Results from a clinical trial evaluating the efficacy of real-time body surface visual feedback in reducing patient motion during lung cancer radiotherapy: Supplementary material

Gareth J. Price[1], Corinne Faivre-Finn[1], Julia Stratford[1], Sheena Chauhan[2], Michelle Bewley[2], Laura Clarke[2], Corinne N. Johnson[1], Christopher J. Moore[1]

[1] The University of Manchester, Manchester Cancer Research Centre, The Christie NHS Foundation Trust, Manchester, UK

[2] The Christie NHS Foundation Trust, Manchester, UK

Introduction

This document provides additional details in support of the above article. It includes:

1. Figure A - illustrating an optical surface reconstruction.
2. Text and Figure B – giving further details of the processing methodology used in the offline analysis of the motion of the optical surface measurement points.
3. Text and Figure C – further details of the method used to calculate the change in tumour Clinical Target Volume (CTV) registration across the 4D Cone Beam CT (CBCT) cycle.
4. A video screen capture of the feedback schema in mpeg 4 format (opticalSensorFeedbackSchema.mp4).
5. Full copy of the patient feedback questionnaire.

Optical surface reconstruction

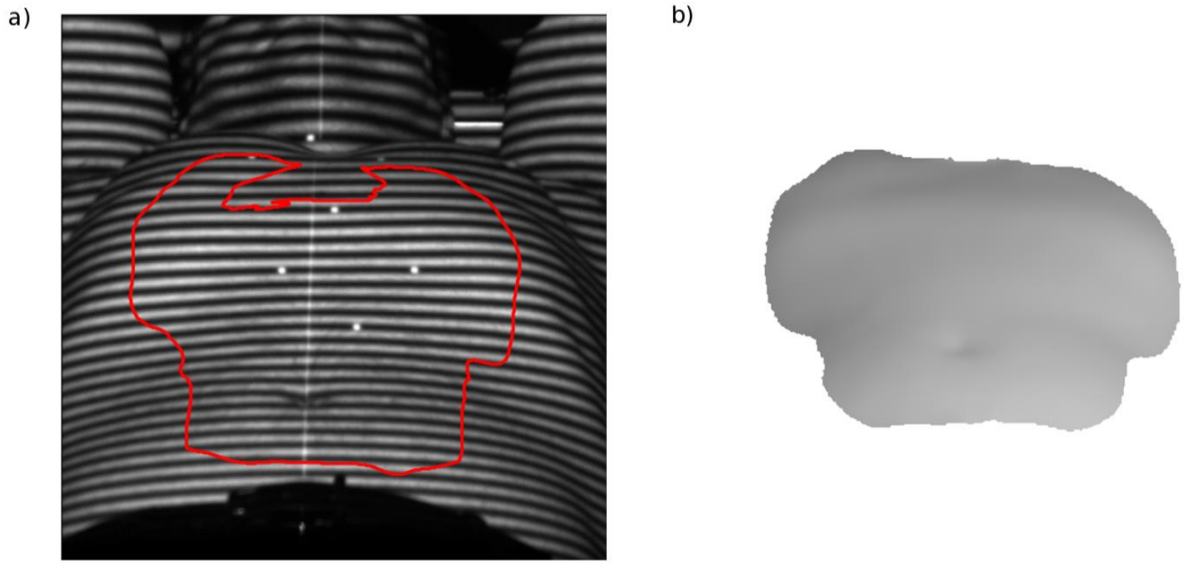


Figure A - (a) Sensor-eye view of a study patient overlaid with the mask defining those measurement points that are valid in each of the 5000+ frames per imaging session. (b) A representative reconstructed surface. Surfaces are acquired at a frame rate of ~22Hz with ~85ms lag time.

Optical surface measurement analysis methodology

External body surface motion is assessed for patients when free-breathing and when using the visualization schema by evaluating respiratory magnitude and regularity over their whole body surface using the optical surface sensor. Data acquisition for each schema consists of up to 512x512 independently measured points recorded at a frequency of 22Hz (recording time 90s optical alone or 240s with simultaneous 4D CBCT – Figure 2 in the main article).

The assumption of signal stationarity required to permit standard Fourier analysis techniques is not valid for the extended periods for which the trial subjects were monitored (see signal trace in Figure 1 in the main manuscript). Instead we perform a dynamic time-frequency analysis using the Continuous Wavelet Transform (CWT) after Torrence and Compo [1], similarly using the scale 6 Morlet mother wavelet to satisfy admissibility criteria. The minimum scale of our analysis, s_0, is calculated from the Nyquist frequency of the sensor measurement frequency of 22Hz, giving s_0 = 0.09s, with subsequent scaling factors calculated in the power of 2. Figure B shows an illustrative time-frequency plot of the free breathing signal from Figure 1 in the main article.

We limit the timescale of the motion we consider to between 1 and 10 seconds, corresponding to a physiologically realistic range of respiratory period, by applying a scale bandpass filter. Total signal energy is conserved under the wavelet transform, permitting the scale averaged signal variance to be calculated from the CWT power spectrum for a given scale band [1]:

$$\bar{\sigma}_n^2 = \frac{\delta j \delta t}{C_\delta} \sum_{j=j_1}^{j_2} \frac{|W_n(s_j)|^2}{s_j}$$

Where δj is the period of sub-octave scaling, δt is the data sampling period, j is the number of scale octaves above the minimum scale, s_j is the corresponding scale, $W_n(s_j)$ is the continuous wavelet transform at scale s_j and offset n, and C_δ is a constant factor calculated by reconstructing the delta function from the CWT mother wavelet (C_δ = 0.776 for the scale 6 Morlet wavelet).

We calculate the scale averaged signal variance within this window and use the fact that the variance of a sinusoid is equal to its average power to approximate the scale filtered signal's instantaneous amplitude as:

$$A = \sqrt{2\bar{\sigma}_n^2}$$

For each surface measurement point we calculate the mean (μ) and standard deviation (σ) of the timescale filtered signal's amplitude. These two scale-filtered parameters are then averaged over the patient's observed surface (composed of up to 512x512 independent measurement points). The optical measurements for each schema of each patient's imaging session can therefore be summarized by 2 parameters:

- The surface average of the mean of the measurement points' scale filtered signal amplitude (μ_μ) corresponding to motion magnitude.
- The surface average of the standard deviation of the measurement points' scale filtered signal amplitude (μ_σ) corresponding to motion regularity.

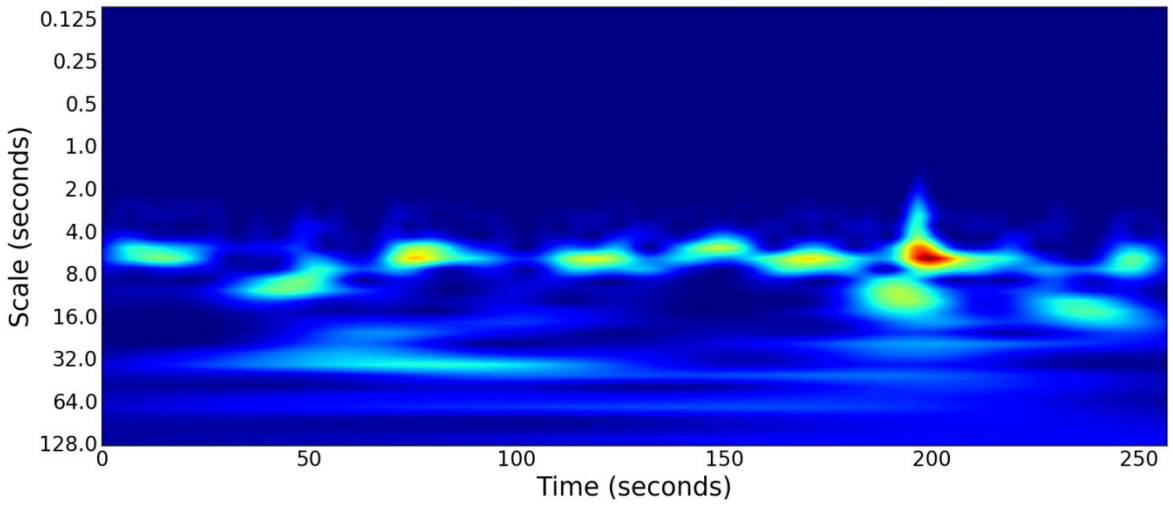


Figure B - The Continuous Wavelet Transform of the free breathing signal from Figure 1 (main text) showing its time-frequency dynamics. The colour-scale indicates signal power. Calculation performed with the scale 6 Morlet wavelet, with minimum scale 0.09s using the wavelets Python module (https://github.com/aaren/wavelets) implementation of [1].

Internal tumour motion analysis

Internal tumour motion is determined from the 4D cone beam CT images acquired simultaneously with free breathing and traffic light feedback optical measurements.

Image data were acquired using an Elekta Synergy linear accelerator with integrated Elekta XVI system (200 degrees gantry rotation, 1320 frames, S20 field size and F1 fliter, at 120kV and 20mA/16ms), and reconstructed in 10 respiratory phases using the standard XVI sinogram analysis approach [2].

Each phase image in the 4D CBCT datasets was matched to the first image using the SimpleITK [3] implementation of a mean squares difference driven multi-resolution rigid matching algorithm to facilitate batch processing. In order to match only on the tumour motion, evaluation of the optimizer metric was confined to within the defined Clinical Target Volume (or Gross Tumour Volume +5mm), in line with standard clinical practice. For each phase we recorded the Cartesian components of registration translation. The magnitude of the motion for a 4D image is then parameterized as the peak-to-trough amplitude of the periodic change in registration components. The resultant motion amplitudes were validated against those calculated using the CE marked clinical XVI workstations (v4.0) as an independent check. Figure C shows a match and change in CTV registration across the 4D cycle for an illustrative patient.

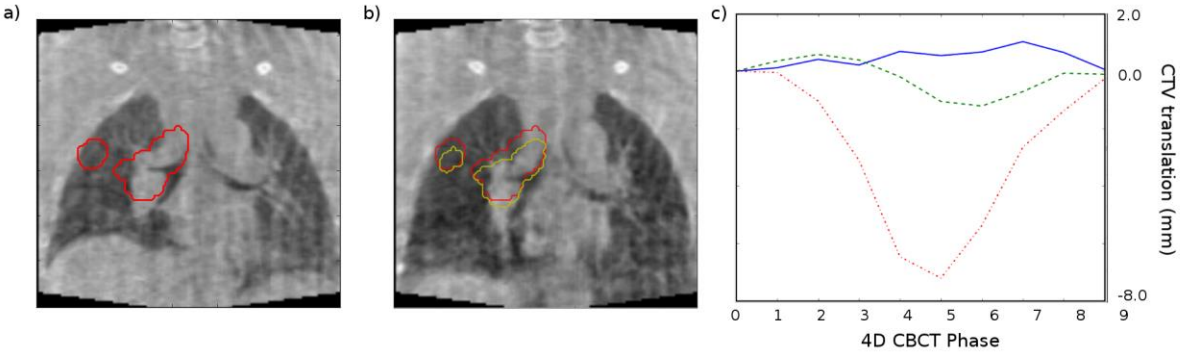
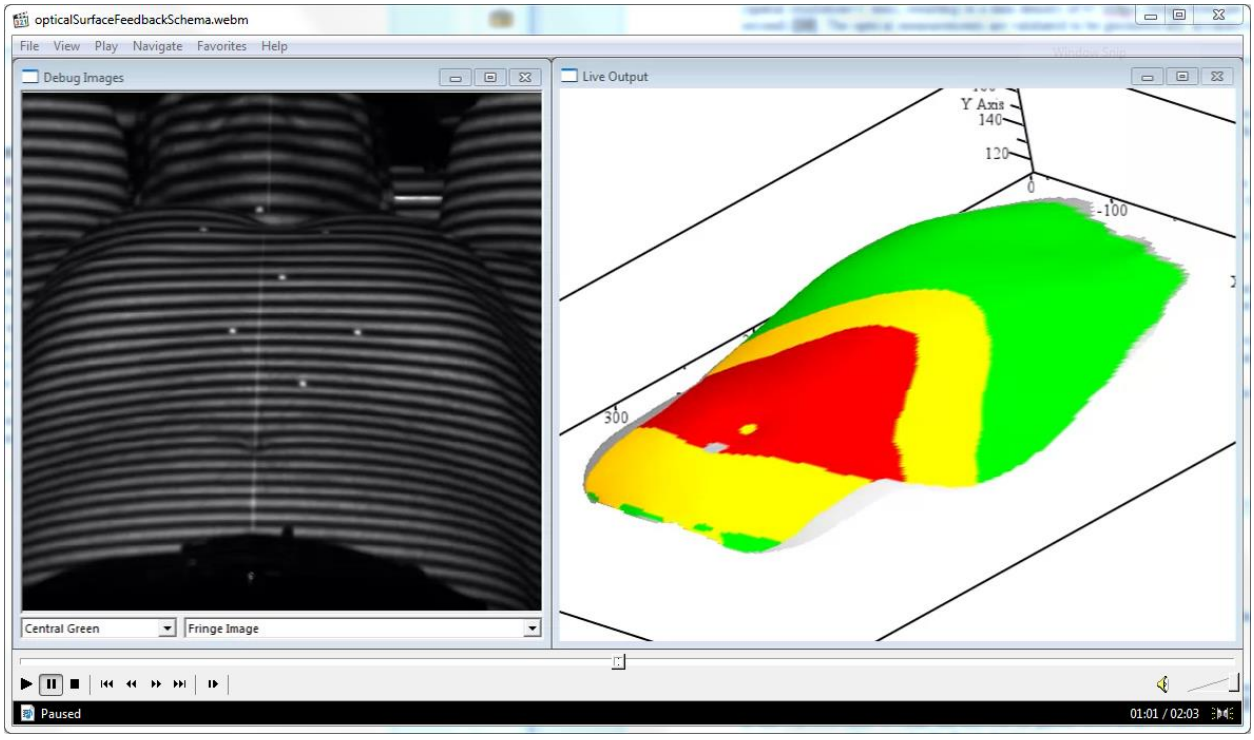


Figure C -*The rigid registration of the Clinical Target Volume (CTV) between maximum exhale and inhale phases for an illustrative study patient (Pat05): a) coronal view of maximum exhale 4D image phase and CTV matched from planning scan (red); b) maximum inhale 4D image phase with CTV matched from planning (yellow) and the corresponding maximum exhale segmentation (red) for reference; c) left-right (blue solid), ant-post (green dashed) and inf-sup (red dash-dot) registration component as function of 4D respiratory phase.*

Video screen capture of the visual feedback schema

The video (supplied as separate file opticalSensorFeedbackSchema.mp4) shows an example surface reconstruction from a study a patient being processed and rendered in real time. The left hand image gives the system's camera eye view, with the right hand image being that displayed to the patient.

1. The first rendering seen is simply the live surface (0:00 to 0:15)
2. The next is the colourwash visualization scheme (0:15 to 1:06). Here the deviation of the patient from their ideal treatment position is calculated from the reference surface and the distance displayed in colour that changes in increments of the patients free-breathing motion standard deviation. Starting with an oblique view, the surface is rotated to a 'patient eye' inferior view from the chest towards feet at 0:22. This is view the patients used for this scheme.
3. The next scheme is the 'lamina' display. This is simply the residual of the live surface subtracted from the reference surface (1:06 to 1:35). At 1:25 the patient coughs, forcing their body surface well out of positional tolerance. By 1:30 the patient has settled back to their normal respiratory motion and is within tolerance again. This highlights the advantage of using such systems in clinical practice to monitor patient positioning and warn of transient motion events.
4. The final display scheme is the 'traffic light'. Here the residual surface is averaged to a single parameter (1:35 to 2:03)


opticalSurfaceFeedbackSchema.webm
File View Play Navigate Favorites Help
Debug Images
Live Output
Y Axis
140
120
0
-100
300
Central Green
Fringe Image
Paused
01:01 / 02:03

Patient feedback questionnaire

ROSS-LC Study **Patient ID** ☐☐

Sponsor Ref: CFTSp076 **Participant Questionnaire** **Patient Initials** ☐☐☐

Today's date ☐☐/☐☐/☐☐☐☐ (DD/MM/YYYY)

We are interested in finding out how you feel about the device. The information that you provide will remain strictly confidential.

Do you wear prescription glasses? *(please tick)* ☐00 No ☐01 Yes

Do you have any eyesight issues? *(please tick)* ☐00 No ☐01 Yes

If yes, did your eyesight affect the viewing of any of the displays?

☐ None *Or tick all that apply*

☐01 The coloured surface (first display)

☐01 The lamina display (second display)

☐01 The traffic light display (third display)

Please answer all of the following questions yourself by circling the number that best applies to you. There are no right or wrong answers.

	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
General Feedback					
1. I found viewing the graphical display using the mirror arrangement acceptable	1	2	3	4	5
2. I found the device comfortable to use	1	2	3	4	5
3. I found the projector lights too bright during treatment	1	2	3	4	5
4. I found the sunglasses made the projector lights comfortably dim when I was not using the graphical display	1	2	3	4	5
5. I think it is a good idea for patients to be involved where possible in improving their treatment	1	2	3	4	5
6. I think patients that are given clear information can help control their breathing during treatment	1	2	3	4	5
7. I think the device will be useful for patients	1	2	3	4	5
Display Screens					
1. I found the graphical display easy to use	1	2	3	4	5
2. I found the colours helped me understand how to use the graphical display	1	2	3	4	5
3. I found the coloured surface easy to understand (first display)	1	2	3	4	5
4. I found the lamina display easy to understand (second display)	1	2	3	4	5
5. I found the traffic light display easy to understand (third display)	1	2	3	4	5

Please turn over

Which of the displays did you prefer? - best = 1, middle = 2, worst = 3

6. Coloured surface (first display) ☐
7. Lamina display (second display) ☐
8. Traffic light display (third display) ☐

Additional comments

Please make a note of anything else you would like to tell us.

Thank you for taking the time to complete this questionnaire.

References

1. C. Torrence and G. Compo, “A practical guide to wavelet analysis” *Bulletin of the American Meteorological Society* **79**(1) p61–78 (1998) doi: 10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2.

2. J.-J. Sonke *et al.*, “Respiratory correlated cone beam CT” *Medical Physics* **32**(4) p1176–1186 (2005) doi: 10.1118/1.1869074.

3. B.C. Lowekamp *et al.*, “The Design of SimpleITK.” *Frontiers in neuroinformatics* **7**(December) p45 (2013) doi: 10.3389/fninf.2013.00045.