Prediction of excess volume in implementing the ABC system for breath-hold treatment: A preliminary study

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Abstract. Deep inspiration breath-hold (DIBH) is a clinical technique intended to reproduce organ position at the chest or abdominal region during radiotherapy sessions [1]. Active Breathing Coordinator™ (ABC) is a system that is used for the implementation of DIBH which has shown to reduce heart dose in breast cancer radiotherapy [2]. Since the ABC system’s main function is motion control of the torso region, attempts were made to apply the system to other cancer cases such as lung, liver, lymphoma and pancreas, in which treatment margins are stricter than in breast cancer. Hence, an evaluation on the technical aspects of the ABC system is essential. Data collection on patients treated with the assistance of the ABC system at the University of Malaya Medical Centre have been carried out since September 2018. The volume at the start of breath-hold moment, the maximum volume in the breath-hold session, the time delay between those two moments, the discrepancy in volume between those two moments, and the air flow rate leading to the breath-hold moment were all extracted from the data. The distribution and correlation of these parameters were evaluated between different groups of nominal threshold volume. The performance of the ABC system was characterised based on the discrepancy between the nominal volume and the real volume (excess volume) of a breath-hold session. The correlation coefficient of multiple regression of excess volume on nominal volume, air flow rate and time delay were 0.760, 0.714, 0.688 in group of nominal volume of 1.2 L, 1.3 L, 1.4 L, respectively. The correlation coefficient of regression of excess volume on air flow rate were 0.883 in group of nominal volume of 2.0 L. The excess volume can potentially be predicted by the nominal volume, the air flow rate and the time delay. Further investigation on assessing these parameters separately and on how the excess volume affects the treatment outcome is needed.

1. Introduction
Thanks to its proven effectiveness and robustness in cancer treatment, radiotherapy remains as one of the main treatment modalities for tumour since it was first introduced in the 19th century. As technology is rapidly evolving, new treatment techniques and its respective systems are being introduced into the radiotherapy practice. Breath-hold technique is such an innovative way of taking into account the uncertainty in the treatment of the thoracoabdominal region.
Interfractional uncertainty in the thoracoabdominal region is significantly affected by the respiratory movement of patients [3], which drastically alters the position of the tumour and compromises the OAR sparing. One of the methods to address this issue is to implement the 4DCT during the simulation phase, in which the ITV is determined by the acquired series of CT images. Alternatively, gating treatment with respiratory surrogate, or breath-hold technique, is also applied in this region. The main concept of the technique is that the radiation should only be delivered whenever a certain breathing position is reproduced. The surrogate can be one of the following: an intrabody landmark to be viewed by a fluoroscopy system, patient surface data obtained by optical imaging technology [4], an external object associated with the thoracoabdominal region of patient monitored by infrared system [5], or a direct measurement of air volume inside the lung [6].

Active Breathing Coordinator™ (ABC) (Elekta, Stockholm, Sweden) is a system that carries out breath-hold treatment in radiotherapy. It monitors the breathing motion of the patient using the air volume measurement. The system will block the airway of the patient if a stated threshold volume is reached, either by inhalation or exhalation. Initially, this system was developed for breast cases [6], in which the gross target and the margins are large. However, recent attempts have been made to implement it to other treatment sites [7, 8]. Hence, an investigation on the technical aspects of this system is needed.

![Figure 1](image)

**Figure 1.** A typical graph displayed on ABC workstation during a breath-hold session.

Figure 1 shows a typical graph displayed on ABC workstation during a breath-hold session. In this particular example, the trigger (threshold) volume is set at 1.3 L. Although the trigger volume is set at 1.3 L, the air flow of patient is only completely stopped at a larger value after an amount of time, creating an excess volume. For a system managing target position and organ sparing based on the air measurement from the patient, this excess volume can potentially affect the performance of the ABC technology. Hence, prediction of excess volume can be an asset for outcome evaluation of treatment. This leads to the objective of this study: to determine a method of predicting the excess volume based on patient data. The detailed objectives are (i) to analyse the technical parameters of ABC system: air flow rate, trigger volume, time delay and excess volume (ii) to develop a prediction formula of excess volume based on patient data.
2. Material and methods

2.1. Data extraction from ABC log file

Retrospective data of patients who underwent treatment with ABC were collected from September 2018 to July 2019 in the University of Malaya Medical Centre, Malaysia. Data from 639 breath-hold sessions of 8 patients were extracted.

Table 1 shows the metadata of the ABC log file. An inhouse MATLAB® (The MathWorks, Massachusetts, USA) programme was developed to extract air flow rate, trigger volume, time delay, and excess volume by applying suitable criteria to this metadata.

| Metadata of ABC log file |
|-------------------------|
| Threshold volume        | Unit: Litre |
| Count frequency         | Constant: 50 Hz |
| Patient information     | As input |
| Session’s date and time | Following the ABC workstation’s date and time |
| Session number          | Each session is saved in a separate file |
| Breath-hold duration    | Unit: second |
| Trigger on inhale       | Logical value |

Table 1. Metadata of ABC log file

| Recorded Data |
|---------------|
| Time          | Unit: second |
| Volume        | Unit: Litre |
| Balloon valve status | 1: deflated 
|                 | 2: ready to inflate at threshold (inhale) |
|                 | 3: ready to inflate at threshold (exhale) |
|                 | 4: inflated |
|                 | 5: fault |
| Patient switch | 0: Disabled |
|                | 1: Enabled |
| Gating mode    | Automated/Manual |
| Gating status  | Enabled: System is ready on gating |
|                | Disabled: system is not ready on gating |
| Relay state    | Open: Breath-hold function is inactive |
|                | Closed: Breath-hold function is working |

Patient data was categorised by the nominal trigger volume: 1.2 L (N = 195), 1.3 L (N = 65), 1.4 L (N = 310), and 2.0 L (N = 69). The recorded trigger volume was taken as the volume at which the Balloon valve status changed from “ready to inflate at threshold (inhale)” to “inflated”. Excess volume was recorded by taking the difference between the maximum value of volume during one breath-hold session while the Balloon valve status is “inflated” and the respective recorded trigger volume. Time delay was recorded as the duration taken to reach the maximum volume from the recorded trigger volume while the balloon was inflated in one breath-hold session. Air flow rate was the first degree’s coefficient of the fit line to the group of data points from the last inhalation leading to the trigger.

2.2. Data analysis

Inter-group comparison using Kruskal-Wallis test was carried out on all of the extracted parameters. Pairwise comparison was further accessed to investigate the distinctness of these parameters between groups.

As for the Intra-group comparison, the correlation analysis was applied to investigate the association of excess volume with other parameters. Subsequently, multiple regression was carried out to investigate the feasibility of predicting the excess volume based on the other parameters.
Figure 2. Results of the Kruskal-Wallis test between four groups 1.2 L, 1.3 L, 1.4 L, 2.0 L on: (a) trigger volume, (b) excess volume, (c) air flow rate and (d) time delay.

3. Result and discussion

3.1. Inter-group comparison using the Kruskal-Wallis test

Figure 2 shows the results obtained through the application of the Kruskal-Wallis tests between four groups: 1.2 L, 1.3 L, 1.4 L, 2.0 L on the four investigated parameters. The recorded trigger volume of each group (Figure 2(a)) was within 2% of their respective nominal value. This deviation is a result of the combination of a relatively fast air flow and the temporal resolution of the ABC system. Nevertheless, the blocking signal was sent at the intended moment.

The variance of excess volume (Figure 2(b)) decreased as the nominal trigger volume increased. This was due to the fact that it was easier for the patient to reach the lower value of volume than the higher value of volume. These results suggest that excess volume may be affected by the air flow rate of the patients.

The same observation on variance occurred in the case of air flow rate (Figure 2(c)). However, the trend of distribution between groups indicated that the excess volume was not solely based on air flow rate. A hypothesis that excess volume was a function of multiple factors was made.

Although time delay’s variance followed the same trend observed in excess volume and air flow rate (Figure 2(d)), the smaller coefficient of variation on every group of this parameter hinted that this factor was less dependent on patient. Technically, time delay was the transition time of the balloon from its deflated state to the fully inflated one. Pairwise comparison between groups yielded significant difference except on the pair of group 1.2 L and 2.0 L, and the pair of group 1.3 L and 2.0 L. Thus, time delay, although hypothesised to be more machine-related, was not a constant.
3.2. Correlation analysis and preliminary prediction formula

Table 2 shows the correlation of excess volume with trigger volume, time delay, air flow rate, respectively. The association of other parameters to excess volume was different between groups.

**Table 2. Correlation of excess volume with trigger volume, time delay, air flow rate in four groups: 1.2 L, 1.3 L, 1.4 L, 2.0 L.**

|                      | 1.2 L | 1.3 L | 1.4 L | 2.0 L |
|----------------------|-------|-------|-------|-------|
| Trigger volume       | 0.537 | 0.488 | 0.446 | 0.474 |
| Time delay           | 0.368 | 0.400 | 0.573 | 0.755 |
| Air flow rate        | 0.621 | 0.420 | 0.495 | 0.900 |

In groups of 1.2 L, 1.3 L, 1.4 L, no single parameter showed a strong correlation with excess volume. Combining with the observation in the parameter analysis, excess volume of these three groups can potentially be predicted using multiple regression of trigger volume, time delay, and air flow rate. For the group of 2.0 L, a strong correlation between air flow rate and excess volume enabled a prediction formula based only on this parameter. Table 3 shows the regression of excess volume based on other parameters in these four groups.

**Table 3. Results of regression of excess volume in groups: 1.2 L, 1.3 L, 1.4 L, 2.0 L.**

| Group | Correlation coefficient (p<0.001) | Linear coefficient – standard error (p<0.001) |
|-------|-----------------------------------|-----------------------------------------------|
|       |                                   | Constant | Trigger volume | Air flow rate | Time delay   |
| 1.2 L | 0.760                             | (-2.389) – 0.498 | 1.954 – 0.417 | 0.074 – 0.009 | 0.123 – 0.017 |
| 1.3 L | 0.714                             | (-3.221) – 0.841 | 2.488 – 0.647 | 0.036 – 0.012* | 0.063 – 0.019** |
| 1.4 L | 0.688                             | (-2.819) – 0.472 | 2.005 – 0.339 | 0.035 – 0.006 | 0.112 – 0.014 |
| 1.5 L | 0.883                             | 0.106 – 0.007 | N/A             | 0.126 – 0.008 | N/A          |

*: p = 0.004; **: p = 0.002; N/A: Not available

4. Conclusion

Although the number of breath-hold sessions included in this study were large, the actual number of patients was relatively small (8 patients). The biasness of age, weight, and condition of patient was inevitable.

Due to the nature of patient data, the parameters could not be investigated separately. Thus, the independent contribution of these parameters to excess volume was not studied comprehensively. A phantom study is needed to address these remaining issues.

Correlation analysis showed that the excess volume had a weak to moderate association with other parameters. However, for maximum lung capacity, the association between excess volume and air flow rate was dominant. In conclusion, the excess volume in ABC system can potentially be predicted using trigger volume, time delay, and air flow rate. A full prediction model for excess volume and an investigation on the significance of the excess volume on treatment outcomes will be conducted in the near future.
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