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Study to improve reproducibility and accuracy of DIBH for breast cancer radiotherapy: A laser-based self-monitoring system

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► ***Original article***

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ABSTRACT

Background: Deep-inspiration breath-hold (DIBH) is a helpful technique during radiation therapy (RT) for breast cancer that can protect vital organs and deliver a more accurate treatment dose to the target. A laser sensor-based position monitoring system is developed to measure the absolute position of an object and achieve high accuracy and reproducibility during DIBH. ***Materials and Methods:*** A laser distance sensor (LDS) was fabricated to be mounted on a commercially available breast board and configured to provide real-time monitoring to assist with respiratory control. DIBH was measured in 10 volunteers with and without self-monitoring. Using an anthropomorphic phantom, we calculated the change in dose distribution due to DIBH error. We estimated the change in dose to target, the heart, and left lung due to DIBH error from the volunteer data. ***Results:*** With monitoring, the DIBH error was within 2 mm; without monitoring, the DIBH error increased to approximately 5 mm. Some of the volunteers who did not perform self-monitoring had large DIBH errors. This resulted in suboptimal dose distributions to the target, heart, and left lung, due to unintended alterations in the intended dose distribution. ***Conclusion:*** A self-monitoring system using LDS can greatly assist in the reproducibility of DIBH, thus helping to maintain the planned prescribed dose.

INTRODUCTION

Breast cancer represents 9% of all cancers and is one of the most prevalent forms of cancer among women [1]. However, with a 5-year survival rate exceeding 90%, clinical practice has shifted its focus from mere cancer removal to enhancing quality of life. Radiation therapy (RT) following breast-conserving surgery (BCS) which can remove cancer cells that may remain near the tumor or its lymph nodes, is effective in reducing the recurrence rate of breast cancer [2] and can minimize the extent of the BCS, helping to improve the patient's quality of life after treatment.

Deep-inspiration breath-hold (DIBH) is widely used in breast cancer to protect normal organs during RT by controlling the patient's breathing to increase the distance between the treatment site and surrounding organs. In particular, it helps to increase the distance between the left breast parenchyma and the heart, thereby reducing the irradiated heart volume [3, 4]. Furthermore, it reduces chest wall motion, thereby minimizing the changes in target and surrounding normal organ positions that may occur during RT [5, 6]. Fixing the position of these organs can significantly reduce uncertainties caused by breathing. The clinical necessity of DIBH has been well-documented in various studies, highlighting its dosimetric benefits over free breathing (FB) [7-10], its advantages in dose-volume histogram (DVH) analysis for the heart [9, 11-15], and its superiority over end-inspiration breath-hold (EIBH) and FB in reducing irradiated volumes of the left anterior descending coronary artery and left lung [9, 11, 12, 16, 17].

As the prescribed RT dose is distributed over several days depending on the fractionation technique, the reproducibility of DIBH is important to maintain the quality of RT. There is ongoing research in respiratory monitoring for accurate DIBH. Real-time position management (RPM) systems are widely used monitoring systems [11, 16, 18]. Self-monitoring studies have been conducted using RPM systems.

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RPM systems have the advantage of being simple set up and observation of breath but have the disadvantage of requiring a dot box to be placed on the abdomen, which can lead to differences in abdominal and thoracic movement. The recent development of surface-guided radiotherapy (SGRT) can be used for patient setup to respiratory monitoring [19-21]. SGRT allows FB and DIBH to be measured by scanning specific areas in the chest. However, the equipment is expensive, and installation is complex. It also measures the relative distance between the devices and the chest, which can lead to errors in height reproducibility due to the ceiling-mounted design. The absolute distance measurement system proposed in this study can significantly reduce patient breathing and patient setup errors. In addition, the equipment cost is relatively low and the installation process is simple, making it easy to integrate with existing radiotherapy equipment.

In this study, we developed a laser sensor-based position monitoring system to quantitatively assess the status of DIBH by continuously measuring the absolute distance between the patient's sternum and the sensor in real time. In particular, the absolute distance measurement can measure and record DIBH position and enables quantitative analysis based on absolute distance error. This study aims to determine the reproducibility and accuracy of DIBH with and without self-monitoring using the developed monitoring system. In addition, the dose distribution of targets and major organs at risk (OAR) was analyzed according to the DIBH error.

MATERIALS AND METHODS

System design

Figure 1(a) shows the setup of the laser distance sensor (LDS) (ODSL 96B, Leuze Electronic Corp., Germany) mounted securely on a commercial breast board (MT-350, CIVCO Radiotherapy, USA) using a dedicated sensor mount. This system, utilizing an LDS to measure absolute distances, enables real-time monitoring of the patient's sternum movement, allowing for self-monitoring. Care was taken to ensure that the system did not cause any physical interference with the computed tomography (CT) scanner or radiotherapy equipment. The patient's first FB signal was measured and used as a reference for the patient setup and a starting point for the DIBH amplitude. The difference between the first DIBH signal and the FB signal was calculated and used as the reference for the DIBH amplitude to be measured subsequently. The PELT algorithm was used to compute the FB and DIBH signals [22, 23]. The DIBH criterion was set at a threshold range of 3 mm and monitored to provide a reference for patient self-monitoring of DIBH [8, 9, 11]. Data processing and post-processing of real-time measurements were performed using in-house software (MATLAB, MathWorks, USA).

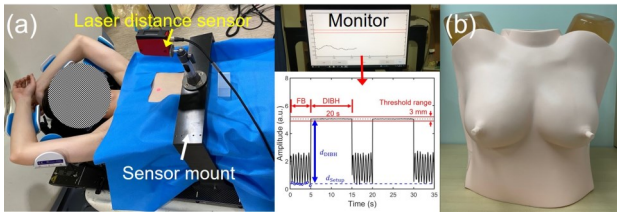

Figure 1. (a) The setup of the monitoring system using a laser distance sensor, and **(b)** the anthropomorphic phantom for dose distribution calculations.

Pre-clinical trials setup

Figure 1(a) illustrates the experimental setup for the clinical trial assessing the degree of DIBH maintenance with and without self-monitoring. Ten volunteers participated in the study, performing four repetitions of DIBH, each lasting 20 seconds. The experiment was conducted three times for each condition (self-monitoring and non-monitoring) a minimum time interval of one day between trials.

During the self-monitoring condition, participants observed their breathing in real-time on the monitor displayed in figure 1(a) and aimed to remain within the red line, which represented the DIBH threshold. All clinical procedures and data analyses were conducted in compliance with ethical standards, following approval and exemption from the institutional review board of Pusan National University Yangsan Hospital (IRB approval numbers: 04-2021-04144).

Dosimetric evaluation of DIBH error

In this study, the absolute distance of DIBH was quantitatively measured using LDS, and the change in dose distribution according to distance error was calculated based on this. The anthropomorphic phantom shown in figure 1(b) (Lungman, Kyoto Kagaku, Japan) was used. This phantom has a removable breastplate to simulate a female human body. It is manufactured in a life-size account for human anatomy, allowing for high-quality X-ray or CT scan images. The CT images used in this study were obtained with a 16-low spiral CT scanner (LightSpeed, GE, USA). Dose distribution calculations were performed using Elekta Monaco software (Elekta, Crawley, UK). The phantom was positioned identically to the treatment setup and a CT scan was performed assuming DIBH. The dose distribution was calculated from the CT image using the field-in-field technique to implement the DIBH error. The field-in-field plans were generated using two fields with 6-MV photon beams of the Versa HD (Elekta, Crawley, UK). The dose distribution was recalculated by shifting the chest height every 5 mm in the simulation under the same irradiation conditions. Figure 2 illustrates the sample planning image of dose distribution for the DIBH error using an

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anthropomorphic phantom. It can be confirmed that as the DIBH error occurs, the dose outside the treatment target or entering the heart or lungs increases.

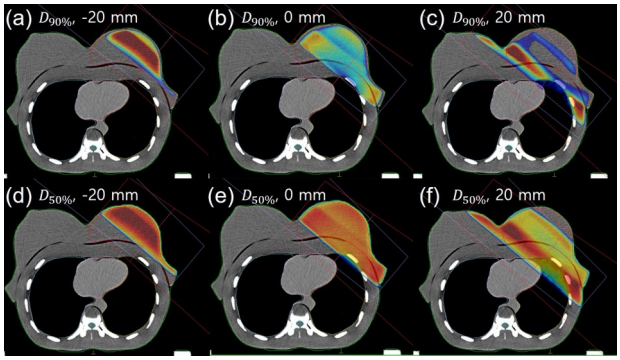

Figure 2. The sample planning images for the DIBH error using an anthropomorphic phantom. The images illustrate the DIBH error with an amplitude of **(a)** 90% of the prescription dose and -20 mm, **(b)** 0 mm, **(c)** +20 mm, **(d)** 50% of the prescription dose and -20 mm, (e) 0 mm, and (f) +20 mm.

Statistical analysis

The volunteer breathing data were collated for each FB and DIBH, and the amplitude discrepancy from the standard DIBH measurement was calculated using in-house software (MATLAB, MathWorks, USA). Furthermore, this study evaluated dose changes in planning target volume (PTV), the heart, and the left lung by analyzing dose distribution according to the DIBH errors, utilizing the dose-volume histogram (DVH) statistical function provided by the Elekta Monaco TPS (Elekta, Crawley, UK). Dose distributions calculated at 5 mm intervals were fitted, and volunteer-specific DIBH errors with and without monitoring were reflected in the dose distributions.

RESULTS

DIBH measurements

Figure 3 shows the DIBH results for one of the subjects with and without self-monitoring. Figure 3 (a) is the standard DIBH measurement. Figures 3(b), (c), and (d) show the volunteer's DIBH results without self-monitoring, which differ significantly from the standard DIBH. They also show how the error persists after the first of four DIBHs. Figures 3 (e), (f), and (g) show the subject's DIBH results with self-monitoring, showing that even after the first DIBH error, the error is corrected by monitoring. It can also be seen that the DIBH remains well within the threshold.

Figure 4 shows the mean and variance of DIBH according to self-monitoring per volunteer. Figure 4 (a) shows the DIBH results without self-monitoring, and we can see that they are generally well outside the threshold range. It can also be seen that the directionality of the amplitude is maintained after the first DIBH and the deviation between rounds is significant. Figure 4(b) shows the DIBH result when self-monitoring is performed, and it can be seen that the DIBH is generally maintained within the threshold range. It can also be seen that the deviation between rounds is not significant. Figure 4(c) shows the mean and variance of the DIBH as a function of whether the volunteer monitored all rounds. Overall, we can see that the DIBH is stable and well within the threshold when self-monitoring is performed.

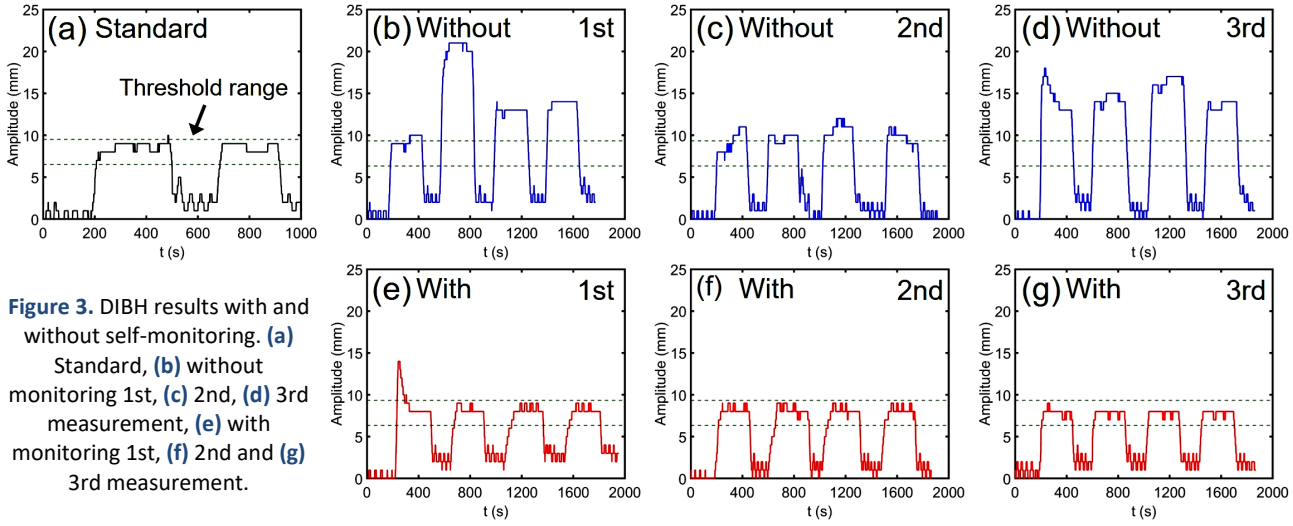

Figure 3. DIBH results with and without self-monitoring. **(a)** Standard, **(b)** without monitoring 1st, **(c)** 2nd, **(d)** 3rd measurement, **(e)** with monitoring 1st, **(f)** 2nd and **(g)** 3rd measurement.

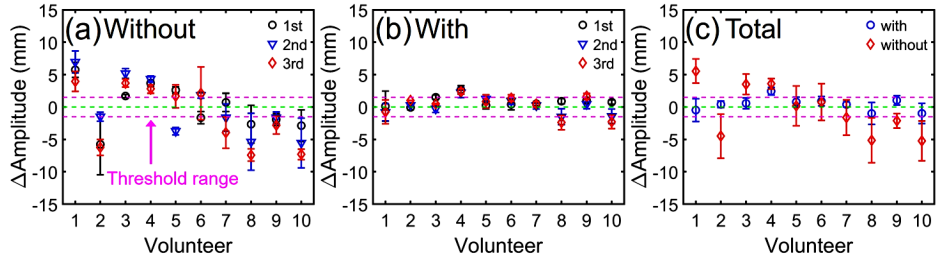

Figure 4. DIBH results by self-monitoring status per volunteer. **(a)** without monitoring, **(b)** with monitoring, and **(c)** total results.

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Calculation of dose distribution by amplitude

Figures 5(a) and (b) show the maximum, average, and minimum values of PTV dose and PTV coverage according to error at every 5 mm interval using CT of the phantom in figure 1(b). Each data was fitted with a quadratic function, with the maximum dose increasing and the average, minimum dose, and PTV coverage decreasing with amplitude around 0 mm. Figure 5(c) and (d) show the maximum, average, and minimum doses to the heart and left lung as a function of DIBH amplitude, and figure 5(e) shows the volumes of 5 Gy and 20 Gy to the left lung. The results presented in Figure 5 were calculated by averaging the results shown in figure 4. Each data point has been fitted with an exponential function that decreases exponentially with increasing amplitude. This is because a decrease in amplitude indicates that the gantry is closer to the thorax, resulting in the heart and left lung becoming situated closer to the treatment field. Conversely, an increase in amplitude signifies that the treatment field is moving away from the treatment target.

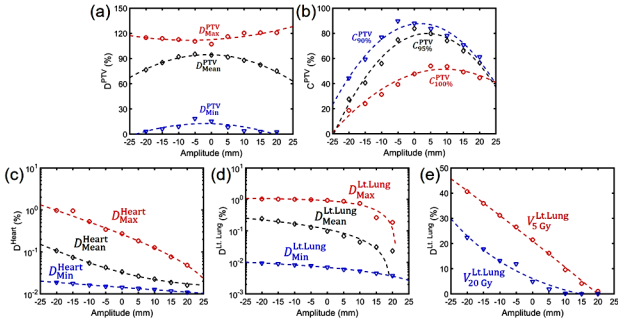

Figure 5. Target and OARs dose distribution resulting from the DIBH error using an anthropomorphic phantom. **(a)** PTV dose, **(b)** PTV coverage, **(c)** heart dose, **(d)** left lung dose, and **(e)** left lung volume. DPTV = PTV dose, CPTV = PTV coverage, DHeart = Heart dose, DLt.Lung = left lung dose, VLt.Lung = left lung volume.

Figure 6 shows the results of predicting the maximum, average, and minimum values of PTV dose and PTV coverage with and without self-monitoring using the volunteer's DIBH data and the fitted values in figures 5(a) and (b). When self-monitoring was performed, PTV dose and coverage didn't fluctuate much. Among volunteers who did not self-monitor, there were cases where DIBH was well maintained from spontaneous respiratory control. In these cases, PTV dose and coverage were not significantly affected. Nevertheless, in a small number of cases, failure to maintain DIBH led to a notable decline in PTV dose and coverage. In the case of volunteer 1, who exceeded the reference DIBH range, we can see that the maximum PTV dose is increased and the average PTV dose is decreased because fewer target areas are included in the radiation field. For volunteers 2, 8, and 10, we can see a significant decrease in PTV coverage due to breathing that did not reach the reference DIBH range.

Figure 7 shows the predicted dose of the heart and left lung with and without self-monitoring using the volunteer's DIBH data and the fitted values in figures 5(c) and (d). The heart and left lung doses for volunteers 2, 8, and 10 who breathe well below the standard DIBH range also increase significantly. In particular, the maximum and average heart doses are expected to be approximately 10% and 1% higher, respectively, compared to volunteers maintaining standard DIBH. Due to the large variation, there is also the potential for different doses to the heart and left lung for each treatment.

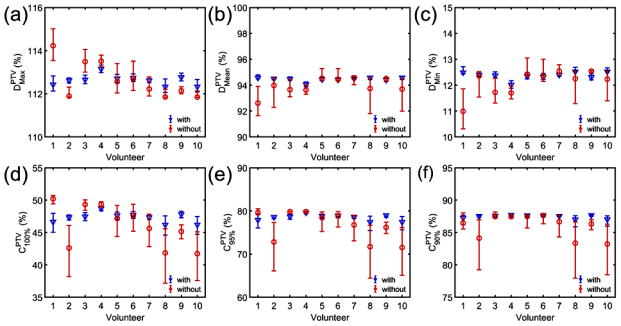

Figure 6. The estimation of the target dose distribution results from each volunteer data. **(a)** PTV maximum dose, **(b)** PTV mean dose, **(c)** PTV minimum dose, (d) PTV coverage for 100% prescription dose, **(e)** PTV coverage for 95% prescription dose, and **(f)** PTV coverage for 90% prescription dose. DPTV = PTV dose, CPTV = PTV coverage.

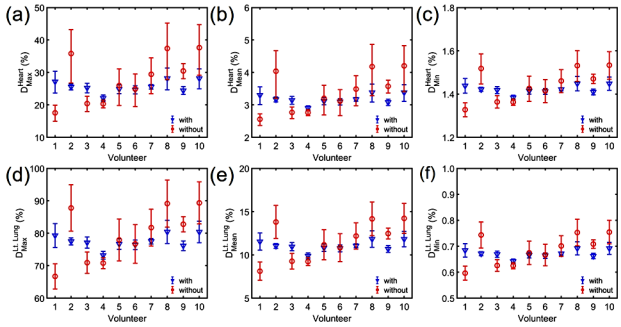

Figure 7. The estimation of the OARs dose distribution results from each volunteer data. **(a)** Heart maximum dose, **(b)** heart mean dose, **(c)** heart minimum dose, **(d)** left lung maximum dose, **(e)** left lung mean dose, and **(f)** left lung minimum dose. DHeart = Heart dose, DLt.Lung = left lung dose.

Figure 8 shows the results of using the volunteer's DIBH data and the fit values from figure 5(e) to predict the left lung volume for specific doses with and without self-monitoring. Similar to the results in figure 7(d), (e), and (f), the left lung volume results for specific doses were shown.

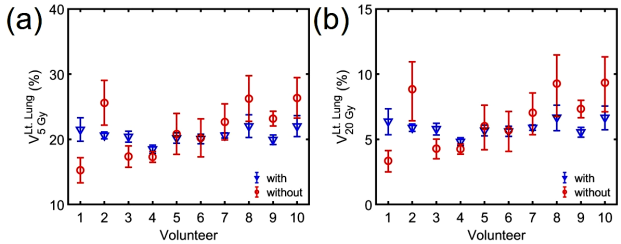

Figure 8. The estimation of the left lung volume for specific doses from each volunteer data. **(a)** 5 Gy, and **(b)** 20 Gy. VLt.Lung = left lung volume.

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DISCUSSION

During radiotherapy, devices such as contact-based respiratory monitoring systems, including spirometers [24], contact-based device [25, 26] or RPM [11, 16, 18, 27], and recently commercialized non-contact systems like SGRT are used to precisely maintain the position for DIBH [19-21, 28-31]. Contact-based monitoring devices allow for direct and intuitive measurement of the patient's respiration, involve minimal signal processing, and avoid physical interference from equipment like the gantry. However, these devices may face challenges in being attached within the radiation field. SGRT utilizes three ceiling-mounted cameras to measure the relative distance between the device and the patient's chest, accounting not only for movements in the XYZ directions but also for rotational adjustments. However, SGRT systems are expensive, require complex installation, and their measurements can be influenced by the movement of equipment such as the gantry. Compared to the aforementioned devices, the LDS system proposed in this study offers several advantages: First, it remains unobstructed by the treatment beam, enabling accurate measurement of respiration and DIBH positioning. Second, the device is designed to be mounted on a commercial chest board, facilitating easy installation and ensuring consistent patient setup throughout the entire RT procedure. Third, the system has a lower signal post-processing burden compared to conventional systems, as it provides a single numerical value for the distance between the sternum and the LDS. This minimizes the risk of data delays during treatment.

The advantages of self-monitoring systems have been unequivocally demonstrated in numerous studies [11, 24-26]. Consistent with the findings of this study, many reports have shown that self-monitoring during DIBH results in errors of less than 2 mm, with inter-fraction errors also measured within 2 mm, significantly improving reproducibility. This improvement contributes to a reduction in cardiac and pulmonary toxicities, with studies reporting a reduction of up to 30% in the maximum heart dose [11, 25]. In our study, while some volunteers managed to maintain their DIBH within acceptable ranges without self-monitoring, most deviated substantially, with errors reaching up to 10 mm. Such large deviations from the prescribed DIBH range could negatively impact PTV coverage, as well as doses to the heart and left lung, increasing the likelihood of deviating from the intended dose distribution as the number of treatment fractions increases. Self-monitoring, by reducing DIBH errors to within 2 mm, enhanced reproducibility and demonstrated a notable reduction in maximum heart dose. These findings underscore the potential of self-monitoring systems to minimize cardiac and pulmonary toxicity across the entire course of radiotherapy.

Since CT images could not be obtained from volunteers, dose distribution analysis was conducted using a phantom. However, there are limitations to using phantoms for such analyses, particularly in accurately modeling respiratory-induced anatomical movements, such as the motion of the chest wall, heart, and lungs. Furthermore, phantoms cannot precisely replicate the unique respiratory patterns, movements, organ positions, and sizes of individual patients. Despite these limitations, we believe that it is still feasible and meaningful to study the effects of DIBH errors on dose distribution caused by respiratory variations among different volunteers [31-33]. The results of this study, which align with other research on dose distributions for targets and organs affected by DIBH errors, suggest that phantom-based studies can also be regarded as reliable [11, 25, 31-35]. Additionally, the LDS used in this study has a distinct advantage in that it measures absolute distances, allowing for the quantification of DIBH errors and enabling the analysis of dose distributions for various error distances.

Although this study did not consider the gating system, combining the LDS with the gating system will allow for more accurate treatment targeting. In addition, the self-monitoring system is expected to shorten treatment time and reduce patient burden by increasing the time for maintaining DIBH within the threshold range.

CONCLUSION

Self-monitoring using a laser-based respiratory monitoring system contributes to treatment reproducibility and can reduce dose distribution bias. In addition, the absolute distance measurement of LDS can help predict changes in dose distribution due to distance error in DIBH. Thus, this system can aid in achieving precise respiratory control and maintaining the planned dose distribution during breast radiotherapy with DIBH, which necessitates accurate real-time respiratory monitoring.

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***Ethics Approval*:** All clinical information was investig ated after obtaining the approval with exemption of t he institutional review board of Pusan National Unive rsity Yangsan Hospital (IRB approval numbers: 04-2021-04144).

***Conflicts of interests*:** All authors declare that they have no.

***Author contribution*:** All authors participated in research and preparation of manuscript and its final

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