TBNA-protocols

Guiding *TransBronchial Needle Aspirations* Without a Computer in the Operating Room

M. Kukuk, B. Geiger, and H. Müller

¹ SIEMENS Corporate Research, Imaging & Visualization, Princeton, NJ, USA

² University of Dortmund, Computer science VII, Germany

kukuk@scr.siemens.com

Abstract We attempt to maximize the success probability for “blind” biopsies by preoperatively estimating four parameters. These parameters well-define the procedure, given that the bronchoscope resides “somewhere” inside the target branch of the tracheobronchial tree. The calculations are based on a patient specific lung model (CT scan) and a digital model of a flexible bronchoscope. Using both models, we simulate the biopsy and derive frequency distributions for each parameter. Based on these distributions, we choose several parameter sets that together maximize the success probability. The parameters are provided to the surgeon in form of detailed step-by-step instructions (protocol) of how to handle the bronchoscope. To control the parameters in the operating room (OR) we use passive controls. First lung phantom experiments show that we could hit in worst-case 12 mm targets (average-case: 5 mm) with three aspirations.

1 Introduction

1.1 Motivation

Transbronchial needle aspiration (TBNA) is a valuable minimally invasive procedure in the bronchoscopic diagnosis and staging of patients with lung cancer [1]. The procedure allows nonsurgical access to lymph nodes from the inside of the tracheobronchial tree. Traditionally this biopsy is performed by maneuvering a bronchoscope to a suitable site within the tracheobronchial tree. Then the surgeon inserts a needle through the bronchoscope and punctures the bronchial wall in order to hit the target behind. This is literally a “blind” puncture since the target object is at no time visible by the bronchoscope. In order to increase the chance of hitting the tumor, the surgeon takes more than one tissue sample for every biopsy. Studies have shown that up to *eight* needle aspirations in the same site can be safely performed, although the optimal number of aspirations is yet to be clarified [2]. However, there is no strategy of how to place the up to eight aspirations beside a simple *trial-and-error* approach.

Despite the fact that the surgeon performs more than one needle aspiration in a single biopsy, this procedure has a failure rate of 60 to 80%, if the bronchial

wall is not yet affected [3]. The relatively “blind” nature of the procedure and the physician’s lack of confidence about where to position the needle are obstacles to the widespread use and positive diagnostic yield of TBNA. Performing a TBNA requires 3D imagination (coordination of the learned three dimensional anatomy with a fish-eye distorted 2D video image) together with the handling of the endoscope (hand-eye-coordination).

1.2 Related Work

Techniques used to guide TBNA can be classified into three different groups: usage of standard imaging technology, on-line visualization of the target and tracking of the bronchoscope.

In the first group we have imaging techniques like fluoroscopy, CT and CT fluoroscopy. These techniques show the endoscope, the advanced needle and the target lesion. Fluoroscopy produces a real-time two-dimensional projection image with poor contrast. The target lesion is usually not visible [4]. Conventional CT produces images of adequate quality but the procedure is cumbersome and time-consuming since real-time imaging is not possible and each sequence must be prescribed in advance. CT fluoroscopy is a term for continuous-imaging CT that allows the visualization of dynamic processes in real-time, like the insertion of a needle into the target lesion. However, this technique is limited to axial images and requires significant CT-scanner time and relatively high radiation dosage.

In the second group we have a technique that tries to visualize the target lesion by inserting an ultrasound transducer through the working channel of the bronchoscope [2]. The study shows no significant difference in sensitivity compared to unguided TBNA.

In the third group we find techniques that try to track in real-time the tip of the bronchoscope to guide the TBNA. One subgroup tries to track the bronchoscope’s tip solely by processing the endoscope images [5], [6], [7]. The Biosense intrabody navigation system [8] uses electromagnetic fields to track a sensor that can be attached to the bronchoscope’s tip. In an in vivo study [9], 10 to 20 markers were secured on the animals’ chest and the respiratory motion was monitored using a second sensor to compensate for breathing motion. The study showed an accuracy of 4.2 mm $\pm$ 2.6 mm ($\pm$ SD).

1.3 Our Approach

We found that the following four parameters non-ambiguously describe how to handle a bronchoscope to perform a successful TBNA (compare to Fig. 1, left):

1. Bronchoscope insertion depth l
2. Shaft rotation about the principal axis α
3. Angle of tip deflection β controlled by the bronchoscope’s angling wheel
4. Needle length d

We denote these parameters as *endoscope configuration* $C = (l, \alpha, \beta, d)$.

Our goal is to maximize the success probability for a TBNA by providing these parameters and detailed step-by-step instructions (protocol) to the surgeon. The four parameters are calculated prior to the intervention, based on a patient specific model of the tracheobronchial tree (derived from a CT scan) and a digital endoscope model. By using both models, we simulate the biopsy by calculating all possible endoscope configurations that reach to the target site. From all configurations, we derive frequency distributions for each parameter. To exploit the fact that it is common practice to perform several (up to eight) aspirations for one biopsy, we select several sets of the most frequent parameters from these distributions. During the intervention, we use *passive controls* (non electronic) to monitor all four parameters. This approach allows us to systematically perform several aspirations, instead of the currently used trial-and-error method. Registration of the calculated parameters to the patient's reference frame is done by using an anatomical landmark based method.

Our digital model of a flexible bronchoscope takes the physical characteristics like flexibility, *bending section*, diameter and length of our real bronchoscope into account. The bending section of a bronchoscope is its highly flexible distal end. It can be controlled using the *angling wheel* located at the bronchoscope's control head, to "look around" and guide the needle to the target.

2 System Overview

2.1 Basic Steps

Fig. 1 center shows an example scenario that gives an overview of the basic components of a TBNA. It shows the tracheobronchial tree and the target mass (tumor) outside the airways. The planned biopsy site B is shown in form of the endoscope's tip together with two possible shaft shapes. Note, that B is the position and orientation of the tip before the alignment and therefore doesn't necessarily have to point towards the target. The calculation of the protocol parameters l, α, β, d is based on our digital model $\mathcal{M}$ of a bronchoscope (see chapter 4) and includes four principal steps:

1. Physician preoperatively plans biopsy site B .
2. Calculation of bronchoscope length l to reach B : $l = \mathcal{M}(B)$
3. Calc. of the *endoscope-space* E to reach B with length l : $E = \mathcal{M}(l, B)$.
4. For all $e \in E$: Calculation of $\alpha(e), \beta = \mathcal{M}(e), d = \mathcal{M}(e)$

Firstly, the physician preoperatively plans the ideal biopsy site. The biopsy site B represents roughly the position and orientation of the bronchoscope's tip within the tracheobronchial tree from where to perform the biopsy.

Secondly, we regard the whole procedure of performing a TBNA as a two-step process: (1) inserting the bronchoscope into the branch that contains the biopsy-site and (2) aligning it with the target lesion. This allows us to *fix the inserted length* l and to calculate the *alignment parameters* α, β, d based on the fixed

Figure 1. Left: Protocol parameters. Center: TBNA scenario. Right: Referencing

inserted length. Thirdly, we use our model $\mathcal{M}$ to calculate a set of endoscope shapes where each element represents an endoscope of length l that reaches into the branch containing the biopsy site B . We refer to this set as the endoscope-space E , since it describes all possibilities of a real bronchoscope to reach the biopsy site.

Finally, given the endoscope-space E we calculate for each endoscope shape the alignment parameters α, β, d . For β and d this is done on the basis of our digital bending section model.

2.2 Registration Between the Virtual and Real Bronchoscope

To register the calculated insertion depth l and shaft rotation α to the patient's reference frame, we use a landmark based approach. We have chosen the *carina*, a keel-shaped part of the tracheobronchial tree that marks the bifurcation of the trachea into the left and right lung as our anatomical landmark.

The situation is shown in Fig. 1, right. It shows the “ideal” biopsy-site B and two possible endoscope length (dotted) from B to the point of reference R . The point of reference is chosen to lie in a bottleneck (vocal chords) in terms of all possible paths an endoscope can take. To calculate the bronchoscope length to B measured from M , we first let the physician touch the landmark L with the bronchoscope (ML) and then have him insert (or withdraw for lesions proximal to the carina) the bronchoscope by the difference between RB and RL .

As the mutual zero-point for the shaft-rotation we choose the rotation of the bronchoscope that shows the carina to appear vertically. In the planning phase the physician rotates a virtual endoscopic camera and during the intervention he rotates the bronchoscope until their views shows the carina to appear vertically.

2.3 Controlling the Protocol Execution

In order to set the bronchoscope to the configuration given by the protocol parameters, we need control over the inserted length l , the shaft rotation α , the tip

Figure 2. Passive controls for monitoring the protocol parameters.

deflection β and needle length d . Since we perform the needle aspirations based on a fixed bronchoscope length, we use a stopper to prevent the bronchoscope from penetrating the body deeper than desired, see Fig. 2. To control shaft rotation, we attach a goniometer (angle-scale) to the base plate of the mouth-piece and a pointer to the stopper (see detail figures). When the base plate stops the insertion of the bronchoscope, any shaft rotation moves the pointer along the angle-scale. We control the tip bending with an angle-scale that we attach to the angling wheel located at the bronchoscope's control head (top detail figure). During the planning phase, we use a look-up table to map the angle of tip deflection to the wheel angle. We control the needle length by marks on its proximal end and using the opening of the biopsy port as a reference point.

3 The TBNA-protocol

The following box shows the universal TBNA-protocol. It can be divided in three parts: Lines 1-5 contain the registration instructions and lines 6-7 describe the insertion / withdrawal of the bronchoscope to the biopsy-site. Lines 8-10 describe the alignment of the bending section with the target lesion. Only the protocol parameters l, α, β, d represent the patient specific part of the protocol. The instructions themselves remain unchanged for different patients.

Depending on the location of B relative to the current endoscope position we either execute the left or right column of lines 6-7. After execution of line 7, the bronchoscope reached the biopsy-site and the following instructions 8-10 use parameters α, β, d to align the bronchoscope with the target lesion. The arrow indicates that it is then possible to systematically perform a series of biopsies.

4 Endoscope Model

Our model $\mathcal{M}$ describes a flexible endoscope as a chain of rigid cylinders interconnected by discrete ball-and-socket joints. The chain interacts with the patient

1. Touch carina with the bronchoscope tip. 2. Move stopper to mouth-piece. 3. Withdraw bronchoscope 30 mm. 4. Rotate shaft until carina appears vertically in the bronchoscope's view. 5. Move stopper to mouth-piece and set its rotation-pointer to 0 degrees.	6. Withdraw bronchoscope l mm. 7. Move stopper back to mouth-piece and lock stopper.
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6. Move stopper l mm away from mouth-piece and lock stopper. 7. Insert bronchoscope into branch of the biopsy-site B until stopper hits the mouth-piece.	8. Rotate endoscope shaft until the shaft rotation-pointer points to α degrees. 9. Set rotation of the bending-wheel to β degrees. 10. Insert needle d mm beyond the working channel outlet.

specific anatomical model via our collision detection method [10]. Each cylinder of the chain is approximated by a cloud of sample points on its surface. Checking for collision of all sample points with the organ model allows us to verify if a chain configuration represents a valid endoscope shape. The flexibility of the chain is modeled by the choice of link length s (span) and joint range θ and is based on the notion *minimal radius* [11].

The overall idea is to exhaustively enumerate all possible chain configurations, given a start cylinder and the following four constraints: organ geometry, gravity, medial-axis and stopping-criteria. Using a recursive backtracking algorithm we create a tree data structure where the nodes represent the joints of the chain. The bending section (95 mm long) is modeled accurately to reflect the properties of our real bronchoscope.

A link is represented by a reference frame (4×4 homogeneous transform matrix) L , where the centerline of the cylinder is the z -axis of the frame and the cylinder bases lie in the $z = 0$ and $z = s$ plane. Given a link L_i of level i , the 9 connected links of the next level are given by:

$$L_{i+1}^j = R(r_j, \theta) L_i T(\hat{z}s), \text{ for } j = 1, \dots, 9,$$

where T is a translation and R a rotation matrix, $\hat{x}, \hat{y}, \hat{z}$ denote the three 4×1 unit vectors, r_j is the j th rotation vector of the set $\{(x \ y \ 0)^T \mid x, y \in \{-1, 0, 1\}\}$ and θ is the rotation angle.

For calculating the endoscope length to a given target link (biopsy-site) the stopping criteria is fulfilled when a link L docks to the target link. For calculating the endoscope-space E the stopping criteria is the recursion depth, see Fig. 3.

For each path from the root to a leaf, we calculate the alignment parameters. The shaft rotation α is only dependant on the orientation of the bronchoscope's bending plane. The bending plane of an endoscope is the plane in which the tip moves under the rotation of the bending wheel at the endoscope's control head. Let tip link L and target vector t be known with respect to the same global reference frame and let L 's $y = 0$ -plane be the bending plane. The desired shaft rotation is the rotation angle about $\hat{z}$ that rotates the $y = 0$ -plane into target t :

$$\alpha = \cos^{-1} \left(\frac{t' \cdot \hat{x}}{|t'| |\hat{x}|} \right) \text{ with } t' = (L^{-1}t)(1 \ 1 \ 0 \ 1).$$

The left-hand-side of the formula calculates the angle between unit vector $\hat{x}$ and t' . Vector t' equals t known with respect to L and orthogonally projected into the $z=0$ -plane.

After shaft rotation, target t lies in the $y = 0$ bending plane and we need to calculate the angle of bending wheel rotation needed to align the tip with t . We found that not the current tip position, but the transition point q from the shaft to the bending section determines the angle of wheel rotation. This is probably because of the used pull-wire mechanism. We also found that the bending movement of the straight tip to the left and right can be approximated by a semi-circle with its center $c = 49$ mm away from the endoscopes end. We determine link Q of the chain that contains q and move it along its $\hat{z}$ -axis by $a = 95 - 49 = 46$ mm. We regard the new origin of Q as the center of the semi-circle. The desired angle of wheel rotation is then given by the angle between $\hat{z}$ and target t :

$$\beta = \cos^{-1} \left(\frac{Q'^{-1}t \cdot \hat{z}}{|Q'^{-1}t||\hat{z}|} \right) \text{ with } Q' = Q T(\hat{z}a). \quad \text{Needle length } d = |Q'^{-1}t| - c.$$

5 Lung Phantom Experiments

5.1 Material

We have implemented this approach on a SGI PC540, 550Mhz (single), 0.5 GB RAM, running Windows 2000 and OpenGL. We have built a lung phantom (Fig. 3, left) using transparent (for visual verification) PVC tubes. We randomly placed 37 marker sticks (4 mm diameter, cardboard) in the model, so that they are aligned with the inner surface of the tubes. The phantom was then scanned (512x512x382, 1 mm slice distance, 1.2 thickness). After the scan, we identified manually these surface points as our target points. The lung phantom is 1.5 times the size (trachea diameter: 30 mm) of an adult lung, to compensate for the fact that no bronchoscope (average shaft diameter: 6.0 mm) but a “Gastrointestinal Videoscope” (Olympus GIF 100, shaft diameter: 9.5 mm) was available for non sterile experiments.

5.2 Objective and Design

We are interested in two questions: (1) What is the repeatability of the *real* configurations $C_r = (l_r, \alpha_r, \beta_r, d_r)$ needed to hit a target incision point? In other words, we need to know the variation of each parameter. (2) How accurate match our *predicted* configurations C_p the configurations C_r ?

The experimental setup is shown in Fig. 3. Out of all 37 markers we choose five (arrows in Fig. 3) as target points, three of them close to the carina. For each target, we execute the protocol 20 times and record the configuration parameters needed to touch the marker stick with the biopsy needle. Note, that the markers can be seen by the endoscopic video camera as a white 4 mm disk.

Figure 3. Left: experimental setup. Center: calculated endoscope-space E and five selected targets (arrow). Right: docking to the biopsy-site with a slightly stiffer endoscope.

To estimate the parameters for each target, our software generates for each parameter a dataset of at least 100 (and up to 25,000) measures. We then read each dataset with a data-analyzing package (IDL, Research System, Inc.) and create frequency distributions to draw histograms and calculate the mean and standard deviations.

5.3 Results

(1) Repeatability: To calculate the variation of the experimentally obtained parameters, we rejected the smallest and largest outlier of all 15 datasets (20 measures each) and calculated the range of each dataset. We found the largest range of α , β and d to be 7° , 6° and 7 mm and the average range to be 6° , 4° and 4 mm respectively.

(2) Accuracy of the prediction: The real error of a configuration $C = (\alpha, \beta, d)$ is given by the distance between the target point and the needle tip after setting the endoscope to configuration C . Since it is not possible to measure distances inside the plastic model we use a theoretical error model to obtain an upper bound error estimation for our parameter prediction. Our results show, that shaft rotation α is by far the most sensitive parameter with an average error of 12° , whereas β (3°) and d (1 mm) can be predicted more accurately. To exploit this fact, we performed a test where we took the configuration $(\bar{\alpha}, \bar{\beta}, \bar{d})$ for the first aspiration, $(\bar{\alpha} + \sigma, \bar{\beta}, \bar{d})$ for the second and $(\bar{\alpha} - \sigma, \bar{\beta}, \bar{d})$ for the third, where the dashed parameter denotes the mean and σ the standard deviation of the respective distribution. The test shows that we could hit in worst-case targets of 24 mm diameter with one aspiration and 12 mm targets with three aspirations. In average we could hit 13 mm targets with one aspiration and 5 mm targets with three aspirations.

6 Conclusion

In this paper, we have presented a method to guide “blind” biopsies by preoperatively calculating parameter sets that describe how to handle the bronchoscope to maximize the success probability. During the intervention, the surgeon follows step-by-step instructions (protocol) which are based on these parameter sets, to perform a series of systematic needle aspirations.

The most important feature of this approach is its simplicity. We don’t need any additional devices or computer that need to be calibrated or operated in the OR. All our controls are passive, intuitive to operate and remain outside the body. After the intervention they can be easily removed and the bronchoscope can be sterilized as usual. Our approach is inherently “real-time” during the intervention, in contrast to some image based approaches. The surgeon operates at his/her own speed. We can use any off-the-shelf bronchoscopes (fiberoptic or video). This makes our system very cost efficient, since hospitals and doctors can use their existing equipment. Registration is not based on external markers, which move considerably during respiration, but on an anatomical landmark that only moves marginally relative to the target.

First results with a lung phantom show that the repeatability is high enough to expect a maximum accuracy of 5 mm. Our tests show that we are able to hit in worst-case targets of ≥ 12 mm diameter (average-case: 5 mm) with three aspirations.

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