ANATOMICAL VARIATIONS

BETWEEN SUPINE AND UPRIGHT POSITIONS

ACROSS MULTIPLE BODY REGIONS

ANATOMY | UPRIGHT MRI | DOSIMETRIC COMPARISON

Kate Yip, Niek Schreuder, Michael Kissick

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WHITEPAPER

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Introduction

Background

Patient positioning plays a critical role in radiotherapy planning and delivery, influencing both organ motion and dose distributions. While most treatments are delivered in the supine position, recent developments in upright imaging and treatment positioning technology have renewed interest in evaluating how a different posture affects internal anatomy. Understanding these positional changes is essential for radiation therapy planning e.g. optimizing dose accuracy, and managing intra-fraction motion.

Despite growing interest, data on anatomical changes between supine and upright positions remain limited.

Scope

This study presents one of the first multi-indication evaluations of anatomical and dosimetric differences between supine and upright positions. Using 159 MRI scans - spanning more than 20 asymptomatic volunteers, for two different upright positions and one supine position – we studied the impact of posture-induced changes for the pelvis, abdomen, thorax, head and neck and intracranial regions. Anatomical shifts were quantified and their impact on proton therapy treatment planning was assessed through MRI-derived synthetic CTs. The majority of cancers occur in the major anatomical regions studied, highlighting the clinical significance of these findings.

Findings

The results suggest that radiation therapy deliveries in the upright position are feasible and at least clinically equivalent to the supine position across multiple tumor sites. Several potential benefits, including reduced diaphragm motion, improved anatomical separation, and improved organ stabilities in the abdominal and pelvic regions, were also identified. The findings from this work provide one of the most comprehensive datasets to date on upright imaging and lay the foundation for further development of upright radiotherapy techniques.

Materials and Methods

Study Design and Cohort

This study was designed to evaluate anatomical and dosimetric differences between supine and upright patient positioning across multiple anatomical regions relevant to radiotherapy. A total of 159 MRI scans were acquired from >20 asymptomatic volunteers, including 58 in the supine orientation and 101 upright or inclined 20 degrees from upright. Imaging was performed across five anatomical regions i.e. pelvis, abdomen, thorax, head and neck, and intracranial. Participants included healthy volunteers with informed consent obtained prior to imaging. Upright imaging, in the majority of the studies, was performed at incremental inclinations of 0°, 20° from vertical, in combination with supine imaging (at 90°) to characterize posture-dependent anatomical changes.

Image Acquisition

MRI data was acquired using an upright-capable open MRI system (FONAR 0.6 T UPRIGHT® MRI at FONAR headquarters in Melville, New York, USA). The MRI scan sequences and protocols were tailored according to the specific anatomical regions. Since one of the objectives were to use the data for treatment plan comparisons, the FOV was set to 40.8 x 40.8 cm2 to ensure that the entire anatomical region was in the image. T1 weighted gradient echo sequences with a 3 mm slice thickness were used for most of the acquisitions. For the lung motion studies, balanced Steady-State Free Precession (bSSFP) sequences were used to acquire the cine loops at a rate of approximately 4 frames per second.

Key anatomical points were identified in each dataset to measure how posture affected their position. Measurements were referenced to fixed bony landmarks along superior–inferior and anterior–posterior axes. Key regions of interest included the liver, diaphragm, kidneys, pancreas, prostate, bladder, tongue, and intracranial structures.

Synthetic CT Generation and Treatment Planning

As MRI does not directly provide electron densities which in turn is used to derive proton stopping powers for proton dose calculations, synthetic CT (sCT) datasets were generated using a conversion model from MVISION (Mvision AI Oy (Helsinki, Finland) trained on supine paired MRI–CT data. A total of 72 sCTs were produced for the abdomen, pelvis, and intracranial regions.

For dosimetric comparison, 64 paired proton treatment plans (supine vs upright) were created using equivalent beam arrangements, dose prescriptions, and optimization constraints. The plans were calculated using the Mevion FIT beam model. Contouring was performed by practicing radiation dosimetrists following standard clinical guidelines and auto contouring benchmarks. Dose–volume metrics, including D95, Dmean, and OAR dose limits, were extracted for quantitative comparison.

Plan Evaluation

All treatment plans were independently reviewed by radiation oncologists practicing in the specific anatomical region of interest and practicing medical physicists. Reviewers assessed:

- Target coverage and conformity,
- Dose to organs at risk (OARs),
- Geometric integrity of target–organ relationships, and
- Overall clinical acceptability.

Plans were categorized as clinically equivalent, superior, or inferior to the reference supine plan. Upright feasibility was also assessed with respect to positioning comfort and potential delivery limitations.

Statistical Analysis

Quantitative measurements of organ displacement, organ motion, and dose variation were analyzed using paired t-tests or Wilcoxon signed-rank tests, as appropriate. A p-value < 0.05 was considered statistically significant. Mean values are reported ± standard deviation.

Comparative data were synthesized across anatomical regions to identify consistent positional trends and to evaluate the overall clinical equivalence of upright and supine configurations.

Data Integration and Synthesis

Regional findings were consolidated to provide a comprehensive overview of positional anatomy across the body. The results were stratified by anatomical region—abdominal, thoracic, pelvic, and head and neck—and integrated with treatment planning metrics derived from sCT data. Multidisciplinary review ensured consistency of interpretation across imaging, dosimetric, and clinical endpoints.

Results

Studies of the abdominal region

Nine volunteers were included in the exploration of organ shift in the abdominal region. The RayStation treatment planning system was used to analyse the MR images of the volunteers positioned at 0°, 20° and 90°. Several anatomical distances: (a) between the right and left kidneys, (b) from the most superior slice of the liver to the most inferior slice of the right kidney, (c) from the most inferior slice of the liver to the iliac crest, and (d) from the head of the pancreas to the iliac crest (see Fig. 1). The results showed that kidney spacing remained relatively stable regardless of posture, while the liver and pancreas both shifted away from the hips by up to 3.7 cm and 3.8 cm when moving from upright (0°) to supine (90°) position. Additionally, there was a borderline significant increase (2.2 cm) in the distance between the liver and right kidney at 90°.

In a complementary study, Siebenthal and Szekely (2007) [1] explored systematic intrafraction motion. They noted organ deformation and motion of the liver when the patient moved from an upright to supine orientation. They observed that the liver continued to drift up for up to 35 minutes after lying down, moving by as much as 5 mm before it settled into its new position.

Together, these findings highlight that while kidney position remains largely stable, abdominal organs such as the liver and pancreas experience measurable gravitational shifts and delayed positional settling when posture changes.

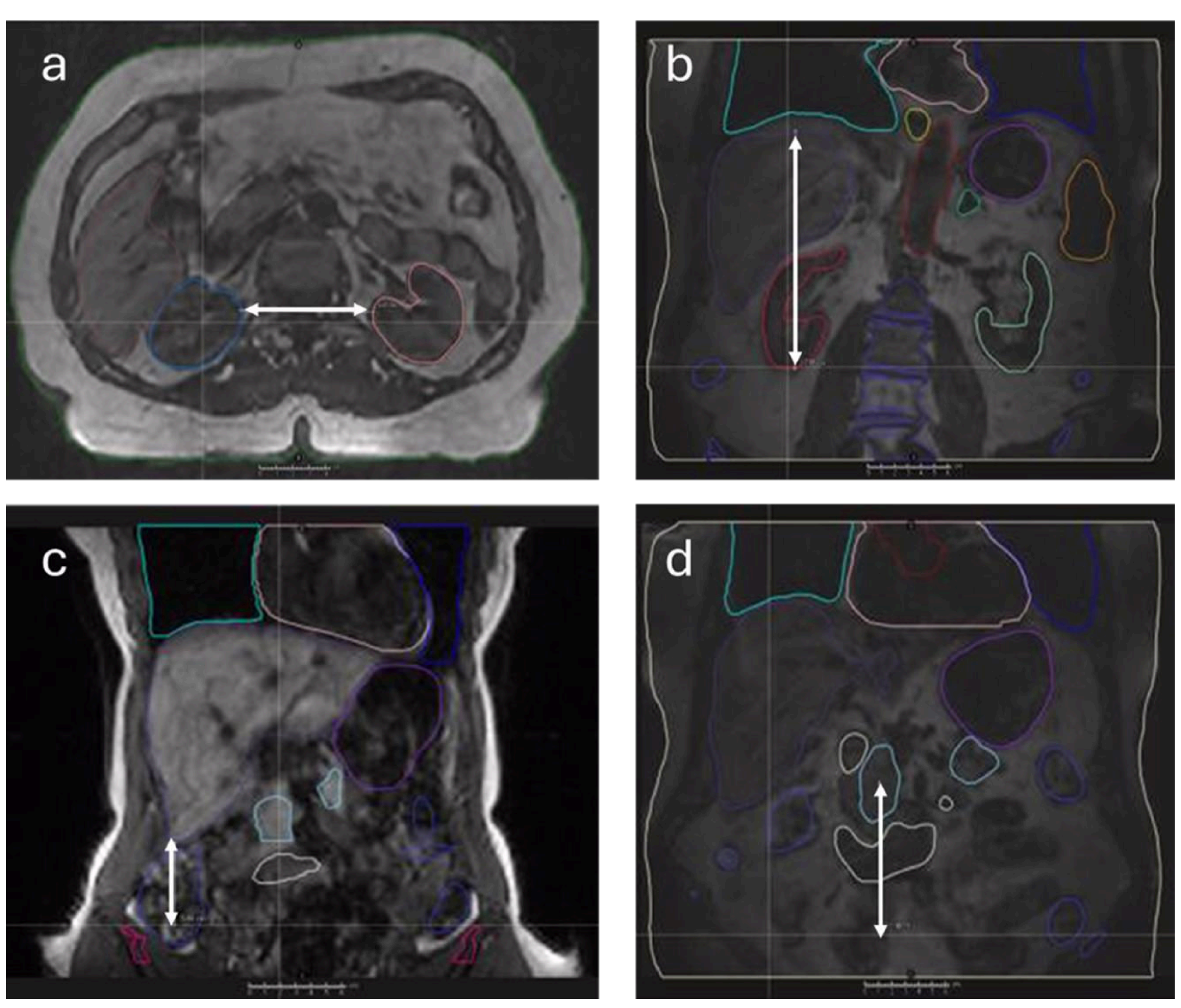

FIGURE 1 The 4 metrics measured in the abdominal space in this study

Studies of the thoracic region

The thoracic region was also investigated to consider how body position affected respiratory motion. MRI cine loops in a sagittal plane through the apex of the right lung were acquired for 5 male and 5 female volunteers in the 0°, 20° and 90° degree postures. For the sagittal cine loop acquisitions, a timing sequence of acquiring images at a rate of approximately 4 frames per second was used. The position of a virtual marker (seen in Fig. 2), placed on the diaphragm, at approximately the closest point to the apex of the lung was measured relative to the apex of the lungs. The results showed that diaphragm excursion increased by 4.8 mm on average i.e. a 67% increase when subjects moved from upright to supine, and by 1.5 mm on average i.e. 20% increase from upright to the 20° reclined position, with both cases being statistically significant. Importantly, the frequency of breathing (respiratory period) remained consistent across all positions, indicating that posture primarily influences motion amplitude rather than breathing rate.

Supportive of these findings is a study by Yang et al. (2013) [2] who investigated the effects of body position on lung volume and breathing motion. They observed a 4 mm reduction in superior–inferior diaphragm excursion when participants were upright and an average increase in lung volume of 27%, suggesting that lung motion may be more controlled in this position.

Another study by Matsumoto et al. (2021) [3] involving 32 volunteers examined changes in airway geometry with posture. The average luminal areas of the trachea, right and left main bronchi, and third-generation airways were greater in the standing compared with the supine position by 3.4%, 6.1%, 5.5%, and 5.2%, respectively. Also, correlations between airway luminal areas and lung function tests (e.g., FEV_1) were stronger when standing, indicating improved respiratory efficiency.

FIGURE 2 Screenshot of a cine-loop, showing the virtual marker on the diaphragm as a circle and the apex of the lung labelled

Collectively, these studies demonstrate that the upright position promotes more stable and efficient respiratory mechanics, with reduced diaphragm excursions, increased lung volumes and greater airway patency. This evidence supports the feasibility and potential clinical advantages of delivering thoracic radiotherapy in the upright position, offering improved patient comfort and potentially enhanced treatment precision. Larger lung volumes in the upright position are expected to lead to smaller volumes of healthy lung being irradiated..

Studies of the head and neck region

In this study ten volunteers, 5 males and 5 females, were scanned at the three different angles to investigate how posture influences the opening of the oropharyngeal airway and the effect of tongue positioning. Five distinct measurements were taken for each posture (see Fig 3). The results did not show any statistically significant changes in the respective metrics between the different positions. The most pronounced anatomical changes occurred at 20° reclined. The researchers noted that the absence of head immobilization, which is typically used in the treatment of head and neck cancers, may have contributed to variability in these findings. It was also very difficult to achieve the 20° position in the scanner due to mechanical limits of the positioner at the 20° angle.

Taken together, these studies suggest that posture can alter cranial and upper airway anatomy in ways that may be clinically relevant for radiotherapy planning. While the current evidence is limited, head and neck radiation oncologists remain optimistic that upright positioning could potentially offer anatomical and comfort-related advantages for patients undergoing head and neck cancer treatment. However, further research with appropriate immobilization techniques and clinical validation is required.

Studies of the intracranial region

Two volunteers, one male and one female, were scanned at the three different angles to obtain data on postural changes in the cranium. This data was used only for treatment planning comparisons since it was generally assumed that intracranial changes will be minimal. This assumption was validated by a complementary study by Yokoyama et al. (2021) [4] who examined the effects of posture on intracranial anatomy in a larger cohort, comparing high resolution diagnostic CT scans obtained in supine and upright positions. The authors reported measurable but modest shifts in several key structures: the pineal body moved 0.68 ± 0.27 mm ventrally and 0.76 ± 0.24 mm caudally; the pituitary stalk shortened by 1.23 ± 0.71 mm; the cerebellar tonsil descended by 2.10 ± 0.86 mm; and the lateral ventricular volume decreased by 5.07 ± 3.24%. Additionally, posture-related changes were observed in the configuration of cerebrospinal fluid (CSF) spaces. Although these displacements were relatively small, they demonstrate that gravitational effects influence both intracranial and upper airway structures.

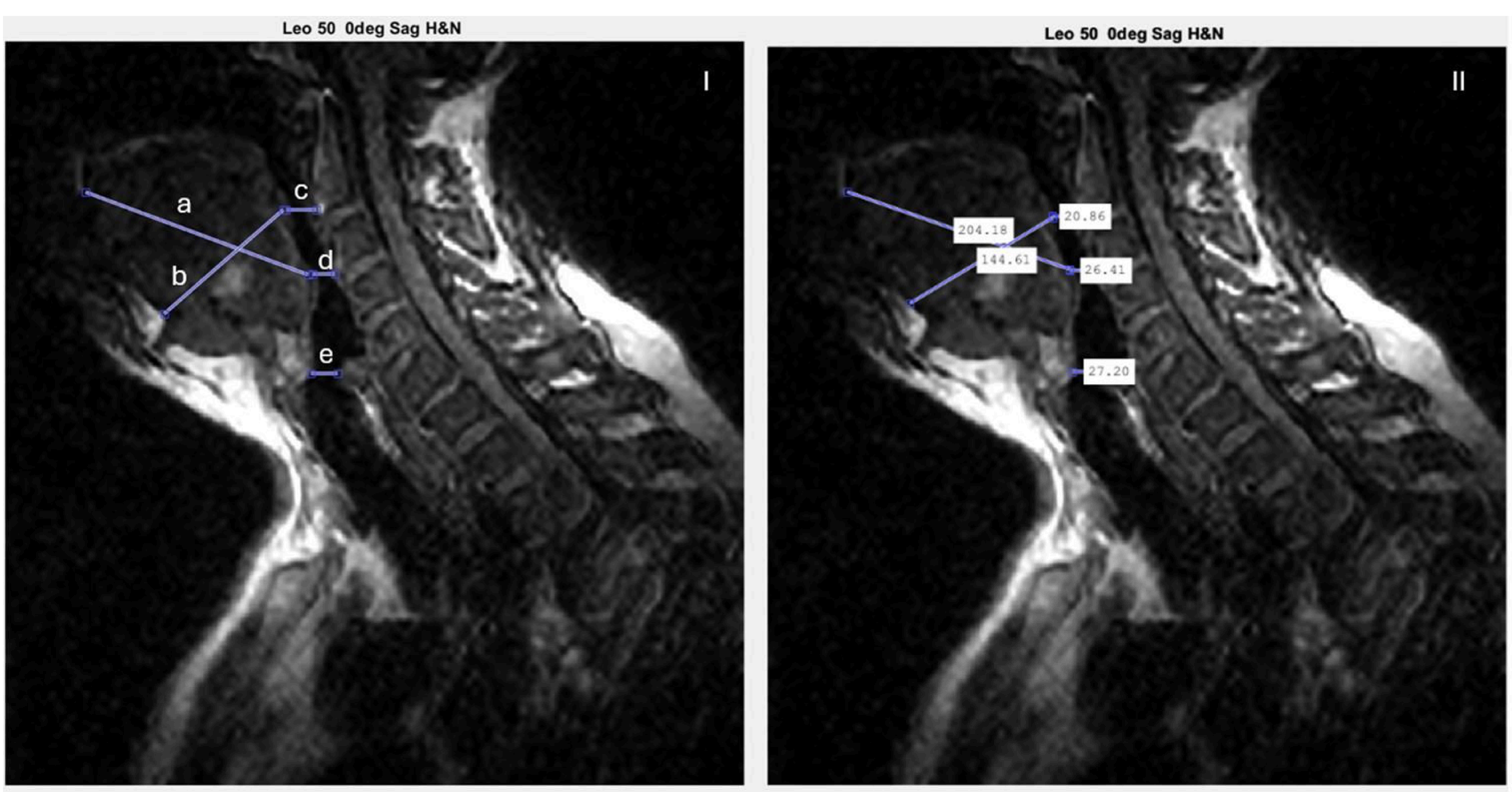

FIGURE 3 The 5 measurements taken to explore the opening of the throat and tongue position

Studies of the pelvic region

Earlier research into the pelvic region predates this investigation, with Schreuder et al. (2023) [5] examining anatomical differences in the male pelvis between supine and upright postures. In this study, 15 volunteers were scanned using a 0.6T upright FONAR MRI system to assess how bladder filling status influenced pelvic anatomy. The key findings were as follows: (i) the position and shape of the prostate was not significantly affected by bladder filling; (ii) the distance between the sacrum and the anterior bladder wall was significantly smaller in the upright position, thereby reducing the volume of small bowel that could descend into this space—a change that may lessen radiation exposure to healthy tissue; (iii) both the anterior–posterior length and width of the bladder increased significantly when upright; (iv) the bladder displaced the seminal vesicles inferiorly, improving their inclusion within the treatment volume. All observed changes were statistically significant.

This study involved ten more volunteers of both sexes i.e. adding 5 females and 5 males and incorporating an additional 20° reclined position. Results were consistent with the earlier work by Schreuder et al. (2022) [5], demonstrating that gravity influences bladder position and form specifically, causing it to shift away from the S1 tip and to widen and flatten in the upright posture compared with supine (See Fig. 4).

These studies indicate that upright positioning produces predictable and potentially advantageous anatomical changes within the pelvic region. The reduced bowel proximity to the prostate and increased organ stability suggest that upright radiotherapy might enhance treatment precision and allow for treating with smaller margins.

However, further clinical evaluation is warranted to confirm these findings and to optimize treatment planning for patients in the upright orientation. A more recent paper by Oguma et. el. (2025) [6] corroborated these findings and also reported that rectal gas moved superiorly i.e. away from the prostate region in the upright position further enhancing the stability of the prostate position during upright treatments.

Treatment planning comparisons

Large FOV upright and supine MRI scans were acquired in the supine, upright and reclined positions for 12 pelvic (6 males and 6 females), 10 head and neck (5 males and 5 females), 9 abdominal (5 males and 4 females), and 2 intracranial cases (1 males and 1 female). Corresponding synthetic CT datasets were generated from the large FOV MRI scans. The synthetic CT data and structure sets were imported into the 2023B version of the RayStation treatment planning system to develop comparative proton plans between the supine and upright postures for randomly selected cases and fictitious targets. In total, 64 comparative treatment plans were created: 18 pelvic, 6 head and neck, 18 abdominal, and 6 intracranial—each assessed at 0°, 20°, and 90° orientations. An additional 16 lung comparative plans were generated for the 20° and 90° positions using actual reclined and supine CT data sets obtained from the North Western proton therapy centre in Chicago. For each anatomical region, the same amount of plans were made on female and male data sets.

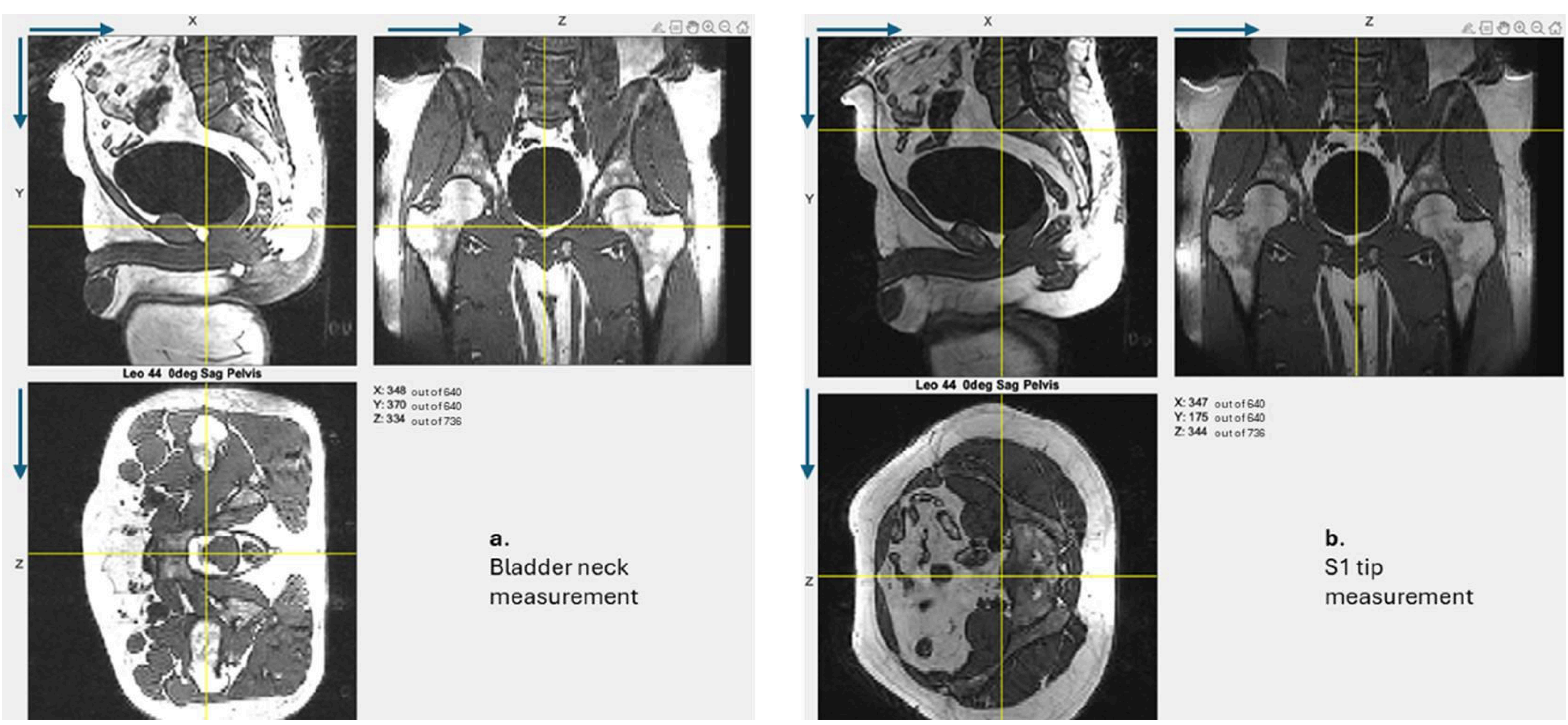

FIGURE 5 Pelvic imaging showing two of the measurements taken at the neck of bladder and tip of S1

All treatment plans were reviewed by practising radiation oncologists. Across all anatomical regions, equivalence between supine and upright plans was confirmed by the reviewers, with some instances demonstrating benefits for the upright configuration. The study was designed to determine whether upright planning achieved outcomes that were equivalent or better than conventional supine treatment—criteria that were successfully met.

For the pelvic region, 18 plans using pelvic scans from 3 female and 3 male volunteers, were developed covering recurrent rectal, prostate, bladder, and utero-cervical cancers in each of the three positions i.e. a total of 18 plans. All upright pelvic plans were found to be equivalent to their supine counterparts. The upright orientation appeared to show some dosimetric advantages e.g. the dose to the penile bulb was observed to be lower in upright prostate plans.

For the abdominal region, plans for all three postures using pelvic scans from 3 female and 3 male volunteers, were created for tumours involving the head of the pancreas, liver, and lower pole of the kidney i.e. a total of 18 plans. Again, all upright plans were at least equivalent to the supine plans. A significant gravitational displacement was observed upright for organs such as the liver, duodenum, and pancreas by an average of 4 cm in the inferior direction across nine evaluated cases.

In the intracranial region, two volunteers (one male, one female) were scanned to evaluate frontal lobe glioma and whole-brain treatment plans for all three postures i.e. a total of 6 plans. No significant anatomical differences were observed between supine and upright positions, and all plans demonstrated equivalent dosimetric quality. Similarly, all head and neck plans were equivalent, with minor advantages observed in upright positioning, including improved tongue positioning and a more open airway.

For the thoracic region, upright plans (generated using the Mevion S250 FIT system) (See Fig 7) were compared with supine proton therapy plans (IBA Proteus Plus) from the Northwestern Proton Therapy Center in Chicago. All upright thoracic plans were dosimetrically equivalent to the supine plans, with one case showing a notable improvement in heart positioning—the heart rotated forward in the upright orientation, moving the left anterior descending (LAD) artery away from the treated lung volume. Additionally, the superior–inferior lung length was significantly greater in the upright position, reflecting natural anatomical elongation due to gravity.

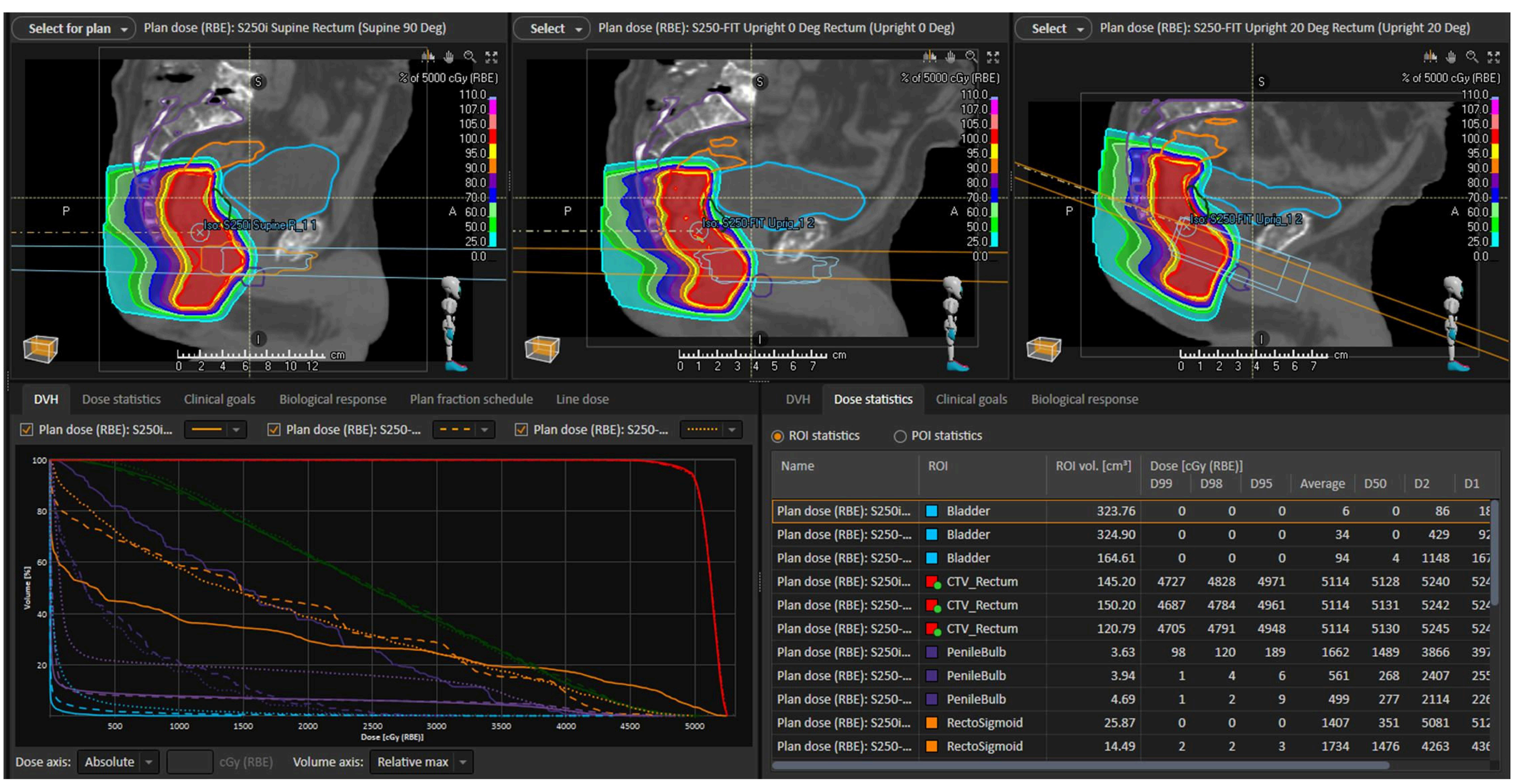

FIGURE 6 Dosimetric plans (L-R) for the pelvic region, with the patient in a supine, upright and 20 degrees reclined treatment position

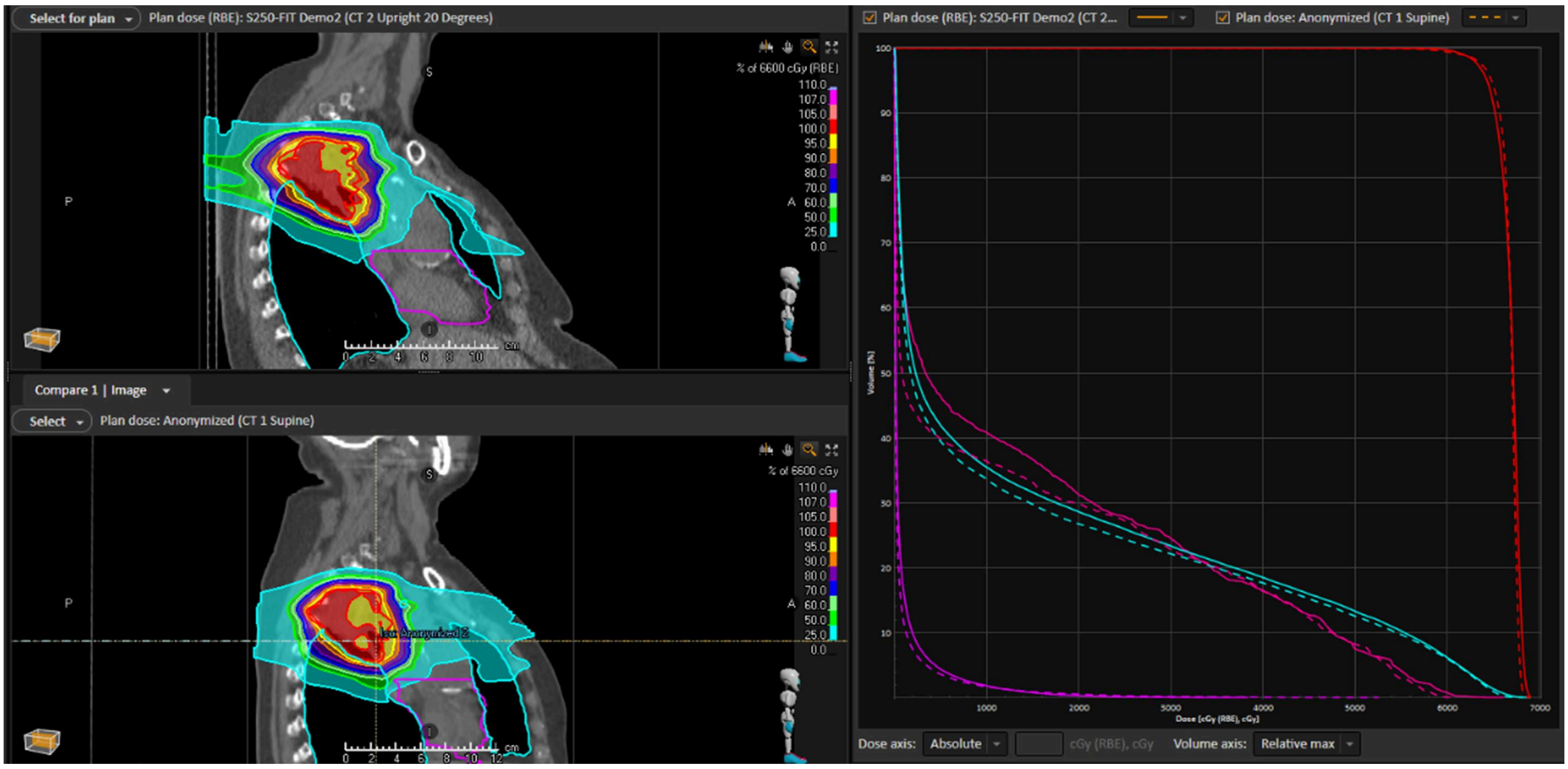

FIGURE 7 Dosimetric plans for upright treatment to the mediastinum/lung

Conclusion

This multi-regional analysis of 159 MRI scans demonstrates that upright positioning produces anatomical configurations that are at least clinically equivalent, and in some cases, superior to conventional supine orientation.

This study indicates that upright positioning may reduce radiation exposure to healthy tissues as a result of favorable organ positioning in some cases, alongside increased organ stability and reduced diaphragm motion. These findings complement other upright radiotherapy studies which investigate aspects such as patient comfort [7, 8]. Together the research collectively supports the feasibility of upright radiotherapy as a clinically viable alternative to conventional supine delivery. There are also indications that upright radiotherapy has the potential to be preferred by both doctor and patient. Further clinical studies are warranted to validate these results in treatment settings and to refine immobilisation and workflow techniques for broader clinical adoption. For the thoracic region, upright plans (generated using the Mevion S250 FIT system) (See Fig 7) were compared with supine proton therapy plans (IBA Proteus Plus) from the Northwestern Proton Therapy Center in Chicago. All upright thoracic plans were dosimetrically equivalent to the supine plans, with one case showing a notable improvement in heart positioning—the heart rotated forward in the upright orientation, moving the left anterior descending (LAD) artery away from the treated lung volume. Additionally, the superior–inferior lung length was significantly greater in the upright position, reflecting natural anatomical elongation due to gravity.

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