REVIEW

EXPERIMENTAL ONCOLOGY

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MINIMAL RESPIRATORY MOTION OF THE BREAST IN FREE BREATHING: A 4D CT NARRATIVE VIDEO REVIEW

Respiratory motion is a concern in radiotherapy of most sites, including breast cancer. Conventional radiation treatment planning routinely increases the margins around breast target volumes to account for motion. However, few studies have quantified the actual extent of respiratory motion during free breathing. A review of publicly available four-dimensional computed tomography (4D CT) video data was conducted to estimate the preponderance of breast respiratory motion. Selected videos were those containing sequences displaying movement of the breast/chest wall. Images were visually categorized as showing minimal motion if movements were estimated as ≤ 3 mm, moderate if about 5 mm, and substantial if about 10 mm or more. Respiratory motion of the breast/chest wall was minimal in 22 of the 38 cases (57.9%), moderate in 12 cases (31.6%), and substantial in 4 cases (10.5%). In line with emerging surface-guided data, this video review shows the frequent observation of minimal respiratory motion of the breast/chest wall. These findings question whether routine respiratory-motion–based target expansion is necessary in all patients.

Keywords: breathing control, breast cancer, lung cancer, respiratory cycle, diaphragmatic, four-dimensional computed tomography, 4D CT, motion tracking, surface-guided radiation therapy, SGRT.

It is a trivial fact that respiration keeps the body supplied with oxygen and protected from excess accumulation of carbon dioxide [1]. This is carried out through breathing that moves air in respiratory cycles alternating inspiratory expansion and expiratory deflation of the lungs. The quiet breathing rate in a healthy adult is 12—20 breaths per minute [1, 2], approximately one respiratory cycle every 2—5 seconds. That might affect breast movements during a radiotherapy session. Depending on the

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technique, the time required to deliver a fraction of 2 Gy to the breast and lymph nodes averages 84—172 s [3]. That is, in the time interval during which the radiation fraction is delivered, over 42 breath motions occur, potentially affecting the dose distribution to the tumor bed, breast, chest wall, and lymph nodes, which may receive insufficient radiation, and affecting non-target tissues, which may receive excess doses. There is a growing awareness that respiratory motion management (RMM) might be the key to ensure the quality of radiation delivery [4—6]. RMM requires increased medical supervision and longer treatment times at the accelerator, thereby decreasing patient throughput. Allocating RMM to a group of patients implies reducing the availability of machine and human resources to other groups. Hence, a decision to allocate RMM requires hard data on the magnitude, pattern, and impact of the respiratory motion in the radiotherapy of the breast.

A recently published study protocol proposed to analyze four-dimensional computed tomography (4D CT) acquired for treatment of lung tumors [7]. A 4D CT records multiple 3D CTs tagged with a respiratory signal in a patient, providing full volumetric CT data on the respiratory phases in the patient. 4D CT imaging is readily available across continents, in high-, low-, and middle-income countries [8—10], and is largely endorsed for thoracic stereotactic ablative body radiotherapy [5, 9, 11, 12]. Even though not intended for the breast, a lung tumor thoracic 4D CT also visualizes the breast movements. Large numbers of 4D CT lung datasets might be available to study the breast images from 4D CTs. However, retrieving the datasets is time-consuming. Considering that the internet could perhaps provide a faster shortcut to comparable data, the present study conducted a systematic search for open-access videos of thoracic 4D CTs in which the breast or chest walls are displayed to assess the importance of breast/chest wall respiratory motion.

A total of 38 eligible video cases were identified (Table). The cases were retrieved from 7 published web or journal communications [14—20], providing 11 cases; 6 webinar or congress-meeting presentations providing 9 cases; 5 lectures providing 6 cases; 4 company showcases providing 4 cases; and 8 web links to 8 stand-alone case views or case studies, one of which had source image files available [21]. The videos displayed both lungs in 31 cases, and only a unilateral chest view in 7 cases, of which 2 were left, and 5 were right. The side of an identifiable lung tumor, pathology, or treatment target was bilateral in 1 case, left in 12 cases, and right in 18 cases.

Counting each video regardless of whether it was a bilateral or unilateral chest view, chest motion was scored as minimal in 22 of 38 cases (57.9%), moderate in 12 cases (31.6%), and substantial in 4 cases (10.5%). Taking into account that bilateral views provided twice as much information as unilateral views, respiratory motion was minimal in 39 of the combined 69 hemi-thoracic views (56.5%), moderate or minimal/moderate in 21 (30.4%), and substantial in 9 (13.0%). Chest motion appeared minimal in the majority of the video cases, as well as in the hemi-thoracic views, ≥56.5%. It was substantial in a minority of the views (≤13%).

Chest wall motion was not uniform in all cases. Some differences according to chest wall area were noticeable laterally (cases 3 & 6), longitudinally in the upper or lower chest (case 10), or focally inward (case 30). Case 36 commented on sub-millimetric measurement differences, right vs. left, upper vs. lower, and outer vs. inner quadrants. Gender could affect respiratory motion. Gender assessed by the video captions or by the presence of a breast contour or a breast implant was reasonably identified in 6 cases, assumed females (Table, cases 8, 12, 29, 34, 35, and 36), and all of them presented minimal respiratory motion (100%). In contrast, among 8 presumed males (Table, cases 5, 7, 15, 24, 31, 32, 37, and 38), only 3(37.5%) presented with minimal respiratory motion.

Almost all cases appeared related to a lung tumor or other pulmonary disease. Observations and motion scoring are summarized in the Table. There was a single radiotherapy breast case (case 12). It showed a dose distribution typical of conventional whole left breast radiotherapy delivered with tangential fields. The dose encroached substantially into the lungs, as could result from tangential fields treatment when the planning target volume expanded beyond the breast. The case showed some notable breathing movement in the upper chest, but almost none in the lower part facing the heart. The heart moved into a high-dose region, not from any movement of the chest but from the diaphragm. Any technique implementing any combi

Thoracic 4D CT video records

Case	Web link	View/ side	Date of upload	Observation	Gender
1	https://www.medscape.com/viewarticle/565577#vp_2 (insert fig2.gif)	B/R	2007.11	Minimal/moderate motion [14]	U
2	https://vimeo.com/10718647	B/0	2010.04	Minimal motion. Volume rendering contrasting large lungs' motion with barely any ribs' motion	U
3	https://youtu.be/b5Ytdxo3nFE	B/L	2012.04	@10:27. Minimal motion. @11:47 zoomed view. Chest motion right > left. Skin markers barely moving	U
4	https://youtu.be/1uBkvOyp1b8	B/0	2012.05	Moderate motion	U
5	https://doi.org/10.1371/journal.pone.0053799 (Movie S1-S3)	B/R	2013.01	Minimal motion [15]	M
6	https://youtu.be/4cEZD-1hJlY	B/L	2013.08	@00:22. Minimal motion left (ipsilateral to lung tumor), substantial motion right (contralateral)	U
7	https://doi.org/10.1159/000357448 (file figshare 5/7)	B/0	2014.02	Minimal/moderate motion [16]	M
8	https://vimeo.com/87497550	B/L	2014.02	@22:17. Minimal motion. Superb dynamic volume rendering. Non-moving breasts, little ribs motion, in contrast with heart, pulmonary vessels, diaphragm, lung tumor	F
9	https://vimeo.com/88175822	B/0	2014.03	@09:09. Moderate motion	U
10	https://vimeo.com/88175822	L/0	2014.03	@12:23. Chest top half non-moving; bottom half moving moderately	U
11	https://vimeo.com/88175822	L/L	2014.03	@24:22. Coaching effects. Quiet breathing 9 bpm, moderate motion. Coached breathing 14 bpm, substantial motion	U
12	https://youtu.be/d6cgyyIp_Xg	B/L	2014.04	Breast case. Minimal motion. The visual dominance of dose color induces the perception that the chest wall moves, but in fact the dose change results from diaphragm-heart motion	F
13		B/L	2014.04	Minimal motion	U
14	https://youtu.be/z3ZT-dt7T7o	B/R	2014.05	Moderate motion	U
15	https://doi.org/10.2147/COPD.S100658 (video S1)	B/L	2016.04	Moderate motion. [17]	M
16	https://youtu.be/B26NSpw-ZIc	B/L	2016.09	@16:55. Minimal motion	U
17	https://youtu.be/X6xV5qV988g	B/R	2018.03	Moderate motion	U
18	https://www.canalc2.tv/video/15033	R/R	2018.06	@00:36. Moderate motion	U
19	https://youtu.be/nBCCxTZNvsw	B/R	2018.07	Minimal motion. Seek@ 00:10: bone-density volume rendering. Lung tumor marker + skin surface markers (6 anterior ExacTrac spheres, 2 lateral lead wires). No motion of surface markers	U

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End of Table

Case	Web link	View/ side	Date of upload	Observation	Gender
20	https://youtu.be/hykkaU6BzHk	R/R	2018.10	@37:37. Minimal motion	U
21	https://youtu.be/iuVo8Wsmckg	B/L	2019.11	@00:37. Minimal motion, coronal view. Seek@ 01:13: likely same case, sagittal view	U
22	https://youtu.be/ smDsX3KuMtM	R/R	2020.02	@04:12. Minimal motion. @ 05:02, reconstructed motion is inverted, lung tumor held as a fixed reference	U
23	https://youtu.be/tI7xkJQnGTs	R/R	2020.05	@13:46. Minimal motion (partial view of lateral ribs)	U
24	https://youtu.be/eyFBu7tN5f0	B/L	2020.05	@00:53. Minimal motion	M
25	https://doi.org/10.1016/j. phro.2021.09.005 (video 3)	B/R	2021.11	Substantial motion. Artifacted CT reconstruction of the lower third of the thorax [18]	U
26	https://doi.org/10.1016/j. phro.2021.09.005 (video 4)	B/R	2021.11	Substantial motion. Artifacted CT reconstruction of the lower third of the thorax. Left diaphragm paresis? [18]	U
27	https://doi.org/10.1016/j. phro.2021.09.005 (video 5)	B/0	2021.11	Substantial motion. Artifacted CT reconstruction at the middle third. Left diaphragm paresis? [18]	U
28	https://doi.org/10.1016/j. phro.2021.09.005 (video 6)	B/R	2021.11	Minimal motion [18]	U
29	https://doi.org/10.1016/j. phro.2021.09.005 (video 7)	B/0	2021.11	Minimal motion [18]	F
30	https://youtu.be/IHIt-95gVI8	B/R	2022.04	@00:59, @26:43, @30:24. Overall minimal motion; substantial localized motion of a rib in two phases, artifact?	U
31	https://innomd.com/article/62 68e60823ce96793b0fccb8.html (Figure uCT-ART的4D-CT)	B/L	2022.04	Moderate motion	M
32	https://youtu.be/rTMHEu6Xveg	B/R	2022.05	@00:35. Moderate motion	M
33	https://youtu.be/rTMHEu6Xveg	R/R	2022.05	@02:05. Minimal motion	U
34	https://www.canalc2.tv/ video/16179	B/R	2022.06	@02:22. Minimal motion	F?
35	https://www.canalc2.tv/ video/16179	B/L	2022.06	@02:45. Minimal motion	F
36	https://vimeo.com/820286236	B/R	2023.04	Minimal motion. Breasts' largest displacements averaged 1.7 mm (range: 1.1, 2.9 mm). ExacTrac sphere surface markers	F
37	https://doi.org/10.1016/j. phro.2023.100529 (video 2—4)	B/R	2023.12	Substantial motion [19]	M?
38	https://doi.org/10.1007/s00134-024-07643-w (video 1—2)	B/B	2024.09	Minimal motion. Pressure-controlled ventilation [20]	M

Notes: Rows ordered by upload date. Links checked on April 26, 2026. Motion assessment refers to breast/chest wall movements. @, timeline pointer to 4D CT if it is not at the beginning of the video. View/side: B — bilateral; R — right; L — left; 0 — no visible tumor. Date upload: format Year.Month. Row color: grey — web or journal article; blue — webinar or congressmeeting presentation; orange — lecture; green — company showcase; white — stand-alone case view or case study. Gender: F — female; M — male; U — uncertain.

https://youtu.be/hxRJmnpsSaI nation of zero expansion margin, prone setup, or deep inspiration breath hold [22] would have avoided the heart irradiation.

That target margins should widely ensure against breast respiratory motion is a common radiotherapy assumption. The breast is a highly deformable organ which changes shape with every minute movement in normal daily life, whether walking, running, or even at rest when turning or bending the body. Attached to the chest wall, the breast moves with breathing movements [23—25]. It follows that the lack of breast respiratory motion is counterintuitive.

Contrary to the common assumptions regarding breast respiratory motion, researchers have observed little intrafractional motion of the breast during radiotherapy. A Dutch study observed no significant breast movements; the maximum deviations on portal images were 1.9—3.7 mm [26]. Among 1709 portal images analyzed by Smith et al. [27], intrafraction variation was minimal; the maximum range for any patient on any day was 0.25 cm. In Kron et al. [28], the intra-fraction variation was 1.1 ± 0.2 mm. In Lirette et al. [29], intrafraction images demonstrate no significant respiratory change in the volume of breast and lung tissue; the standard deviation for the central lung distance was 1.8 mm. In Prabhakar et al. [30], the standard deviations in various intrafraction motion measurements were between 0.7 mm and 1.36 mm. In a 2012 systematic review of motion during radiotherapy to the breast in the supine position without respiratory motion management, Michalski et al. [31] reported that the magnitude of intrafractional movement was generally very small and almost the same across the studies reviewed. More recently, a comprehensive review of intrafractional or respiratory motion in breast cancer radiotherapy also found movements less than 2—3 mm in most studies [4].

Several factors can explain why most cases showed minimal respiratory motion of the breast. Chest expansion in quiet breathing decreases with age (cancer patients are older than the active population), with body mass index (weight increases with age), and, most importantly, with supine position during radiotherapy, which shifts the breathing pattern from a thoracic respiration to a predominantly abdominal respiration [32—34]. Furthermore, reduced chest mobility can be associated with chronic pulmonary disease [35—37]. Chest wall pain, or pleural effusion post biopsy, or fiducial implant could also contribute.

Intriguingly, gender appeared to affect respiratory motion. All 6 of 6 females (100%) presented with minimal motion, as compared with 3 of 8 males (37.5%). In 1846, Hutchinson [38] observed that "the ordinary breathing in the two sexes differs. *In men it is chiefly by the diaphragm; in women chiefly by the ribs*", corroborated a century and a half later [39]. During quiet breathing and at vital capacity, the female ribcage contribution to tidal volume is *higher than in men*, particularly in the seated position and at different inclinations, *but not in the supine* position [39]. Verschakelen et al. [32] observed in healthy male and female subjects that the abdomen contributed more to quiet breathing than the rib cage in the supine position, in contrast to standing or sitting. Romei et al. [40] investigated the effects of posture — from seat without then with back support at different angles, to supine on a rigid flat bed — and gender on thoraco-abdominal motion and breathing pattern. Posture strongly influenced the displacement of the rib cage, which decreased from seat position to supine. Abdominal volume and diameters increased *significantly from seat to supine in women*, but not significantly in men [40]. Thus, there is a complex interplay between gender, anatomical differences, and breathing patterns, which is not the purpose of this study to elucidate. Nevertheless, because diverse types of support are used in the radiotherapy of breast cancer, the effect of the support's inclination on respiratory motion might warrant attention.

The impact of minimal breathing motion on breast radiotherapy might be important. Conventional radiotherapy adds 5 mm expansion to clinical breast targets to account for respiratory motion on top of setup uncertainties [41], up to 15 mm in the earlier recommendations [42]. Despite a low incidence of severe pulmonary parenchymal changes, thoracic radiotherapy for breast cancer may lead to significant impairment in functional capacity and exercise performance, through muscle weakness and restriction of chest wall mobility [43]. Reducing the expansion margin would decrease the doses not only to critical organs but also to the normal tissues surrounding the targets [36, 44]. Identifying the actual breathing motion might be critical to avoid applying inadequate motion management in patients who have no need for such

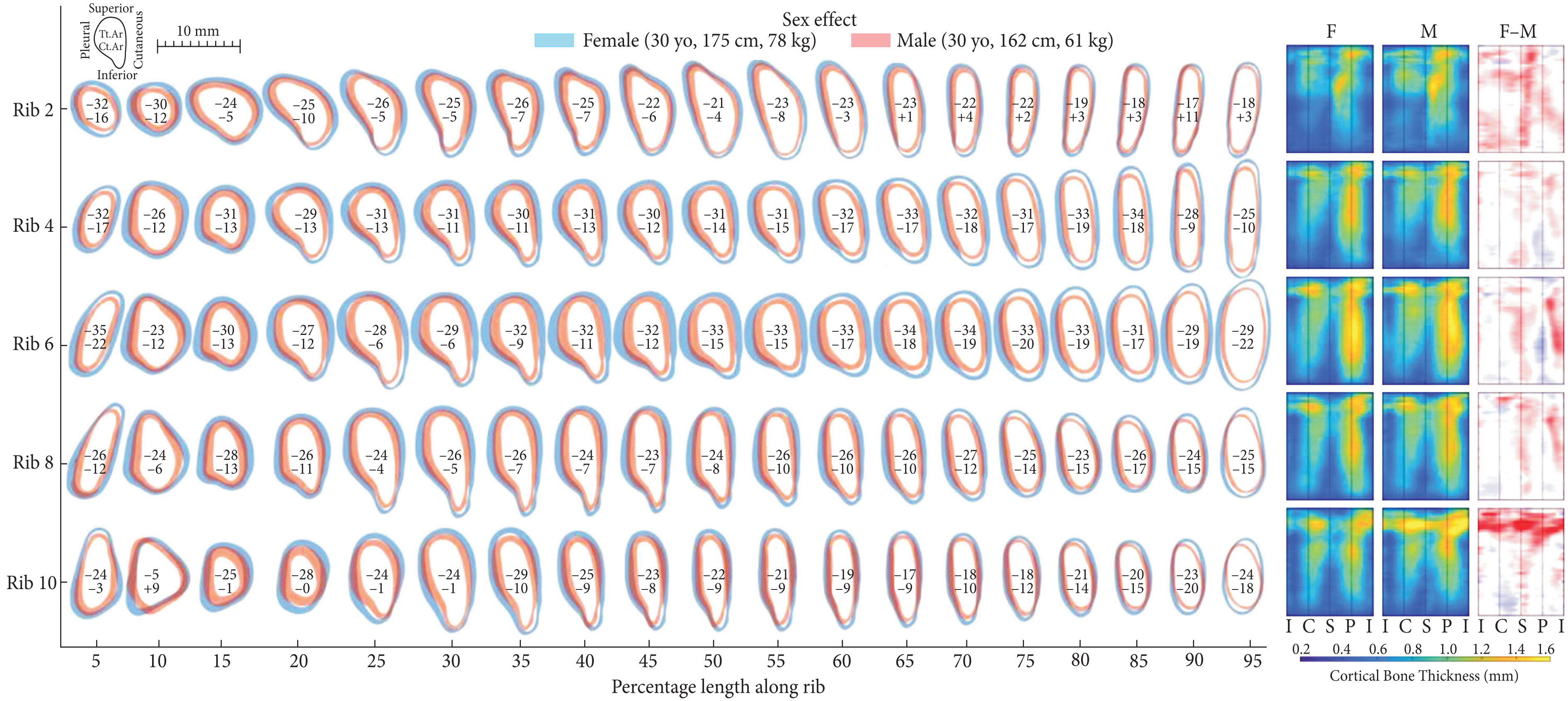

Fig. 1. Rib sectional differences between males and females for average statures and weights (above) and for equal statures and weights (below) [52]. Available from: https://doi.org/10.1111/joa.13999. Reproduced under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License

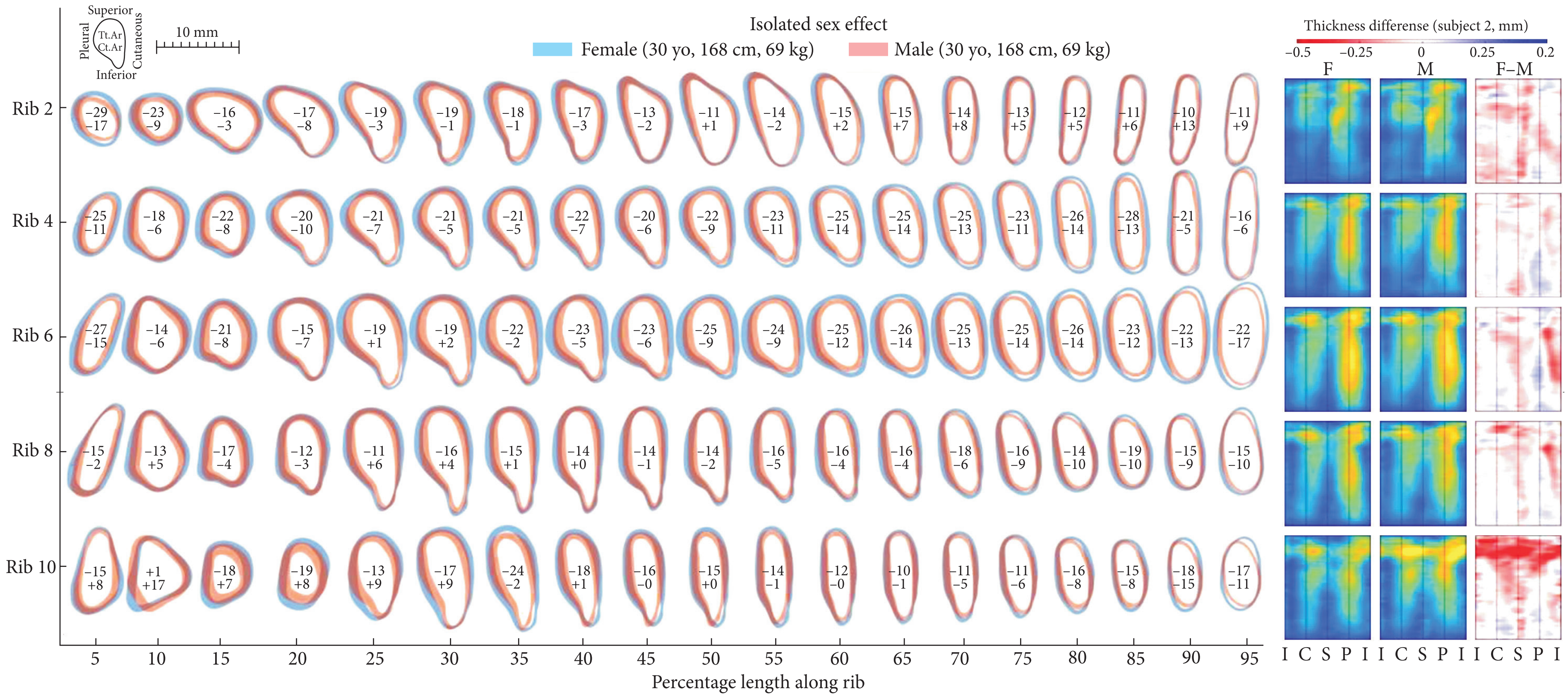

Fig. 2. 4D CT axial view (left panel) and respiratory motion of the breasts (right panel). Left panel: axial view at the level of the nipple-areola (Table, case 36). Right panel: surface display during breathing, computed from case 36 in the original DICOM files. Variations in Moiré effect are indicative of subtle surface change between respiratory phases. There is barely any significant movement relative to the nipples, breasts, and ExacTrac sphere markers

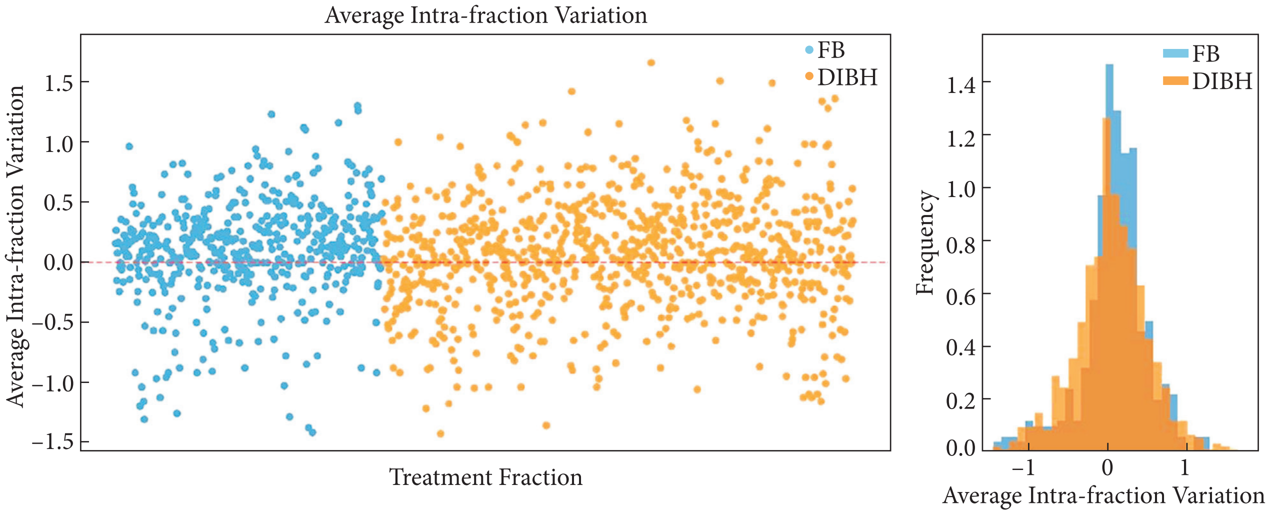

Fig. 3. Intrafraction motion, free breathing (FB) compared with deep inspiration breath hold (DIBH) [58]. Intrafraction variation in mm. Reproduced with permission from Elsevier

management [45]. Of interest, various areas of the breast/chest moved differently, upper vs. lower, anterior vs. posterior, and laterally right vs. left. The differential motion suggests the possibility of individualizing margins according to the patient's breathing pattern [46].

The study has several limitations. The video review suggests that the breast/chest wall's respiratory motion is minimal. However, some caveats need to be addressed before generalizing for breast radiotherapy practice.

• The breast is not a rigid object. Lack of motion of surface markers does not warrant that a deep-seated tumor bed or lumpectomy cavity would not move.

• Breathing continues even though the chest wall might remain entirely immobile. Intrathoracic organs do move according to diaphragmatic movements and the heart beating, which might affect the doses delivered to non-target organs. Almost all videos reviewed in the Table showed the preponderant importance of diaphragm movements. This is most remarkably illustrated in video case 12 (Table), which showed the heart moving into a high-dose region, *not* from any breast or chest wall motion, but from diaphragmatic motion.

• As noted earlier in the discussion, chronic pulmonary disease reduces chest mobility [35—37]. The majority of the 4D CT videos identified in this review pertained to lung tumors. Lung cancer and chronic obstructive pulmonary disease are closely linked [47, 48], whereas breast cancer patients most often have normal pulmonary function.

• 4D CT simulation acquires images in a single simulation session. However, radiotherapy is delivered in multiple sessions. The present review could not identify if a given breathing pattern observed with 4D CT remained the same throughout the whole course of radiotherapy. The reproducibility of the patient's respiratory pattern would need to be assessed.

• Breast surgery may affect breathing motion. Reduced chest movements in both quiet and deep breathing on the side of the mastectomy have been reported in a small study comparing mastectomy patients with healthy subjects [49].

• The impact of axillary surgery on breast motion is unknown. A non-negligible incidence of scapula alata has been observed in a prospective cohort of breast cancer patients [50]. Scapula alata, or winged scapula, is a sign of lesion to the long thoracic nerve. The nerve is responsible for the innervation of the serratus anterior muscle, which lifts the ribs, assisting in respiration.

Three cases presented with skin-surface fiducials (cases 3, 19, and 36), two of which are ExacTrac infrared reflective spherical markers. ExacTrac markers have been shown to provide sub-millimetric setup accuracy [51]. The accuracy does not depend on the marker size (incidentally, 13.2 mm diameter by caliper and by CT measurement in case 36), but on the identification of the markers' centroids. The video assessment of motion in these cases might be considered to have millimetric precision.

In cases lacking screen measurement references, the use of ribs as a surrogate of scale warrants a note. The size and shape of ribs vary according to the rib number, location along the rib's length, patient's age, sex, height, and weight (Fig. 1) [52]. The ribs cannot replace precise measurements, but, like the fruit size model used in medicine teaching [53] or the eyeball estimation of left ventricular ejection fraction used in critical care [54], we hope that the ribs may help reduce inter-observer variability when assessing chest wall motion.

The results of this video review correlate with previous studies. It should be stressed that the review's simple approach can help highlight studies of higher precision. Incidence of breathing patterns, confounding by the patient's condition, and changes secondary to surgery are issues that will have to be considered when data become available. Observations based on mostly lung cancer cases can only be hypothesis-generating. Further research in breast cancer radiotherapy is needed, notably regarding the use of real-time magnetic resonance imaging [55] and surface imaging [56].

Surface imaging is important. 4D CT can visualize the respiratory motion of the surface (Fig. 2). But using 4D CT for the sole purpose of imaging the surface appears to be overkill, besides the issue that extracting measurements from 4D CTs requires non-negligible computer and human resources [7].

In contrast, optical surface scanning systems, implemented with a surface-guided radiotherapy (SGRT), do measure and record real-time deviations of selected surface areas during the whole course of radiotherapy sessions [56]. SGRT is adopted in many radiotherapy centers. In 2023, France counted 174 centers authorized for external radiotherapy [57]. The two major providers for SGRT, C-RAD and VisionRT, reported 130 centers implementing SGRT in France, i.e., in 3 of 4 centers. Assuming a similar adoption rate of 75% in other countries, we expect a tremendous amount of motion data to emerge. SGRT is changing the field. Already, a recent SGRT breast study reported on 102 patients undergoing 1360 fractions [58]. The authors found an average intrafraction motion of less than 0.4 mm. There was no clinically meaningful difference in intrafractional deviation between free breathing and deep inspiration breath-hold. The distribution of the respective deviations was almost identical (Fig. 3).

The previous studies, this video review, and the emerging surface-guided breast cancer radiotherapy data may herald a transition toward highly individualized margin strategies based on measured respiratory motion.

In line with emerging surface-guided data in breast cancer radiotherapy, this video review shows the preponderance of minimal respiratory motion of the breast/chest wall. The breast/chest wall may remain immobile despite large intrathoracic movements. Further studies are needed to identify the actual prevalence and patterns of breast/chest wall respiratory motion to individualize planning target volumes in accordance with the reality of respiratory motion.

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Conflict of interest

The authors declare no relevant conflict of interest.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

The authors used ChatGPT Plus to enhance readability and correct grammar. This was done at the final draft stage of the manuscript. ChatGPT was not involved in any other conceptual framework aspects of the work, such as study design, data analysis, interpretation, reference sourcing, or manuscript drafting. After using ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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МІНІМАЛЬНЕ ДИХАЛЬНЕ ЗМІЩЕННЯ ГРУДЕЙ ЗА ВІЛЬНОГО ДИХАННЯ: ОПИСОВИЙ ОГЛЯД ВІДЕОМАТЕРІАЛІВ ІЗ 4D КТ СКАНАМИ

Зміщення пухлини під час дихання слід враховувати при променевій терапії пухлин різної локалізації, включаючи рак грудної залози. Зазвичай при плануванні променевої терапії розширюють межі навколо цільового об'єму, щоб урахувати це зміщення. Однак лише в небагатьох дослідженнях обраховують фактичну величину зміщення за вільного дихання. В огляді проаналізовано загальнодоступні відеоматеріали з 4D КТ-сканами з метою оцінювання превалювання дихального зміщення грудей. Скани розділено на категорії в залежності від візуалізованої величини зміщення, а саме: мінімальне (до 3 мм), помірне (до 5 мм) або суттєве (понад 10 мм). Мінімальне зміщення відзначено у 22 із 38 випадків (57,9%), помірне — у 12 випадках (31,6%), суттєве — у 4 випадках (10,5%). Проаналізовані дані свідчать про те, що превалює мінімальне зміщення за рахунок дихальних рухів грудей та грудної клітки, у зв'язку з чим постає питання про доцільність збільшення відступу від меж цільового об'єму у всіх хворих.

Ключові слова: контроль дихання, рак грудної залози, дихальний цикл, чотиривимірна комп'ютерна томографія, контроль за дихальними рухами, променева терапія з поверхневим наведенням.