Intraoperative localized constrained registration in navigated bronchoscopy

Erlend Fagertun Hofstad (MSc)\textsuperscript{1}, Hanne Sorger (MD)\textsuperscript{2,3}, Janne Beate Lervik Bakeng (MSc)\textsuperscript{1}, Lucian Gruionu (PhD)\textsuperscript{4}, Håkon Olav Leira (MD, PhD)\textsuperscript{2,3}, Tore Amundsen (MD, PhD)\textsuperscript{2,3}, Thomas Langø (PhD)\textsuperscript{1}

\textsuperscript{1} Department of Medical Technology, SINTEF Technology and Society, Trondheim, Norway
\textsuperscript{2} Dept. Thoracic Medicine, St. Olav’s Hospital, Trondheim, Norway
\textsuperscript{3} Department of Circulation and Medical Imaging, Faculty of Medicine, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
\textsuperscript{4} Department of Automotive, Transportation and Industrial Engineering, Faculty of Mechanics, University of Craiova, Romania

Corresponding author:
Erlend Fagertun Hofstad, MSc, Research Scientist
SINTEF Technology and Society
Dept. of Medical Technology
PB 4760 Sluppen
7465 Trondheim, Norway
Phone: +47 911 96 173
Fax: +47 93 07 08 00
e-mail: erlend.hofstad@sintef.no
Abstract

Purpose
One of the major challenges in electromagnetic navigated bronchoscopy is the navigation accuracy. An initial rigid image-to-patient registration may not be optimal for the entire lung volume, as the lung tissue anatomy is likely to have shifted since the time of computer tomography (CT) acquisition. The accuracy of the initial rigid registration will also be affected throughout the procedure by breathing, coughing, patient movement and tissue displacements due to pressure from bronchoscopy tools. A method to minimize the negative impact from these factors by updating the registration locally during the procedure is needed and suggested in this paper.

Methods
The intraoperative local registration method updates the initial registration by optimization in an area of special interest, e.g. close to a biopsy position. The local registration was developed through an adaptation of a previously published registration method used for the initial registration of CT to the patient anatomy. The method was tested in an experimental breathing phantom setup, where respiratory movements were induced by a robotic arm. Deformations were also applied to the phantom to see if the local registration could compensate for these.

Results
The local registration was successfully applied in all 15 repetitions, 5 in each of the three parts of the airway phantom. The mean registration accuracy was
improved from 11.8 – 19.4 mm to 4.0 – 6.7 mm, varying to some degree in the different segments of the airway model.

Conclusions

A local registration method, to update and improve the initial image-to patient registration during navigated bronchoscopy, was developed. The method was successfully tested in a breathing phantom setup. Further development is needed to make the method more automatic. It must also be verified in human studies.

Keywords navigated bronchoscopy; electromagnetic navigation; registration; local registration
**Introduction**

Bronchoscopy is used for endoluminal inspection and diagnostic procedures in the lungs. It is the essential diagnostic tool when investigating lung lesions that could represent malignant tumors. Precise navigation of the flexible bronchoscope through the airways to a defined target is challenging due to the numerous divisions and the lack of direct visibility of lesions in the lung periphery. The diagnostic success rate in bronchoscopy for non-visible tumors can be as low as 10-15%, depending on tumor localization, size, the experience of the pulmonologist, and the method used for obtaining tissue specimen, compared to 80-90% for visible tumors [1-3].

In electromagnetic navigated bronchoscopy (ENB), the instruments may be traced by attaching an electromagnetic (EM) sensor to the tip of the bronchoscope and tools for tissue sampling. The positions of the instruments are furthermore displayed on maps made from preoperative images of the patient, e.g. computer tomography (CT). Using ENB to reach non-visible tumors in the lung has increased the diagnostic yield to 70-80 % [4]. Commercially available systems like superDimension™ Navigation System (Covidien, Inc., Minneapolis, USA) and SPiN® Thoracic Navigation System (Veran Medical Technologies, Inc., St. Louis, USA) provide navigation based on electromagnetic tracking (EMT) of the bronchoscopic tools. Alternative tracking techniques for navigated bronchoscopy has also been tested, such as externally mounted sensors for measurement of endoscope insertion depth, rotational angle and tip bending angle [5]. A detailed description of the existing commercial and research systems
for navigated bronchoscopy can be found in Reynisson et al. [6].

Preoperative registration of the CT images to the patient anatomy is one of the essential steps to achieve adequate sampling accuracy with the ENB technology. The registration procedure can either be conducted using the EMT system, by image based registration [7] or a combination of both [8, 9]. Registration methods using information from the EMT system can furthermore be divided into landmark [8, 10] or centerline based approaches. Centerline based methods matches the shape and exact location of the airways extracted from the CT images to the positions of the bronchoscope sampled while advancing through the airways. Centerline based registration methods have been presented by Deguchi et al. [11, 12], Mori et al. [13] and Feuerstein et al. [14]. Our group have previously suggested an automatic centerline based registration method [15], which utilizes both the positions and orientations of the bronchoscope and the airway centerline from the CT images in the registration process. The previously published method was compared to the registration method of Feuerstein et al [14] by using simulated data, and similar results were found [15]. The method was also shown to function to its purpose on data acquired from patients. The registration method was implemented in our open source research navigation platform, CustusX [1], and successfully used in ENB procedures on patients [16].

The rigidity of the method is a drawback. It does not handle anatomical deformations from the CT, which is acquired during a short segment of the respiratory cycle, often several days or even weeks ahead of the procedure. Enlargement of tumor or lymph nodes from the time of CT acquisition may also
impact the anatomy. Lung tissue and airway movement due to breathing and
coughing cause further complications to the registration, and can result in local
variations in the navigation accuracy. During the bronchoscopy procedure, after
the initial registration, a consciously sedated patient might move on the
operating table, and the movement measured by e.g. a sensor on the patient’s
chest, will not necessarily be transferable to the displacement inside the lungs.
Pressure from the bronchoscope itself may also deform the lung tissue compared
to the CT images [17].

A dynamically updated registration could reduce the negative effects from these
factors. We have by adaptation of the registration method presented in [15],
developed a local registration to be used during bronchoscopy, intended to
compensate for anatomic transformations and deformations. To our knowledge,
a registration method to optimize the accuracy in an area of interest, e.g. close to
a tumor, has not previously been suggested. The registration can be updated
during the procedure, and thus compensate for anatomic deformations from CT
acquisition to the bronchoscopy, or anatomic shifts and/or deformations during
the procedure.

To test the new registration method, we adapted a commercially available lung
airway phantom and simulated breathing motions to the phantom in a robotic
setup. This allowed testing of the method with realistic breathing and other
potentially appearing influences. We also induced deformations to the airway
model to assess the local registration method.
Materials and Methods

Local registration method

The local registration method suggested in this paper is based on a previously published global registration method [15]. The new method is, as the initial registration, a rigid method, but the dataset is reduced to a segment of the airways instead of the entire airway structure. The intention is to perform a local registration correction during bronchoscopy to improve the navigation accuracy. Before a local registration can be conducted, an initial registration of the CT data to the patient is required. This is performed by maneuvering the bronchoscope through the bronchi, normally during the initial part of bronchoscopy while applying topical anesthetics, and running the registration method described in [15], by matching bronchoscope positions to the airways centerline from preoperative CT. This results in a transformation, \( ^{CT}T_{EM} \), between the EMT and the CT coordinate systems. This registration initializes the local registration:

\[
^{CT}T_{EM}^{Local} = ^{CT}T_{EM}
\]  

In the local registration method, positions from the EMT sensor at the tip of the bronchoscope is acquired while it is maneuvered through airway bronchi close to the area of interest, e.g. a lymph node or tumor in which a transbronchial needle aspiration (TBNA) is to be performed. To compensate for variations in the speed at which the bronchoscope is advanced, and thus the distribution of the recorded tip positions, a filter ensures that only positions at a Euclidean distance of >1 mm from the last included position are used in the local registration.
In the registration method presented in [15], all positions in the CT centerline were used as input. In the local registration procedure, only CT centerline positions close to the acquired bronchoscope tip positions are used. A filter selects CT centerline positions at a certain distance from any of the recorded bronchoscope tip positions. This distance was set to 20 mm in this study, which has proven to be a value large enough to compensate for typical local variations.

An iterative closest point (ICP) registration algorithm is then run matching these tracking data with the centerline of the airways, which is extracted from the CT images prior to the procedure. In an ICP algorithm the distance between two clouds of points, in this case the EMT positions of the bronchoscope tip and the CT centerline, is minimized by transforming (translation and rotation) one of the clouds of points. In the registration algorithm we have utilized, in addition to the distances, the orientations of the bronchoscope by matching it to the running direction of the CT centerline (equation 4). A good correspondence between the orientation of the bronchoscope and the running direction of the centerline is an indication that the correct set of branches is matched. The combined Euclidian and orientation distance between the EMT positions of the bronchoscope tip and the CT centerline is calculated by:

\[ d_{c}^{i,k} = d_{p}^{i,k} + \alpha^{i} \cdot d_{o}^{i,k} \]  
\[ d_{p}^{i,k} = \| CT_{EM}^{Local} \cdot BT \cdot p^{i} - CT \cdot p^{k} \| \]
\[ d^{i,j}_{o} = \sqrt{\sum_{c}^{CT_{EM}^{Local}} BT_{o}^i - CT_{o}^k} \]  

(4)

\[ \alpha^j = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \frac{d^{i,k}_{p}}{d^{i,k}_{o}}} \]  

(5)

where \( p \) is position, \( o \) is orientation, \( c \) is combined, \( BT \) is bronchoscope tip, \( CT \) is CT centerline, and \( j \) and \( k \) are the sample indices of the bronchoscope tip and CT centerline points. \( \alpha \) is a weighting factor between the deviation in position and the deviation in orientation for all possible point pairs in the two datasets. Using the \( \alpha \) factor ensures that both the Euclidian distance and orientation are significant components in the combined distance independent of the Euclidian distance.

Each bronchoscope position \((j)\) is paired to the centerline position \((k)\) at the smallest combined distance:

\[ d^{i,j}_{c} = \arg \min_{k} d^{i,j}_{c} \]  

(6)

A small deviation between the orientation of the bronchoscope and the running direction of the centerline indicates that the corresponding branches in the two datasets are matched. To increase the likelihood of bronchoscope positions being paired with centerline positions from the corresponding branch, we select a partition (70%) of the bronchoscope positions with the smallest orientation.
deviation \( \left| d_{o}^{ij} \right| \) from its paired centerline position to serve as input to the paired-point registration. The next iteration of the calibration matrix is found by:

\[
235 \quad T_{EM'} = \arg \min_{T_{EM'}} \sum_{i=1}^{N} \left\| T_{EM'} \cdot T_{Local}^{EM} \cdot B \cdot p_{j} - T_{EM'} \cdot p_{k} \right\|
\]  

which is calculated using a closed-form method [18].

The local registration is then updated:

\[
240 \quad T_{EM} = T_{EM'} \cdot T_{Local}^{EM}
\]  

before the next iteration of the algorithm, starting at equation (2). The algorithm is run until the registration matrix, \( T_{EM} \), converges.

An overview of the steps in the local registration algorithm is presented in Fig. 1.
Phantom setup

For the experiment, we used an airway phantom, the Ultrasonic Bronchoscopy Simulator LM-099 (KOKEN CO., LTD, Tokyo, Japan). To make the phantom CT compatible, it was transferred from its original container into a plastic box, and all metal parts were replaced with plastic. In total ten markers, Tantalum balls (D = 0.8 mm, Tilly Medical Products AB, Lund, Sweden), were attached to the outside of the airway wall. The markers can easily be identified both in the CT images and in physical space. CT images were acquired using a thorax lung scan protocol with 631 slices of 512x512 pixels, element spacing 0.752x0.752x0.499 mm, and slice thickness 1.0 mm.

The airway model was divided into three local parts for the phantom experiments: right lung (RL) (markers 1-4 in Fig. 2), left upper lobe (LUL)
(markers 5-7) and left lower lobe (LLL) (markers 8-10). With this setup it was possible to compare the registration results in an entire lung, RL, to the results in lung segments, LUL and LLL. Comparing the results in LUL and LLL was intended to demonstrate the difference between central and peripheral parts of the airways.

Figure 2: A 3D model (from CT images) of the phantom and the Tantalum ball marker positions.
We used a robotic arm to induce motions to the airway phantom, similar to human breathing, see Fig. 3. The UR5-robot (Universal Robots, Odense, Denmark) was connected to the airway phantom using rubber bands. The robot was programmed to move 50 mm in the inferior/superior direction to simulate breathing cycles with respiration frequency of 12 breaths per minute: 1.5 seconds inspiratory motion, 1.5 seconds expiratory motion and 2 seconds pause after exhale.
Figure 3: The experimental setup with a robotic arm inducing respiratory motions to the airway phantom. The EMT field generator is placed to the right of the phantom.
**Navigation system**

The open source navigation research platform, CustusX [1] (SINTEF, Trondheim, Norway, www.custusx.org), was used in the experiments. The system can import preoperative radiology images and stream real-time images, such as ultrasound. Information from the images is combined with EM or optical tracking systems. The local registration method presented in this paper is implemented in CustusX.

We used the Aurora® EMT System (Northern Digital Inc., Waterloo, ON, Canada). The field generator unit was placed on the right side of the phantom, as shown in Fig. 3. A position sensor with six degrees of freedom (DOF) (Northern Digital Inc., Waterloo, ON, Canada) was attached close to the tip of the bronchoscope (Fig. 4). The CT DICOM data was imported into CustusX, and the airways and its centerline were extracted using the automatic method described in [19]. The positions of the Tantalum ball markers were sampled in the CT images. The physical positions of the markers were sampled by using an EMT pointer (Aurora 6DOF Probe, Straight Tip, Standard, Northern Digital Inc., Waterloo, ON, Canada).
Accuracy calculation

The accuracy was calculated by comparing the CT position of each of the Tantalum ball marker to the physical position measured by an EMT pointer. The physical positions of the Tantalum ball markers were measured at both inspiration and expiration position by pausing the robotic breathing motion. Each marker’s position was calculated assuming linear movement at constant velocity during the breathing cycle. The deviation from the markers CT position was then found, and the average accuracy from all markers was calculated:

\[
\text{Navigation accuracy: } \frac{1}{N} \sum_{i=1}^{N} \| \hat{p}_{CT}^i - \hat{p}_{EM}^i \| \quad (9)
\]
where \( p \) is the positions measured in the CT volume (CT) or by the EMT pointer (EM), and \( i \) is the number of the Tantalum ball marker.

325  **Experiment**

*Breathing movement measurement*

The size of the breathing motions in the lung model was measured by pausing the robot at both end inspiration and end expiration position. The Tantalum ball markers were pinpointed using the EMT pointer at both robot positions.

330  **Initial registration**

An initial registration was performed by acquiring positions of the bronchoscope tip while maneuvering the bronchoscope through the lumen of the lung model, and applying the registration method described in [15]. The phantom breathing was enabled during the registration process.

335  **Deformation**

Local deformations were applied by displacing parts of the lung model, by moving the robot in the anterior/posterior and medial/lateral direction. The robot was moved 20-40 mm. The movement of the phantom airways was lower
due to the connection through the elastic rubber bands. The navigation accuracy was measured after the deformation.

*Local registration*

After the deformation, a local registration was applied to one of the three parts of the lung model, RL, LUL or LLL. In total 15 local registrations were performed, five to each part. The navigation accuracy was measured again and compared to the accuracy before local registration, both with and without deformation.

**Results**

*Breathing movement measurement*

The mean breathing motion measured at the ten Tantalum ball markers was 7.7 mm (max: 16.0 mm, min: 2.8 mm). This is illustrated in Fig. 5 where the end inspiratory and end expiratory positions are plotted in a 2D projection view, on top of the centerline of the airways. The displacement for each marker and mean displacement for each subpart of the phantom is presented in Table 1. The peripherally located markers (2-4, 8-10) are more affected by the breathing motions (mean 10.5 mm) than the markers in the upper lobes (1, 5-7) (mean 3.5 mm).
Figure 5: A 2D frontal view of the Tantalum ball markers' displacement from respiratory movements. The markers (1-10) at end-inhale (blue) and end-exhale (red) position. The airway centerline from the CT of the phantom in green.
Table 1: The displacement of each of the 10 Tantalum ball markers from respiratory movements, and the mean displacement for the markers in each subpart of the phantom

<table>
<thead>
<tr>
<th>Part</th>
<th>Marker no.</th>
<th>Displacement (mm)</th>
<th>Mean displacement each part (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Right lung</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>12.1</td>
<td>RL:</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9.7</td>
<td>7.8</td>
</tr>
<tr>
<td><strong>Left upper lobe</strong></td>
<td>5</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.2</td>
<td>LUL:</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Left lower lobe</strong></td>
<td>8</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>12.1</td>
<td>LLL:</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>16.0</td>
<td>11.6</td>
</tr>
<tr>
<td><strong>Mean (mm):</strong></td>
<td></td>
<td></td>
<td>7.7</td>
</tr>
</tbody>
</table>
**Initial registration**

The bronchoscope tip positions for the initial registration were acquired in 114 seconds, while the bronchoscope was maneuvered through totally 14 airway branches. The navigation accuracy for all ten Tantalum ball markers after the initial registration was measured to $5.4 \pm 3.1$ mm (Table 2), when using the mean inhale-exhale value as described in *Materials and Methods, Accuracy Calculation*. The theoretical optimal registration for these positions was found to be $4.1 \pm 2.0$ mm by applying a closed form paired-point registration [18] to the two sets of Tantalum ball marker positions (from CT and EMT).

The navigation accuracy for each of the three parts of the lung (RL, LUL and LLL) is shown in Table 2.
Table 2: The navigation accuracy after initial registration at each of the ten marker positions, and mean accuracy for the marker positions included in each part of the lung and for all positions totally.

<table>
<thead>
<tr>
<th>Part</th>
<th>Marker no.</th>
<th>Mean (mm)</th>
<th>Mean accuracy each part (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right lung</td>
<td>1</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.0</td>
<td>RL:</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6.0</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>Left upper lobe</td>
<td>6</td>
<td>4.5</td>
<td>LUL:</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>3.7</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>Left lower lobe</td>
<td>9</td>
<td>7.2</td>
<td>LLL:</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>11.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Mean (mm):</td>
<td></td>
<td></td>
<td>5.4</td>
</tr>
</tbody>
</table>
Deformation

Three different deformations were applied to each of the three parts of the lung phantom by shifting the robots expiration and inspiration position. The resulting accuracy after the deformation was 5.9-14.4 mm in RL, 7.7-11.8 in LUL and 11.6-30.6 in LLL (Table 3-5).

Local registration

In total 15 local registrations were performed, by maneuvering the bronchoscope at the part of the lung deformed. The positions for the local registrations were acquired in 22 – 69 seconds (880-2760 acquired positions at 40 Hz sampling rate), while maneuvering the bronchoscope through 4-6 branches. The processing time of the registration algorithm was <1 second.

Figure 6 shows an example of a local registration in the LUL and how the acquired bronchoscope tip positions and Tantalum ball marker positions are changed.

The navigation accuracy was measured both before and after the local registration (Table 3-5). All local registrations resulted in improved navigation accuracy. From a mean accuracy of 11.8 mm, 12.2 mm and 19.4 mm to 6.0 mm, 4.0 mm and 4.7 mm in RL, LUL and LLL respectively. For 7 of 15 local registrations the accuracy was even better than before the deformation (after initial registration). In the two smallest local regions, the mean accuracy after
Local registration was the same (4.0 mm LUL) or better (9.0 – 6.7 mm in LLL) than before deformation.

Table 3: Right lung (RL): The navigation accuracy for local registration 1-5.

<table>
<thead>
<tr>
<th>Repetition no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition time (seconds)</td>
<td>58</td>
<td>42</td>
<td>43</td>
<td>39</td>
<td>22</td>
</tr>
<tr>
<td>Accuracy after deformation</td>
<td>5.9</td>
<td>10.0</td>
<td>14.4</td>
<td>14.4</td>
<td>14.4</td>
</tr>
<tr>
<td>Accuracy after local registration</td>
<td>3.1</td>
<td>7.9</td>
<td>5.9</td>
<td>7.1</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Mean accuracy

| Mean accuracy | After initial registration: 3.8 | After deformation: 11.8 | After local registration: 6.0 |

Table 4: Left upper lobe (LUL) results: The navigation accuracy for local registration 6-10.

<table>
<thead>
<tr>
<th>Repetition no.</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition time (seconds)</td>
<td>32</td>
<td>47</td>
<td>52</td>
<td>59</td>
<td>65</td>
</tr>
<tr>
<td>Accuracy after</td>
<td>7.7</td>
<td>17.9</td>
<td>11.8</td>
<td>11.8</td>
<td>11.8</td>
</tr>
</tbody>
</table>
deformation

<table>
<thead>
<tr>
<th>Local registration</th>
<th>4.3</th>
<th>6.2</th>
<th>2.8</th>
<th>2.5</th>
<th>4.4</th>
</tr>
</thead>
</table>

| Mean accuracy | After initial registration: 4.0 | After deformation: 12.2 | After local registration: 4.0 |

Table 5: Left lower lobe (LLL) results: The navigation accuracy for local registration 11-15.

<table>
<thead>
<tr>
<th>Repetition no.</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition time (seconds)</td>
<td>61</td>
<td>36</td>
<td>52</td>
<td>43</td>
<td>69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accuracy after deformation</th>
<th>11.6</th>
<th>30.6</th>
<th>18.3</th>
<th>18.3</th>
<th>18.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy after local registration</td>
<td>6.5</td>
<td>7.3</td>
<td>6.2</td>
<td>4.8</td>
<td>9.5</td>
</tr>
</tbody>
</table>

| Mean accuracy | After initial registration: 9.0 | After deformation: 19.4 | After local registration: 6.7 |

430
Figure 6: A zoomed 2D frontal view local registration in the LUL (experiment no. 6), before (left) and after (right) registration. The centerline of the airways from CT in green and the positions of the sensor at the tip of the bronchoscope in black. The markers at end-inhale (blue circle) and end-exhale (red circle) position, and CT position (magenta star).

**Discussion**

A novel, intraoperative method for updating the CT-to-patient registration locally during ENB has been developed and demonstrated. The method was tested on an airway phantom connected to a robot simulating breathing motions. To our knowledge, this technique of updating the image-to-patient registration locally using a centerline based method in ENB has not been presented before.

The breathing motions of the lung phantom was measured to 7.7 mm on average, which is slightly smaller than an average motion of 10 mm described in other studies [17, 20]. Especially in the upper lobes the motions created by the robot were smaller than what was reported by Zhang et al.[20], 7.2 mm vs. 3.5 mm. The breathing motions could also have been made more realistic by including a
small random length in the extent of the inspiration/expiration. Motions simulating the patient coughing could also be included in a more advanced setup.

The EM tracking system is vulnerable to surrounding metal, affecting the accuracy. In this study, part of the robotic arm was within the EM field and could potentially have an impact on the tracking system accuracy. However, we believe this is not unrealistic compared to the situation in the bronchoscopy suite, where equipment used both in and close to the EM field contains metal, even though it is avoided as far as possible in navigated bronchoscopy using EMT. It is possible that the local registration is less vulnerable to disturbances causing deformations to the EM field, as the deformations most likely are relatively small within a limited local area of the lungs.

The average initial registration error was 5.4 mm, while the theoretically lowest average registration error was 4.1 mm. The main reasons for the optimal registration accuracy not being closer to zero are deformation in the soft and flexible airways from the CT acquisition to the phantom setup and deformations caused by the breathing motions. Using a more rigid lung model or encapsulating the airways in a flexible material (e.g. gelatin) would result in less deformation from CT to experiment. However, some anatomical variations from CT acquisition to bronchoscopy can be expected in humans as well. The initial registration error is higher than found by simulated data using the same method [15], but comparable to the average fiducial error in a similar breathing phantom study, using a different centerline registration algorithm (5.8 mm) [21].
The local registration was successfully performed by acquiring positions of the bronchoscope tip while maneuvering the scope in a subset of the airway branches and matching it to the centerline of the same airways extracted from the CT volume of the phantom. All 15 registrations improved the navigation accuracy, and for seven of the registrations the accuracy was even better than after the initial registration. The results after local registration were better in LUL than LLL and RL. The lower accuracy in the LLL was likely caused by the larger breathing motion and larger deformations compared to LUL. On the other hand, the accuracy improvement was highest in LLL. The accuracy after local registration in RL was probably affected by the larger area covered by the RL markers, causing a high variation in the accuracy after initial registration and more inhomogeneity regarding both deformation from CT to experiment and from breathing motions. From this it appears as a more limited region than one entire lung (left or right) should be included in the local registration.

In the calculation of the accuracy (CT to EMT deviation), we used the average position of each Tantalum ball on the phantom. The average position was found by measuring the position at end inhale and exhale, and assuming linear movement at constant speed. Due to the elasticity of the rubber bands used to connect the robot to the airways, the assumption of constant speed is probably not correct, however this has a very limited effect on the average position. It should be noted that a CT scan is normally performed while the patient is holding the breath after inhaling. This phantom scan was acquired in the end exhale state, as the airways was pulled by the robot in the inferior direction to form the end inhale position. This might have a minimal effect on the registration
result as the breathing motion pauses in the end exhale state, and thus the EMT position is more weighted to the same state as in the CT volume compared to a real human bronchoscopy setting.

The main requirement for the local registration method to function to its purpose lies in matching the correct branches from EMT and CT. To maximize the likelihood of a correct match, the algorithm utilizes information about the orientation of the branches. In addition, the method searches for branches in the close approximation to the acquired EMT positions, eliminating the risk of matching it to e.g. branches in the opposite lung with similar orientations. In our experiment the bronchoscope tip was moved through 4-6 branches in 22-69 seconds for the local registration. By comparing the length of the acquisitions with the registration accuracy in Table 3-5, there is no indication of a longer acquisition resulting in better accuracy. It is likely to be more important that the registration acquisition covers branches in which the deviation in the orientation is sufficiently large. I.e. the method is more likely to succeed if the bronchoscope makes large turns whilst acquiring positions.

One could argue that a deformable initial registration would be a possible solution to compensate for deformations in patient anatomy from CT acquisition to the bronchoscopy. This approach would, however, not be valid throughout the procedure if e.g. the patient is moving slightly or the instruments are affecting the position of the lung tissue. A deformable registration approach does not necessarily improve the alignment outside the airways included in the registration either, e.g. other airways or a biopsy position. Vijayan et al. [22]
showed this in a porcine model study where deformations in the liver was attempted compensated for by both rigid and deformable vessel centerline registration. The centerline were better aligned using deformable registration. However, this was not transferable to tumor models in the liver, which were best aligned using only the rigid part of the centerline registration.

Different approaches have previously been suggested to update the image-to-patient registration in bronchoscopy. The position of the bronchoscope can be projected to the nearest centerline [10] with the risk of projection to the wrong position on the centerline or even an adjacent branch. An alternative approach to perform local corrections is imaged-based registration [8, 9], by matching the camera image to the CT image. This approach is, however, only valid for tracking the bronchoscope itself and cannot be used to update the position of tools deployed into the periphery of the airways from the working channel of the bronchoscope.

The suggested method in this paper has potential to improve the clinical application of navigated bronchoscopy, by ensuring improved local accuracy and robustness by correction of anatomical shifts or deformations. However, further development of the presented local registration method should include making it more automatic, by e.g. dynamically using the latest positions of the bronchoscope or other navigated tools like a biopsy forceps to update the registration when necessary. The method also needs to be tested in human studies to verify its accuracy and robustness, and to identify and resolve potentially practical complications.
Conclusion

We have developed a novel local registration method for ENB, which compensates movements or anatomical deformations during the ENB procedure or from CT acquisition to the procedure. The method was tested successfully in a phantom setup, where a robot induced motions mimicking breathing. Further development should be made to make the method more automatic, requiring very limited or no input from the operator of the navigation system. The method should also be verified in a human ENB study.

Acknowledgements

This work was supported by the Norwegian National Advisory Unit for Ultrasound and Image-Guided Therapy (St. Olav’s Hospital, NTNU, SINTEF), a service appointed by the Norwegian Ministry of Health and Care Services. Funding was also received through EEA Financial Mechanism 2009-2014 under the project EEA-JRP-RO-NO-2013-1-0123 - Navigation System For Confocal Laser Endomicroscopy To Improve Optical Biopsy Of Peripheral Lesions In The Lungs (NaviCAD), contract no. 3SEE/30.06.20.

Conflict of interests

The authors declare that they have no conflict of interest.
References


14. Feuerstein M, Sugiuara T, Deguchi D, Reichl T, Kitasaka T, Mori K: Marker-free registration for electromagnetic navigation bronchoscopy under


