Reproducibility and correction of the respiratory phase shift for enhanced internal-external motion correlation

ANDREW R. MILEWSKI[1], DEVIN OLEK[1], WILLIAM MARTIN[1], ANDREAS RIMNER[2], and GUANG LI[1]
[1] Department of Medical Physics, Memorial Sloan-Kettering Cancer Center, New York, New York
[2] Department of Radiation Oncology, Memorial Sloan-Kettering Cancer Center, New York, New York

JULY 12–16 2020 VIRTUAL
JOINT AAPM | COMP MEETING
EASTERN TIME [GMT-4]

INTRODUCTION

Respiratory motion causes significant uncertainty in targeting thoracic and abdominal tumors during radiotherapy, particularly in hypo-fractional stereotactic body radiotherapy (SBRT). Strategies that have been advanced to address this challenge possess several limitations: High-frequency x-ray imaging delivers large radiation doses to the patient and may require additional procedures for implanting fiducial markers. MR-guided treatment, although promising, requires substantial funding and is not widely available in radiotherapy clinics. Methods employing an external motion surrogate suffer from inaccuracy and unreliability due to breathing irregularities, including frequency, amplitude, and phase variations between the surrogate and actual tumor motions. As a consequence, large volumes of healthy tissue are often irradiated to ensure adequate margins around the internal tumor volume [1].

AIM

To evaluate the stability of patient-specific, respiratory phase shifts across time and to examine whether correcting the phase shift effectively enhances the correlation between external- and internal-organ motions.

METHODS

Under an IRB-approved protocol, ten healthy volunteers received two respiratory-correlated four-dimensional magnetic resonance imaging (RC-4DMRI) scans 10 minutes apart. Each 4DMRI scan lasted 5-16 minutes. Internal-navigator and external-bellows waveforms were simultaneously acquired during each scan: The navigator interrogated the lung-diaphragm interface and the bellows was placed 5cm inferior to the sternum. We designed an algorithm that maximizes the waveforms' cross-correlation (Figure 1) to calculate and correct the phase shift between the two waveforms within a series of automatically selected ten-second time windows. We compared the phase shifts and correlation enhancement effected by phase-shift correction between the two scans.

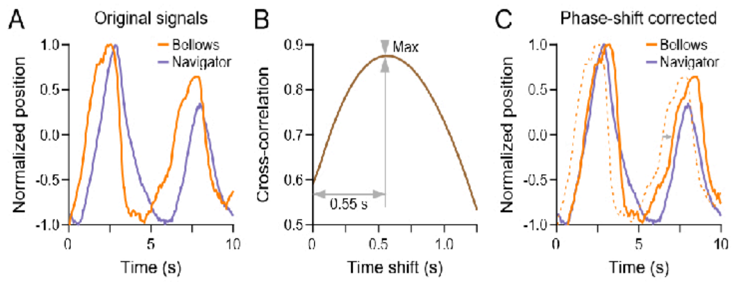

Figure 1. Illustration of the phase-shift–correction method. (A) A graph displays the original external-bellows and internal-navigator signals. The initial cross-correlation between the signals is 0.59. (B) Maximizing the signals' cross-correlation identifies a time shift. Multiplying the time shift by the signal's frequency yields the phase shift between the bellows and navigator. (C) After correcting the phase shift, the signals' cross-correlation is 0.88.

RESULTS

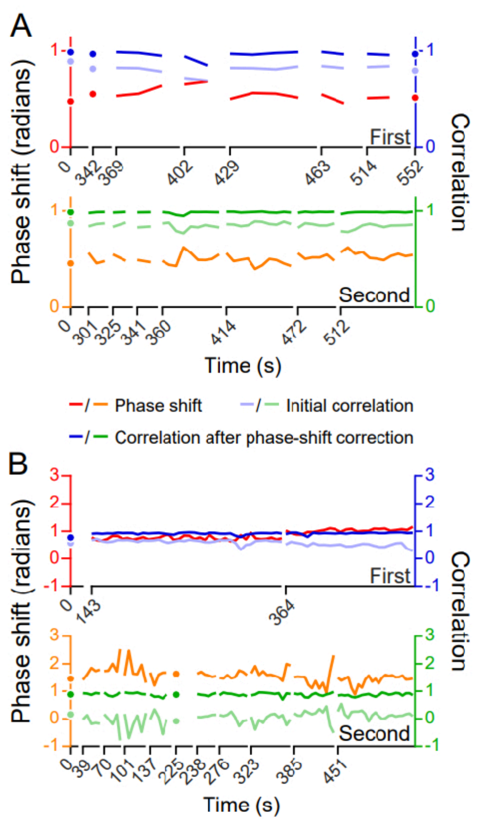

Figure 2. Example phase-shift calculations and corrections. (A) The calculated phase shifts (red or orange), initial cross-correlation (light blue or light green), and cross-correlation following phase-shift correction (dark blue or dark green) during the first (top) and second (bottom) RC-4DMRI scans for volunteer 3. (B) Same as panel A, but for volunteer 7. In both panels the correlation between the external bellows and internal navigator following phase-shift correction exceeds the initial correlation at every time point. The traces reveal that the initial correlation and estimated phase shift are negatively correlated: As the initial correlation decreases, the phase shift increases, and vice versa. The red traces demonstrate that the phase is fairly constant over time for both volunteers during the first scan. Comparing the orange traces to the red traces reveals that the phase shift is highly reproducible for some individuals (i.e. volunteer 3) and not for others. Moreover, the variability in the phase shift was much greater during the second scan of volunteer 7. The entire scan protocol exceeded 25 minutes for both volunteers.

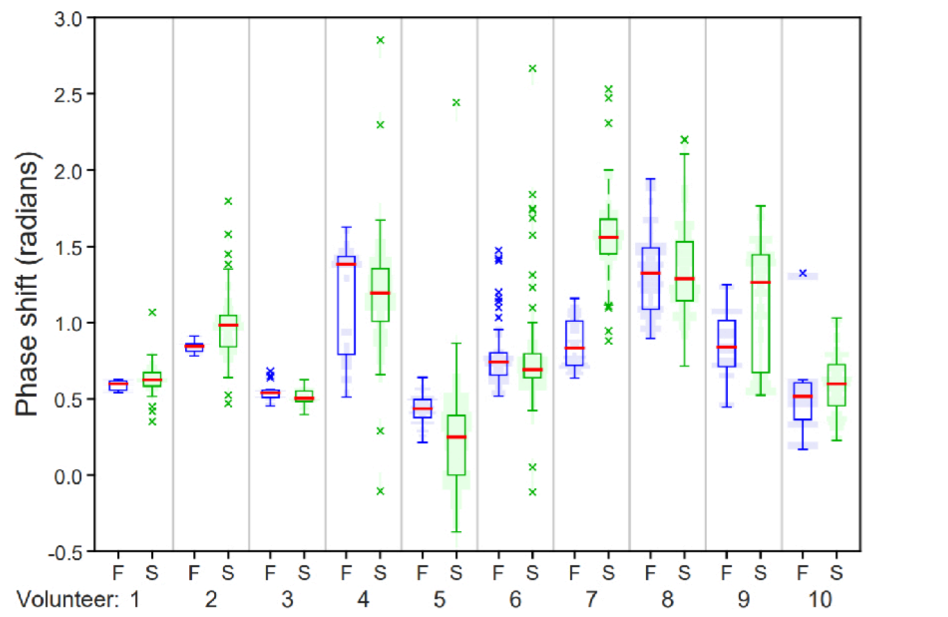

Figure 3. Box-and-whisker diagrams for the phase shifts calculated during the first (F) and second (S) scans for every volunteer. The red, horizontal lines indicate the median phase shift, the length of the box displays the interquartile range, the whiskers show the overall range, outliers (determine by Tukey's fences) are marked by "x" symbols, and the lightly shaded bars portray the normalized distributions. The median phase shift found in the second scan was similar to that found in the first scan for volunteers 1, 3, 6, 8, and 10, accounting for half of all the volunteers.

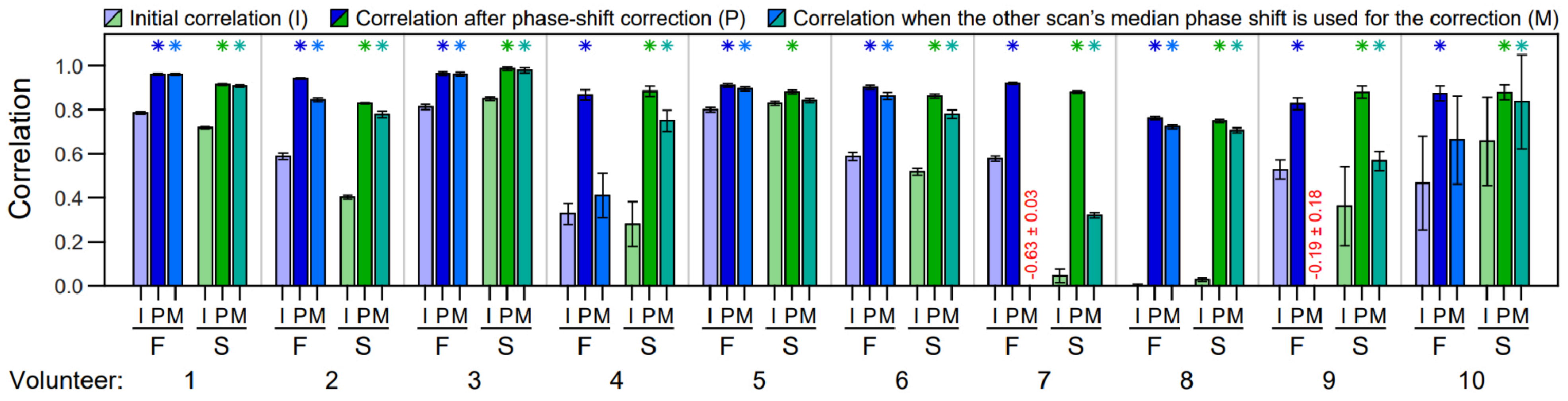

Figure 4. Bar chart showing the average initial cross-correlation between the bellows and navigator (I) during the first (F) and second (S) RC-4DMRI scans for each volunteer, the enhanced correlation after phase-shift correction (P), and the correlation that results when the median phase shift of the second scan is used is used to correct the phase shift in the first scan (M,F) or vice versa (M,S). Error bars represent the standard error of the mean. An asterisk above a bar indicates that the employed phase-shift–correction strategy effected a statistically significant improvement compared to the average initial cross-correlation (Mann-Whitney U test, $p < 0.05$). To conserve space, negative average correlations are indicated by the red numbers for volunteers 7 and 9.

DISCUSSION

- The second scan was often longer than the first and several volunteers were noted to have fallen asleep during the second scan. Together, these points may partly explain the greater variability in the phase shift that was found during the second scan for half of the volunteers (Figure 3).
- The greater variability did not prevent the phase-shift–correction strategy from enhancing the cross-correlation between the bellows and navigator signals: The strategy improved the cross-correlation to a similar extent in both scans for every volunteer (Figures 2, 4).
- The median phase shift found for the first scan could adequately correct the phase shift in the second scan for more than half of the volunteers (Figure 4), suggesting that the phase shift is stable over time for those participants. This approach failed for volunteers (i.e. 7 and 9) who displayed a large change in the phase shift between the two scans (Figure 3). In fact, the difference was so large that the using the median phase shift from the second scan to correct the first scan's phase shift yielded a negative cross-correlation for two volunteers (Figure 4).

CONCLUSIONS

- This study suggests that the phase shift between internal- and external-respiratory motions is stable over at least 25 minutes in many individuals.
- Correcting the phase shift significantly enhances the correlation between the internal- and external-respiratory motions, even though minor fluctuations may occur.
- The phase-shift–correction technique is potentially useful for respiratory-gated radiotherapy.

ACKNOWLEDGEMENTS

This study is in part supported by the NIH (U54CA137788). The authors thank participating volunteers and Philips Healthcare for technical support.

REFERENCES

[1] **Milewski AR et al**. Enhancement of long-term external-internal correlation by phase-shift detection and correction based on concurrent external bellows and internal navigator signals. *Adv Radiat Oncol.* 2019;4(2):377-89.

CONTACT INFORMATION

E-mail for corresponding author: lig2@mskcc.org (G. Li).