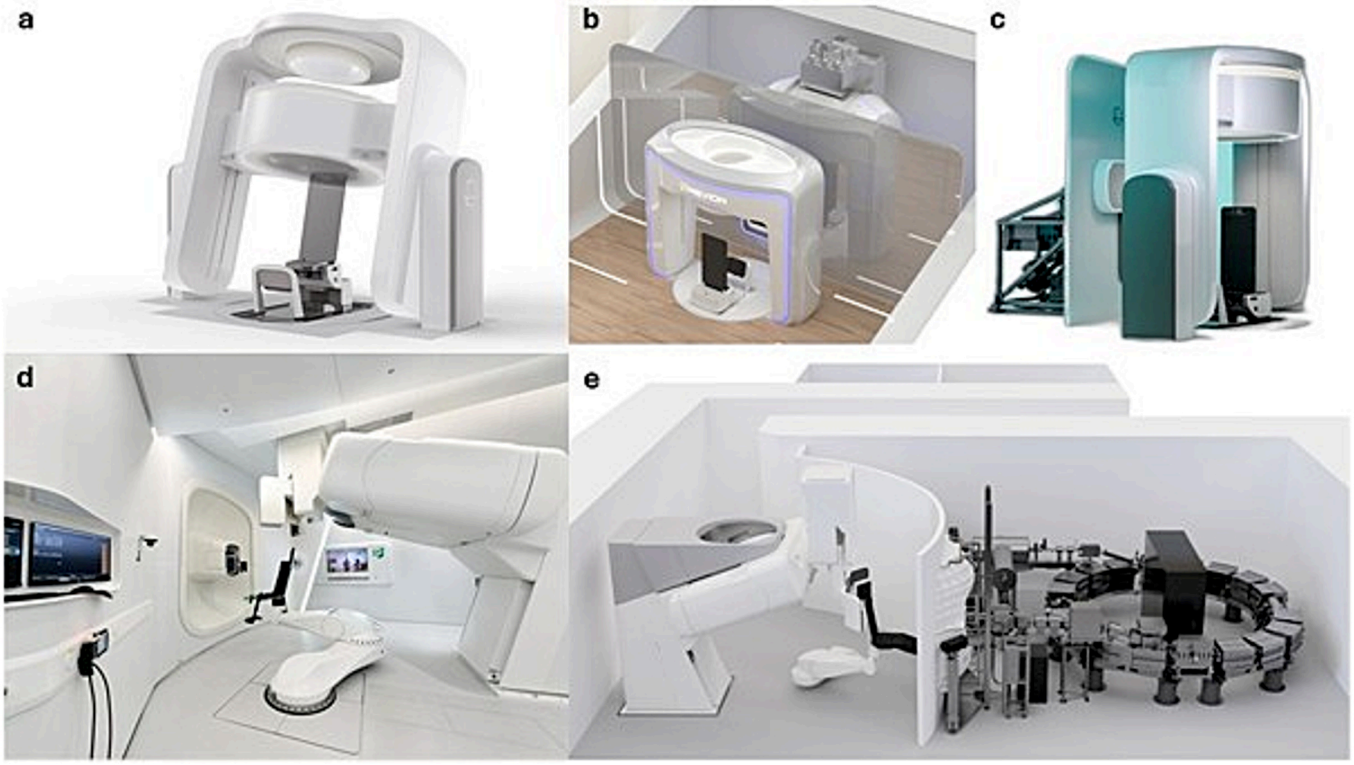


Fig. 1. Overview of commercial systems: (a) The Marie™ system (FDA cleared, and CE marked) from Leo Cancer Care consists of an upright patient positioning system and CT scanner. It can be combined with beamlines from various particle therapy vendors. (b) The S250-FIT™ system from MEVION medical systems (FDA cleared, and CE marked) consists of the Marie® system from Leo Cancer Care and a compact fixed-beam proton delivery system from MEVION. (c) The Grace™ system from Leo Cancer Care consists of Marie® and a 6MV fixed-beam medical linear accelerator. It is under development and not cleared or approved for sale. It is presented for research and discussion purposes only. (d) and (e) P-Cure Proton Therapy System (FDA and TFDA cleared for full-body patient treatments) is an integrated solution combining the P-Cure P-ARTIS™ with the P-Cure compact synchrotron, installed within the same treatment vault. P-Cure P-ARTIS™ is a robotic patient positioning and imaging system consisting of a vertical 4DCT scanner and an additional orthogonal 2D X-ray imaging system at the treatment isocentre.

Table 2
Comparison of mechanical and immobilization features across upright chair systems.

Feature	P-Cure	LCC	Protom/ Prometheus	SPHIC 6D Chair	PMCC upright RT platform
Backrest Material	Carbon-fibre, curved	Carbon-fibre (interchangeable backrests)	Carbon-fibre plate	Carbon-fibre plate	No backrest: forward leaning supports (mixed materials)
Head Fixation	Thermoplastic mask to backrest	Thermoplastic mask to backrest	Thermoplastic mask to back panel	Thermoplastic mask to carbon plate	Chin rest
Lower-Body Support	Knee + shin + foot supports	Knee + shin + foot + heel supports	Leg/foot supports	Vac-lok thigh and back cushions	Footrest and Vac-lok cushions
Rotation	Via robotic arm	Slip-ring enables consecutive 360° rotations in either direction	360° chair rotation	360° + hexapod	360° rotation, but treatment angles would be limited
Stability Data	<1 mm daily QA <2 mm shifts (H&N cohort)	<1 mm daily QA	<2 mm shifts (H&N cohort)	<1 mm daily QA	<1 mm daily QA
Primary chair use	Multi-site proton therapy	Multi-site, proton, ion or photon therapy	Proton fixed beam for H&N	Proton/Carbon fixed beam for H&N	Clinical trial of CBCT imaging with a Varian TrueBeam
Associated imaging system	Fixed fan beam CT ring (upright patient is raised into the CT ring using the robotic arm)	Fan beam CT ring lowered down over the upright patient at the room isocentre (CT ring is tiltable to match the backrest angle)	X-ray CBCT upright imaging.	No upright imaging is currently available	CBCT system on the Varian TrueBeam can be used to perform imaging in the upright position

Legend: LCC = Leo Cancer Care; SPHIC = Shanghai Proton and Heavy Ion Centre; PMCC = Peter MacCallum Cancer Centre; H&N = head and neck; QA = quality assurance, (CB)CT = (cone-beam) CT.

structurally rigid under dynamic loads, which shaped design choices such as retractable foot components and load-path minimization.

All modern upright chairs support wide anatomical variability. P-Cure provides backrest-height adjustment, interchangeable head plates, and optional paediatric configurations. LCC has interchangeable backrests, seat height adjustment, seat pan pitch adjustment, backrest angle adjustment, and shin support distance; SPHIC uses height-adjustable fixation plates. These similarities reflect global consensus on maintaining posture reproducibility while accommodating patient diversity.

2.5. Beam delivery system

A key advantage of implementing a gantry-less radiotherapy system is the reduction in complexity of the beam delivery. For photon-based machines, more modest reductions in footprint are achieved by removing the gantry. The simplification for PT beam delivery is much more significant. By removing the gantry, a large portion of the civil engineering needed for a PT system with a rotating beamline is redundant. Even for multi-room systems, the beam delivery can be made considerably more compact since most of the quadrupoles installed on PT gantries are no longer needed.

Greater size reduction is possible by removing magnetic beamline entirely. However, magnetic beamlines act to optimise the transverse beam parameters: removing magnets necessarily provides less control over these properties. In addition, a gantry behaves like a spectrometer, removing particles with errant energies before they reach the patient. Whilst placing the nozzle immediately after the accelerator extraction point minimises the potential for beam and emittance blow-up, it places tighter constraints on the quality of the extracted beam.

2.6. Implementation challenges

2.6.1. Integration into existing clinics

Introducing upright treatment into an established clinic involves logistical, technical, and organizational considerations.

A first point is understanding if the upright treatment is coupled with a supine CT simulation. The main challenge is the posture mismatch, gravity-driven changes in target/OAR shape, relative position, and respiratory mechanics which can make a supine CT poorly suited as an anatomical representation for upright treatment delivery. This would increase uncertainty in target and OAR definition, likely requiring conservative margins and/or robust strategies, and placing higher reliance on upright on-board imaging (CBCT) and surface guidance for daily verification. DIR will play a pivotal role in such a workflow and therefore, careful validation and QA to avoid systematic geometric errors must be implemented. In addition, the absence of an indexed upright immobilisation setup during CT can complicate isocentre transfer and reproducibility. Upright CT for simulation is almost universally being prioritised in new treatment centres.

In case of a fully upright workflow with upright CT simulation, the posture consistency between planning and delivery is resolved, but several practical implementation challenges remain. First, the workflow depends on tight geometric/coordinate consistency between the upright CT and the treatment system: immobilisation, indexing, and isocentre definition must transfer reproducibly across rooms, with end-to-end QA demonstrating that the planned geometry is recovered at the point of treatment, within clinical tolerances. Second, upright setups often rely on novel and complex chairs/support structures that could introduce non-trivial mechanical uncertainties (e.g. sag, small rotations, patient settling), so robust fixation and fast, reliable image-guidance protocols (CBCT and surface guidance) are essential to control both inter- and intra-fraction motion. Finally, target delineation and multimodality integration may still require registration to diagnostic imaging acquired supine (diagnostic CT, MRI, PET/CT), meaning that validated DIR remains a key dependency even in a fully upright RT chain.

One important aspect is backup planning. Starting centres should perform double CTs in both upright and supine positions to ensure safe treatment delivery and gain confidence, while also unlocking upright versus supine treatment comparisons.

2.6.2. Psychological and organizational barriers

Adoption of upright workflows is likely to be associated with psychological barriers for both clinicians and vendors [53]. Starting with palliative treatments could facilitate acceptance and provide experience, while allowing advanced planning to be gradually integrated into clinical practice. CT simulation may represent a limitation; if upright CT is only available within the treatment room, scheduling simulation as “fraction 0” could potentially slow-down the workflow. Compliance with regulatory requirements and reimbursement policies is also likely to influence implementation.

2.6.3. Immobilization

Proper immobilization is critical for patient comfort and reproducibility. Using multiple chairs for different indications could help with this but would increase development and purchasing costs. For abdominal and pelvic tumours, thermoplastic body wraps may be used, as additional customized immobilization [10]. Preliminary studies demonstrate that upright positioning for H&N is reproducible with similar tolerances as supine positioning [12]. For other treatment sites, the investigation is yet to be performed.

2.6.4. Paediatric consideration

Paediatric implementation adds complexity because upright devices and workflows must accommodate a wide variability in body size and levels of cooperation. Adolescents may use adult solutions, whereas younger children often need highly adjustable supports plus structured preparation and audio-visual distraction to achieve reproducible positioning within short sessions. Upright imaging should use paediatric-specific protocols—minimising dose and acquisition time with age-appropriate field-of-view and motion-tolerant strategies—aligned with immobilisation and the planned IGRT approach. For the youngest patients, general anaesthesia is often required; upright delivery must therefore ensure unobstructed airway access, continuous monitoring, and rapid evacuation from the chair (and, where applicable, the upright CT bore) in case of emergency. These needs affect room layout, staffing (anaesthesia team availability), and rehearsal of emergency procedures, and they constrain the design of radiolucent immobilisation and monitoring interfaces compatible with image guidance.

2.6.5. Workflow

In general, software intercompatibility and coordinate transfer is critical, as multiple systems (TPS, OIS, TCS, PPS, surface guidance, motion management, and real-time adaptive systems) must operate seamlessly. Decisions around simulation imaging, isocentric verification, and verification after rotation must be made carefully. Surface guidance and motion management are essential to ensure precision in daily delivery and their application for upright positioning is still under development.

2.7. Opportunities

2.7.1. Improvements in hardware design in photon radiotherapy

Photon upright RT can offer multiple advantages in terms of machine capabilities and geometric flexibility. The use of a rotating treatment chair in front of a stationary beam enables more capable MLC motors than for a gantry-based system, allowing markedly faster leaf motion. Corresponding improvements in treatment plan optimization are, however, needed to take advantage of the speed gains. Vertical translation of the chair during delivery can produce helical fields with a greatly extended maximum field size, analogous to motorized couch motion for a gantry-based system. Variation of the chair backrest angle could also enable non-coplanar arcs. Without a gantry, fixed photon beamlines can be more modular in nature, improving upgradability and treatment room sustainability.

2.7.2. Improvements in hardware design in particle radiotherapy

For PT, returning to a fixed beamline relaxes the technology constraints of the beam delivery system allowing greater flexibility in design, implementation and capability of multi-leave collimators, scanning magnets and dose/profile monitors. Additionally, beam modifying devices like range shifters, energy selectors, slit collimators, FLASH pin ridge filters can be easily attached. The upgradability of the whole system will be simpler as the complexity of the system will be reduced [54].

It also opens the door for more compact accelerator systems, although care is needed to ensure that the desired particle energy is delivered to the patient, without unnecessary increases in neutron dose. In the absence of rotation and long beamlines, compact systems will allow faster energy changes. Despite the larger footprint, linear accelerator-based PT machines become more feasible, with the attendant possibilities for extremely high current and pulse-by-pulse energy changes.

2.7.3. Daily online adaptive radiotherapy

Upright gantry-less RT with high-resolution imaging could be directly implemented with online adaptive workflows [55,56], improving day-to-day accuracy. In photon RT, online adaptation is slowly becoming state-of-the art for the treatment sites with large inter-fractional motion with increasing evidence of reduced treatment toxicity. However, the PT clinical implementation is lagging due to reduce in-room imaging capabilities [57]. For integration of MRI with PT, upright positioning, where the MRI scanner can be decoupled from the beam delivery system, might be the only way forward [58].

Integrated online adaptive workflows may also ease the implementation of upright positioning. Planning directly on upright CT scans could facilitate “Direct-to-Unit“ or “Simulation free” approaches, eliminating the need for the upright pre-treatment imaging [59].

2.7.4. Particle arc therapy

Particle arc therapy (PAT) [30] aims to deliver arcs in a similar way to photon volume modulated arc therapy, either continuously during rotation (dynamic arcs) or via step-and-shoot arcs providing high-quality plans [60–62]. Static proton arcs were used in the first clinical treatments using a gantry-based system [62,63]. A major PAT advantage is the delivery with a coplanar beam setup without range shifters, while reaching superior plan quality compared to non-coplanar IMPT beams with a range-shifter beam-splitting technique [60,62,64]. A rotating upright chair allows for PAT implementation without building heavy gantries.

For some compact proton systems, where the energy selection is performed close to the patient, it could be beneficial to add transmission or shoot-through proton beams into the plan [29]. While shoot-through beams enhanced proton plans can be created for IMPT, the combination with arcs is even more attractive, since the exit dose is spread over many beam angles.

2.7.5. Range probing and in-vivo verification for ions

Precise verification of proton range is critically important in PT, as small uncertainties can lead to significant deviations in dose deposition. A practical and clinically viable strategy is to infer the proton range by measuring the energy or residual path length of protons after they have traversed the patient, using detector systems developed for proton radiography [65,66]. This approach has already been successfully translated into clinical practice in gantry-based systems, where it is employed for the routine assessment of patient-specific range deviations [67]. In addition, proton radiography measurements have been used to assess and validate the accuracy of synthetic CT images derived from daily CBCT acquisitions [68]. However, these measurements can in a gantry-based system practically only be performed with the gantry delivering a horizontal beam. With an upright solution, the range detector can be fixed directly behind the patient, where there is more space relative to a gantry-based system, and the detector can register all treatment angles as the chair rotates.

An additional and promising direction is to combine in-vivo proton range verification with concepts originating from proton tomography [66]. Especially in PAT, the wide angular sampling plans could be exploited to perform a back-projection of range discrepancies measured either from auxiliary range probing beams prior treatment or from additional shoot-through beams integrated in the treatment, thereby enabling localization of range uncertainties within the three-dimensional patient anatomy. If using integrated shoot-through beams during treatment, the limited fluence of such beams during treatment would be insufficient to generate a high-resolution proton CT, they could still yield coarse spatial information identifying regions along the proton trajectories where deviations occur. This low-resolution map of range errors could then be co-registered with the planning CT, a repeat CT, or daily CBCT to improve anatomical interpretation of the observed discrepancies. A further application worth investigating is the use of the range verification system during treatment as a real-time safety mechanism, capable of interrupting treatment delivery if measured range deviations exceed predefined tolerance thresholds [29].

Prompt gamma is another approach for in-vivo range verification for ions [69,70]. Although prompt gamma techniques have been

investigated extensively in research for many years, widespread clinical adoption has not yet been achieved, in part due to the complexity of the reconstruction and detection methodologies [71]. An upright position with a fixed beam will facilitate the detector design and the integration of prompt gamma in ion treatment rooms.

2.7.6. *New modalities and multi-modality treatments*

The combination of different modalities into the same treatment, as well as the implementation of emerging techniques, such as boron neutron capture therapy (BNCT) and very-high-energy electrons (VHEE), will in many cases be more straightforward in an upright treatment position where the gantry is removed. For example, delivery systems for two different radiotherapy modalities (e.g. protons and photons), could be co-housed within one treatment room, with one rotating upright patient positioner mounted between them.

The integration of multiple treatment modalities has the potential to improve plan quality by leveraging the distinct physical advantages of each modality. For example, the sharp penumbra of photon beams can be used alongside proton Bragg peaks to enhance dose conformity [28]. For light ions, combining different ion species within a single multi-ion treatment plan can offer substantial dosimetric and biological benefits [72,73]. Further combining multi-ion delivery with arc therapy expands the degrees of freedom available during plan optimization, potentially improving dose distributions [74]. However, this increased complexity also presents challenges for optimization and delivery speed; to incorporate multi-ion planning into clinical workflows efficiently, further development of efficient algorithms is required. While multi-ion arc plans might be deliverable with an advanced gantry, chair-based solutions will be necessary to enable broader clinical adoption.

VHEE represent an emerging technology, currently explored primarily for FLASH radiotherapy applications [75]. Because the FLASH effect depends on ultra-fast delivery from a limited number of beam directions, overall plan quality could benefit from combining volumetric modulated arc therapy (VMAT) with VHEE delivery [76]. As with combined photon–proton treatments, an upright treatment position would enable the integration of both modalities within the same treatment room.

Accelerator-based BNCT relies on a fixed neutron beamline rather than a rotational gantry and integrating an upright patient positioner can improve angular access for delivering neutron irradiation through the patient's anatomy. Strategic partnerships between developers of compact accelerator-based BNCT sources and upright patient positioning systems have been formed explicitly to support such configurations.

2.7.7. *Wishlist for vendors*

All workshop participants developed a wishlist and ranked the options according to their priority for the implementation of upright systems. The results were weighted and summarized in the consensus Table 3 referring to vendors in simulation, treatment delivery, treatment planning, oncology information systems, QA device, auto-contouring and DIR.

Table 3
Wishlist for vendors defined by the workshop participants. Ranking is from the highest priority lo lowest.

Rank	Item	Description
1	Upright immobilization	**Hardware** for patient immobilization. This can be in the form of new equipment or adaptation of supine equipment.
2	Fallback planning supine <-> upright	**Software**. For centres to operate a single upright unit with a supine alternative, fallback planning is essential in case of upright equipment breakdown.
3	Deformable image registration supine/upright (MR)	**Software**. Multi-modality DIR between supine and upright for contouring with MR/PET, anatomical comparison of CT/CT and DIR-based synthetic CT produced from the upright imaging system and supine MR scans. Validation and potential adaptation of current tools are needed.
4	Open interfaces that support adaptation, vendor interoperability	**Software/Hardware.** Vendor interoperability will give departments the ability to adopt the new technology more easily without having to invest in a new infrastructure.
5	2D x-ray imaging and 2D/3D registration for monitoring during treatment	**Software/Hardware.** Monitoring during treatment will ensure confidence in patient stability.
6	Ready made QA tools and workflows	**Software/Hardware**. These tools can be used to address the change in paradigm and the impact on QC procedures.
7	Low dose CT for daily adaptive	**Hardware**. Low dose CT is desirable in implementing adaptive workflows
8	Surface guidance for patient treatment monitoring	**Hardware**. Surface guidance is commonly used supine for intra fraction motion monitoring, it is desirable upright also.
9	4D CT	**Software/Hardware**. This is a common tool in supine RT to manage margins and motion, particularly for advanced treatment techniques such SABR.
10	Respiratory motion management	**Hardware**. Respiratory motion management is widely used for Breast and Lung SABR
11	Upright auto-segmentation CT	**Software**. More data on the usability of current software and the necessity or otherwise of making new models for upright scans.
12	Simulate and treat in one appointment	**Software**. Automated planning and contouring could allow for single appointment treatments. This could be particularly beneficial for palliative patients.
13	Surface guidance for patient set-up	**Hardware/software**. Surface guided set-up can be used to ensure a patient's initial position is suitable.
14	Online adaptive tools	**Hardware/software**. Online adaptive workflows will be required. In principle, supine workflows could be utilised if vendor interoperability allows.
15	Support for non-coplanar treatment	**Software/Hardware.** Non-coplanar treatments are common for certain supine treatments, such as SRS, to increase the angle of entry for dose optimisation.
16	Chair can be integrated with existing C-arm linac as test system or for treatment	**Hardware**. This would allow departments to offer supine and upright positioning on a single photon system.

(*continued on next page*)

3. Discussion

Gantry-less RT with upright patient positioning holds significant promise, particularly for enhancing accessibility and reducing hardware complexity resulting in better upgradability. It offers a promising platform for facilitation of clinical translation of many emerging RT approaches like MR-guided PT, PAT, in-vivo verification, VHEE and BNCT. However, many technological, workflow and implementation challenges remain to be addressed before large scale clinical adoption can be reached.

One of the most noteworthy benefits is the upgradability of fixed beamlines without rotating gantries. Long-term support and maintenance are real issues in everyday clinics. With modular, upgradable

Table 3 (*continued*)

Rank	Item	Description
17	Vendor funded clinical trials	**Other**. Funded clinical trials could help to build the evidence –base for upright RT.
18	Support for off-axis isocentre treatment	**Hardware**. Off-axis isocentres may be needed for tumours that are not central.
19	Range probing for protons/ions	**Hardware/software**. Range probing uses exiting particles to verify the range through the patient.
20	Computational phantoms in upright position	**Software**. Digital phantoms that can facilitate research. Phantoms that accurately represent the difference anatomy for upright would be particularly useful
21	Deformable image registration supine/upright (MR)	**Software**. Multi-modality DIR between supine and upright for contouring with MR/PET, anatomical comparison of CT/CT and DIR-based synthetic CT produced from the upright imaging system and supine MR scans. Validation and potentially adaptation of current tools are needed.

systems the lifetime of RT treatment rooms can be prolonged, and the integration of new treatment approaches and upgrades can be streamlined. However, the trade-off between cost / size and quality of PT accelerators should not be neglected. Optimizing a compact system may compromise beam quality in a counter-productive manner.

The weakest point in the potential roll-out of upright gantry-less RT is lack of clinical evidence to date. To understand and properly address implementation challenges and gaps in clinical workflows, early adopters should be actively providing feedback to the community. To identify which clinical treatment sites will benefit from upright RT, multi-centre clinical trials must be designed together by all health care professionals [77]. However, the collection of data under clinical trial is a lengthy process and alternative way to collect the evidence must be explored, e.g. planning studies [78], virtual trials [79] and prospective data collection. As one of the biggest limitations is lack of the clinical data for further investigations, data sharing from the clinical centres via international multi-institutional registries should be developed.

With increasing evidence, a roadmap for clinical implementation with key steps should be provided by the experts. The most important aspects to address include recommendations on which tumour sites to start with; how many patients with both supine and upright CT scans must be considered to gain confidence; evaluation of any cost reductions and socio-economic aspects; feedback on patient comfort, compliance and positioning reproducibility. As upright gantry-less radiotherapy will not be a solution for all treatment sites (initially at least), evidence-based and value-driven decision tools should be provided.

To aid smooth and safe adaption, close involvement of national and international radiation oncology societies is warranted to support building evidence bases and open discussion. ESTRO, ASTRO, AAPM and PTCOG should provide platforms for scientific sections on this emerging topic during their annual congresses, they should initiate educational programs, call for working groups, encourage preparation of guidelines and build awareness. As with every new technology, close collaboration between clinical centres, academia and industry is crucial to steer the translation.

While upright gantry-less radiotherapy represents an exciting evolution in treatment delivery with the potential to improve accessibility and patient experience, its ultimate role in the radiotherapy landscape will be determined by accumulating clinical data and technological refinements in the coming years.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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