

Biopsy Planner - Visual Analysis for Needle Pathway Planning in Deep Seated Brain Tumor Biopsy

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Abstract

Biopsies involve taking samples from living tissue using a biopsy needle. In current clinical practice they are a first mandatory step before any further medical actions are planned. Performing a biopsy on a deep seated brain tumor requires considerable time for establishing and validating the desired biopsy needle pathway to avoid damage. In this paper, we present a system for the visualization, analysis, and validation of biopsy needle pathways. Our system uses a multi-level approach for identifying stable needle placements which minimize the risk of hitting blood vessels. This is one of the major dangers in this type of intervention. Our approach helps in identifying and visualizing the point on the pathway that is closest to a surrounding blood vessel, requiring a closer inspection by the neurosurgeon. An evaluation by medical experts is performed to demonstrate the utility of our system.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Display algorithms

1. Introduction

Most of the tumor investigations require that tissue samples are taken from one or more tumor points. A common medical procedure handling this problem is a biopsy. It involves inserting a biopsy needle until the desired target point is reached. The neurosurgeon then manipulates the needle in such a way that tissue samples are taken. Brain tumor biopsies are especially hard to perform as the patient can sustain severe neurological damages. Deep seated tumor biopsies require a considerable amount of time of preoperative planning. In this case a large number of blood vessels has to be avoided, taking into account a necessary safety margin.

Current medical workstations used for biopsy preoperative planning offer just 2D slice views for identifying the blood vessel closest to a specific point on the biopsy needle pathway. Therefore, there is a necessity for new visualization approaches to assist the neurosurgeons in their path planning and validation processes. A fully automated algorithm that would select a needle pathway is very hard to achieve. This is mainly due to the target tumor point of the biopsy needle being highly dependent on the type, shape and other physical aspects of the tumor. Also, the experience of the neu-

rosurgeon plays a very important role in choosing the target point.

This paper introduces an approach that provides means of identifying, visualizing, analysing and validating biopsy needle pathways. The techniques introduced aim to minimize the risk that a blood vessel is hit when the biopsy procedure takes place. This constitutes the primary concern, as hitting a brain blood vessel could lead to severe neurological lesions for the patient [SJSS09]. Our techniques help the neurosurgeon in the process of identifying an optimal needle pathway but do not eliminate the human factor. This paper specifically focuses on biopsy procedures performed on deep seated brain tumors. For a tumor that is relatively close to the skull, the risk of hitting a blood vessel using current medical workstations is low. Our system provides a top-down approach for identifying safe needle pathways. Based on a user-specified area of potential entry points, we display information about the quality of the corresponding needle pathways that reach the tumor. This path can then be investigated further in a multi-view setup which provides information about the anatomical context. This is achieved through 2D and 3D visualizations as well as dedicated views which alert the surgeon of nearby blood vessels.

The remainder of this paper is structured as follows: Section 2 reviews related work. In Section 3 we discuss the medical background regarding brain tumor biopsies in current medical practice. An overview of our system is provided in Section 4. In Section 5, we discuss our multi-level visualization techniques for needle pathway planning. Section 6 presents implementation details. The evaluation and the results are described in Section 7. The paper is concluded in Section 8.

2. Related Work

Most surgeries dealing with tumor investigations require thorough preoperative planning before the actual procedure takes place. Many medical procedures involve the insertion of a needle to the point of interest, leading to an extensive research area in planning and validating the needle pathway. An example for a medical intervention that requires such a process is the ablation of liver tumors. Significant efforts in the scientific community have been made in trajectory planning of hepatic ablation procedures [BVSS07, VSG05, WHC*10]. A GPU-based visualization of the tumor ablation zone that incorporates the cooling effect of the blood vessels has been developed [RKSH11]. These approaches are not well suited for brain tumors as different constraints apply. One example is the insertion angle of the needle with respect to the liver surface. Specifically, pathways that are tangent to the liver surface are avoided. In brain tumor biopsies pathways that are tangent to the tumor surface are preferred by most neurosurgeons.

Another related area of research focuses on biopsy needle path planning for digital breast biopsy [VSMM11]. The major issue when dealing with this kind of intervention is the tissue deformation caused by the insertion process. A method for predicting the behavior of deformable tissues upon needle insertion was introduced by Alterovitz et al. [AGPH09]. The brain does not sustain significant deformations during the biopsy procedure, so this kind of algorithm is not useful for the case considered in this paper.

In neurosurgery, planning procedures that require the insertion of a probe and the automated computation of deep brain stimulation for patients with Parkinson disease were developed [BVVV*07, EHJ10, GPP07]. Multi-modal data such as multiple MRI datasets and CT data for segmentation and planning the intervention are used. Also, several restrictions for the whole process are considered, such as path length and orientation of the electrode.

Many of the automated approaches aim to take the decision of selecting the insertion path for the physician. Most neurosurgeons still want to inspect the selected path, as a safety measure and due to legal requirements in many countries. A method of planning straight trajectories in image guided keyhole neurosurgery was developed by Shamir et al. [STD*10]. The authors include a step of computing the

outer surface of the head. No methods for the inspection of individual needle pathways are included. Another recent approach for tumor accessibility planning was introduced by Khlebnikov et al. [KKMS11]. In their approach, the structure of interest is considered to be a light source. All the safe paths to a tumor are computed, together with available leeways. This approach seems less-suited for brain tumor biopsy because the directions from all entry points to all tumor points would have to be computed. This would result in a very large computational load. Also, no method of validating a selected path is presented. Another automated technique for finding the best viewpoint for interventional planning was developed by Mühler et al. [MNTPO7]. The authors also present an algorithm for the automated detection of the closest region of interest to a specific structure.

A method of generating access maps for neurological procedures was developed by Navkar et al. [NTS*10]. The authors use multi-modal data. They generate various maps on the pre-extracted surface of the head depending on the cost function used. There are methods employing visualization techniques of the planned needle pathway based on cutting surfaces and ghost views [JSV*08, KTP10]. A system for neurosurgical procedures with high-quality interactive multi-modal volume rendering was also developed [BHWB07].

Extensive research in assisting neurosurgical planning through visualization was presented as part of the Vis Contest 2010. A pre-operative planning method used for brain tumor resection was proposed by Diepenbrock et al. [DPL*10]. In their method, the authors project the tumor surface onto a 2D plane to allow a better user interaction. Upon selecting a tumor point, the distance to the closest structure of interest is shown. The authors do not provide the user with a guidance when choosing the incision point, which requires an empirical approach. Another technique uses cavity slicing to visualize the resection area, starting from the tumor [RED*10]. Born et al. [BWR*10] rendered a semi-transparent safety region around the tumor and the blood vessels near the resection area. The distances from the tumor to the nearest blood vessels are presented with color coded arrows. Another contest entry [ZZM10] maps the risk of the resection procedure directly on the brain surface. It also includes a line plot of spatial risk distributions.

Most of the mentioned techniques present various methods to define an entry points mask or to choose or validate an insertion pathway. Typically they employ multi-modal data, requiring a high computational load for providing the needed prerequisites. We are not aware of previous work which presents a complete system for assisting the neurosurgeons from the step of choosing the entry points mask over pathway selection to validating a single pathway for deep seated brain tumor biopsies.

3. Medical Background

When investigating a brain tumor, information about the cerebral vasculature and about the liquid accumulations in the brain is needed. As mentioned, the cerebral vasculature has to be avoided in the biopsy process. Liquid accumulation regions provide information about how severe the lesion caused by the tumor is, or if it is filled with liquid. Because MRI provides high contrast between soft tissues, this scanning technique is primarily used when investigating brain tumors. If data about the cerebral vasculature is needed, a MRI scan in the presence of a contrast agent is performed. Usually, an MR angiography is used as scanning procedure, but the physician can opt for another one that also depicts blood vessels well, such as T1 weighted MR scanning.

Current medical procedures for performing a biopsy on a deep seated brain tumor involve the manual inspection of MRI slices to determine the biopsy needle direction. The main purpose is to establish a needle pathway that will ensure sufficient distances to the brain blood vessels. Based on his/her previous experience, the neurosurgeon chooses an entry point and a target point for the biopsy needle. For the patient to sustain as few neurological lesions as possible, the entry point has to be located in specific areas of the skull. These areas correspond to the region from the middle frontal gyrus to the inferior parietal lobule. Choosing other areas could result in a loss of sight, permanent paralysis, or other significant neurological injuries. For the target point, the proliferative parts of the tumor are aimed for. These parts are the regions from which the tumor is expanding. Tissue samples taken from there provide the information needed to establish a future medical action. Depending on the biopsy result, the neurosurgeon can perform a resection, or can try to stop the tumor growth through radiation therapy.

With the entry and target points selected, the needle direction is depicted on the screen, using four 2D visualization windows. Three windows show axis-aligned slices of the MRI data and one window shows a reformatted slice normal to the needle direction. The physician carefully inspects the slices, usually starting from the target point. (S)he checks if any blood vessel is hit by the needle, or if the desired minimum distance to any surrounding blood vessel is achieved. If these conditions are not met, (s)he adjusts the previously defined points and the process takes place again. For a deep seated brain tumor, this process can be time consuming and prone to human error.

After the process of selecting the needle pathway is completed, the medical framework returns information concerning the entry point, the length of the pathway and the direction of the biopsy needle. This data has to be manually correlated to a stereotactic frame attached to the patient. This frame is mounted prior to the MRI scanning, and it is removed after the biopsy. For a more detailed description of the biopsy procedures used in current clinical practice, we refer the reader to the related literature [MR08].

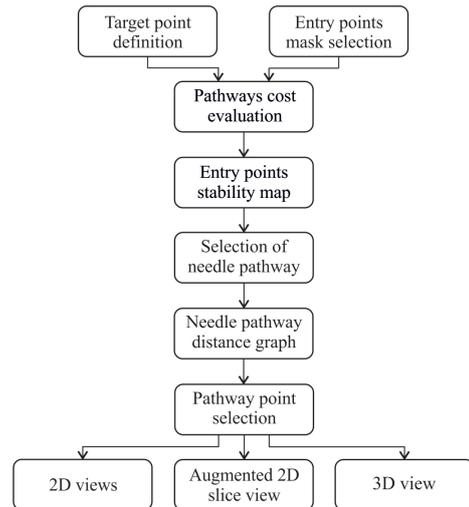


Figure 1: Biopsy Planner - conceptual overview.

The techniques introduced in this paper aim to help the neurosurgeon in finding and validating a biopsy needle pathway. One task we address is finding safe regions of biopsy needle entry points, given a fixed target point. This process will eliminate a time consuming step in the currently used medical procedure for determining a safe needle pathway. As an addition, we introduce visualization tools for navigating along the pathways. In these tools, the distance to the closest blood vessel for a point along the pathway is presented in an intuitive way. These introduced elements minimize the risk of hitting a blood vessel in the biopsy procedure. Also, our system allows the identification and inspection of the safe regions of all entry points. The current medical procedure of finding a suitable needle pathway usually already ends when the first one is found.

4. System Overview

The Biopsy Planner application presented in this paper provides visualization and validation tools that help the neurosurgeon at different interaction levels. They are represented by the *entry points stability map*, the *needle pathway distance graph* and the *augmented 2D slice view* normal to the needle direction. An automatic computation of all possible pathway directions and their associated costs is also implemented. Figure 1 shows the Biopsy Planner workflow, with the interaction levels integrated. The cost function of a needle pathway is the minimum distance to a blood vessel, considering all the points of the pathway.

In the following, we describe the Biopsy Planner workflow in more detail. The first step the physician has to perform is the selection of a tumor point that will serve as the target point for the biopsy needle. Our implementation allows an interaction very similar to the one used in current

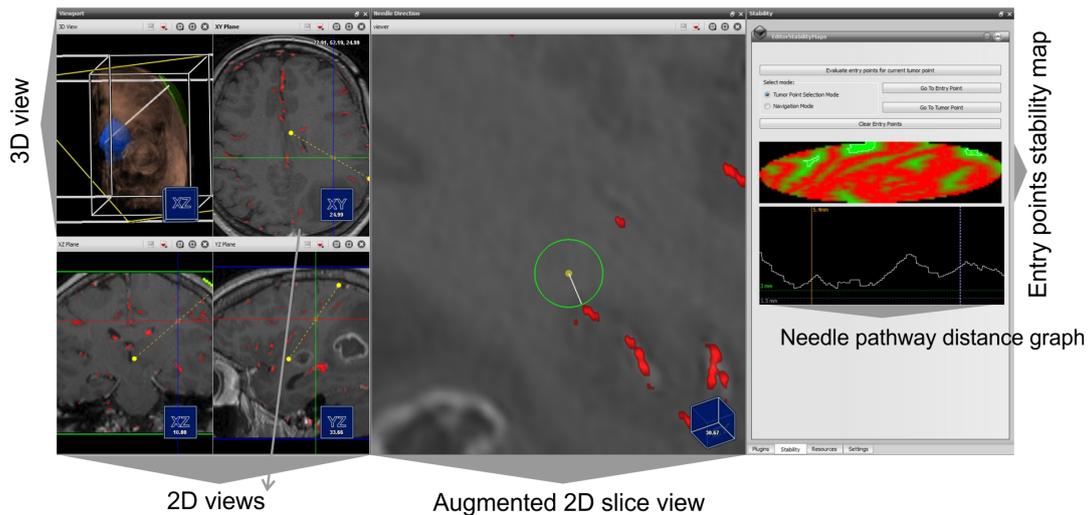


Figure 2: Biopsy Planner overview.

medical workstations. This was a deliberate choice, as it allows users to quickly adapt to our new system. We use three 2D slice views to determine the target point. The next step is to choose the mask of possible entry points on the skull of the patient. All these entry points will be considered in order to create the entry points stability map. This map is created by considering all the paths from the entry points mask to the chosen tumor point. The cost function for each pathway is evaluated, and a color coding scheme is used for providing a visual representation in the entry points stability map. By controlling two parameters, namely the biopsy needle diameter and the required safety margin, the selection of an entry point is now made according to the associated cost. This process eliminates the laborious step of manually determining the needle pathway as done in current clinical practice. Having the needle pathway selected, we introduce a distance graph, that for every point of the pathway depicts the distance to the closest blood vessel. The interaction element is linked to an augmented 2D slice view normal to the needle direction. This 2D view displays the distance to the closest blood vessel and the direction towards it on the corresponding 2D slice. These elements allow the neurosurgeon to rapidly inspect in the neighborhood the areas that are closest to a blood vessel. The full inspection of the needle pathway, as performed in current medical practice, is no longer necessary. This reduces the time needed for validating a possible pathway. For further enhancing the understanding of the whole biopsy procedure, a 3D view is also provided. This view helps in accurately locating the tumor and allows the inspection of the chosen needle pathway in a volumetric manner. The other structures of interest, like the cerebral vasculature and the entry points mask, can also be added in order to provide a full spatial context for the biopsy needle.

The techniques described in this paper use a set of prerequisites, presented in the following:

- Intracerebral vasculature segmentation:** the Biopsy Planner employs a manual segmentation of the intracerebral vasculature. The main reason for using manual segmentation is the type of data used, i.e., T1 weighted MRI scans with a contrast agent applied. This type of MRI scan can be used for the blood vessel investigation, but does not represent the best choice for segmenting the cerebral vasculature. The typical medical scans used for the automated segmentation of the brain blood vessels are Magnetic Resonance (MR) Angiography (Angiogram) or CT Angiography. Most of the scientific work in the field of cerebral vasculature segmentation uses this type of data [BPVU*11, PRB*05]. There the achieved results are very close to a ground truth manual segmentation. The manual segmentation does not represent a major limitation to the techniques proposed in this paper, as the neurosurgeons can perform a CT or MR Angiography instead of the T1 weighted scan. The discomfort induced to the patient by using a contrast agent cannot be avoided, no matter which type of scan is used.
- Tumor segmentation:** segmenting the brain tumor helps the neurosurgeon in understanding the anatomy of the investigated structure and also in locating it more easily in a 3D view. For tumor segmentation we have used a simple watershed algorithm, as it gives satisfactory results. Watershed algorithms provide good results in segmenting homogeneous regions bounded by high intensity borders. A brain tumor in a T1 weighted MRI scan in the presence of a contrast agent does have such properties. We have applied the watershed algorithm from the ITK framework, with the parameters *level* and *threshold* set to 0.6

and 0.04 respectively [Sch05]. The tumor segmentation mask is used in our system only for identifying the point where the needle is entering the tumor. This point is not necessarily the same as the target point of the biopsy procedure. In the case of a highly irregularly shaped tumor or if a tumor cannot be segmented, only this functionality will be affected.

5. Multi-Level Needle Pathway Planning

The Biopsy Planner employs a multi-level approach that helps the neurosurgeon in selecting safe needle pathways. These pathways together with stability information are visualized in order to minimize the risk of hitting a blood vessel. Figure 2 depicts a screenshot of the Biopsy Planner interface. It contains specific parts for each level of interaction. These levels are described individually in the following along with the other employed visualization techniques.

5.1. Entry Points Stability Map

When performing a biopsy, neurosurgeons select a specific region for the entry points of the biopsy needle. The goal is that the patient sustains as little damage as possible. By selecting specific areas, the physicians make sure that the biopsy needle does not pass through any critical regions of the brain, such as motor-sensor regions. In this way the physician can also control the length of possible needle pathways, as a short pathway is desirable. Computing the cost function for all the possible incision points can take up to 15 minutes [BVVV*07]. To considerably reduce this computational cost, we use an intuitive algorithm for selecting the desired entry points region. The computational time is reduced to a few seconds. For selecting the entry points region, we have implemented a volume painting algorithm. It allows the selection of an ellipsoidal region directly in the 3D volume. This region is then projected onto a sagittal plane, and will serve as an entry points mask for computing the corresponding stability map. The sagittal plane is a longitudinally orientated plane that divides the human body into right and left parts. Projecting a surface onto such a plane is done by rendering the surface with the x coordinate (in the DICOM patient coordinate system) ignored. Based on the typical anatomical location of the entry points region, the projection is made onto the sagittal plane as this gives the most intuitive perspective of the region.

With the tumor point and the entry points mask defined, all possible needle pathways are considered and a cost function is computed for each of them, similar to the approach of Herghelegiu et al. [HMG11]. They generate a disk orthogonal to the needle pathway with the centre in the target point. This disk displays a stability map, based on the assumption that errors can appear during the needle insertion process. In our work, we do not take errors into consideration, as the use of the stereotactic frame in the biopsy procedure gives a precision of up to 0.1 mm.

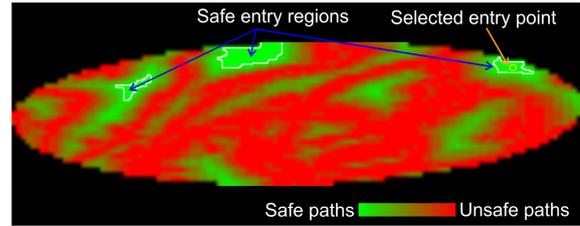


Figure 3: Entry points stability map. Areas in red indicate pathways that are too close to a blood vessel. Green areas represent the entry points regions that respect the required minimum distance to any surrounding blood vessel. White contours represent the boundary areas between the safe regions and the less safe ones.

As cost function we use the minimum distance to a surrounding blood vessel, considering all the points along the pathway. For the distance computation, a distance transform (DT) has been used [FH04]. The algorithm has been applied to the segmented blood vessels mask, as it requires a binary volume as input data. First, the distances in pixels were computed. The resolution of the MRI data is $512 \times 512 \times 85$, with anisotropic voxel size. In the final DT volume, distances are transformed to Euclidean distances. Every voxel contains the Euclidean distance to the closest blood vessel. The final DT volume is generated in a few seconds. According to the cost of each pathway, a color coding scheme is implemented. The scheme is dependent on two parameters which the neurosurgeon can control:

- **Needle diameter:** This parameter is introduced to accommodate various biopsy needle types, which usually differ in size.
- **Safety margin:** This parameter represents the minimum required distance from the biopsy needle to any surrounding blood vessel. This parameter is specified by the neurosurgeon depending on various medical conditions and previous experiences.

The cost associated with each needle pathway is color-coded and assigned to the respective entry points which are then projected onto the sagittal plane. The minimum distance a safe pathway needs to have is given by the sum of the needle radius and the safety margin. The pathways that present this minimum distance are considered safe pathways and are depicted in light green. The ones that are too close to a blood vessel have a red color associated. The values in between are linearly interpolated from these two colors. Figure 3 depicts a projected ellipsoidal entry points region. It is defined by the neurosurgeon using the volume painting algorithm previously described, color-coded and projected on a sagittal plane. Based on experimental results, we have observed that usually there are regions consisting of only safe pathways. We have used a white contour to bound them. The boundaries represent regions where the associated cost is on the

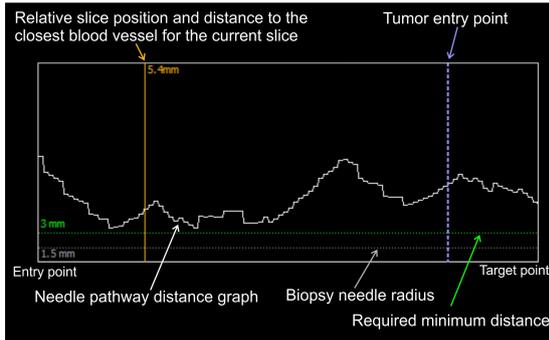


Figure 4: Needle pathway distance graph. For every point of the needle pathway, the distance to the closest blood vessel is shown. The needle radius and the required minimum distance to any surrounding blood vessel are presented with dotted gray and green lines. The blue dotted line represents the point where the biopsy needle is entering the tumor.

limit between a safe pathway and an unsafe pathway. The points just outside the contours correspond to needle pathways for which the distance to the closest blood vessel is almost equal to the required safety margin plus needle radius. The contours allow the neurosurgeon to identify and inspect only these regions without having to empirically search for a safe pathway. We project the entry points mask on the sagittal plane to allow a better user interaction. By selecting one point on the projected map, the neurosurgeon chooses a needle pathway. Upon selection, the pathway becomes visible in the 3D view. Also, a needle pathway distance graph is displayed for validating the chosen pathway.

5.2. Needle Pathway Distance Graph

The needle pathway distance graph depicts the needle pathway, together with the distances to the closest blood vessels for every pathway point (see Figure 4). The needle pathway is represented by the horizontal axis of the graph. The needle radius is depicted by a gray dotted line. Any blood vessel below this line will be hit directly by the biopsy needle. The required minimum distance, as specified by the physician, is represented by a green dotted line. The entry point of the biopsy needle is located on the bottom left and the target point on the bottom right of the view. A dotted blue vertical line indicates the point where the pathway is entering the tumor. This point is important from a medical point of view, as many neurosurgeons decide to take samples from several tumor regions located on the initially planned needle pathway. Also, this gives a visual indication of the distance that the needle will go through the tumor. By interactively selecting one point of interest, the chosen position on the needle pathway will be indicated by an orange vertical line, and the distance to the closest blood vessel will be displayed. This selection will trigger the next level of interaction for the nee-

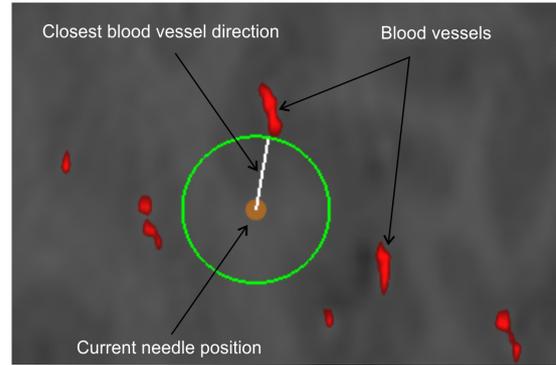


Figure 5: Augmented 2D slice orthogonal to the needle direction. For validation purposes, a visual representation showing the distance and the direction to the closest blood vessel is introduced.

dle evaluation. It is represented by the augmented 2D slice view. The position of the selected point on the pathway will be displayed in the 3D view. The distance graph looks rather jaggy because of the low resolution of the MRI dataset.

The needle pathway distance graph allows the neurosurgeon to rapidly detect parts of the needle pathway that require further investigation. Our system permits the inspection of these parts directly, without having to browse through all the slices. In this way, the attention of the physician is concentrated only on the critical regions, decreasing the time needed for validating the selected needle pathway.

5.3. Augmented 2D Slice View

The most common depictions used in current medical procedures are 2D slice views. A slice view orthogonal to the direction of the needle is currently used in clinical practice to identify the anatomical structures that the biopsy needle will encounter during the surgical procedure. We have augmented this slice view by including information regarding the distance to and the position of the closest blood vessel to the point on the biopsy needle pathway currently investigated. The distance is represented as a circle, and the direction to the closest blood vessel is indicated by a line pointing to it. The circle uses the same color coding scheme as the entry points stability map described earlier. The physician can interact with the view by changing its position along the pathway. Our system permits the immediate identification of the closest blood vessel by clicking on the white line pointing towards it (see Figure 5). This interaction was introduced because, in most of the cases, the position of the blood vessel that is closest to a specific needle pathway point does not lie in the corresponding augmented 2D slice. Therefore, the neurosurgeon will not need to browse through multiple slices to identify the closest blood vessel. For a better visual identification of the blood vessels, we have used a transfer

function for all the slice views used in our application. The transfer function only modifies the appearance of the pre-segmented structures (blood vessels and the tumor), while preserving the appearance of the original MRI dataset.

5.4. 3D View

The volumetric 3D view provides the possibility of inspecting the MRI dataset in a 3D manner. Along with the MRI dataset, information about the biopsy process is displayed. The entry points mask is visible, together with the segmented blood vessels and the tumor. The selected needle pathway and the position of the augmented 2D slice are also integrated. The 3D view helps to define the entry points mask using the volume painting algorithm. The 3D view is mainly used for providing the spatial context of the needle pathway and of the tumor. Figure 6 presents the 3D view along with three 2D slice views.

5.5. 2D Slice Views

The 2D views show slices of the MRI dataset along the three main scanning directions, namely the sagittal, the axial and the coronal direction. They are particularly useful for selecting the tumor point that will serve as target point for the biopsy needle. The Biopsy Planner allows two interaction modes. The first one is used to select the target point and the other one to navigate through the slices, after a needle pathway has been selected. The three 2D slice views are linked together and consistent color coding is used for rapid and intuitive navigation. The slices are enhanced with data about the needle pathway. The entry point and the target point are marked, and the pathway is presented as a dotted line. These elements are always depicted on the 2D slice views. If the currently viewed point is not located on the pathway it will change its color from orange to purple. This helps the neurosurgeon to know the exact slice positions with respect to the needle pathway. Our application also allows the direct inspection of the slices corresponding to the target point and the entry point. This is realized through two navigation buttons. By using the 2D slice views, the physician can also verify that other potentially important regions which are difficult to segment, can be identified and avoided during the biopsy procedure.

5.6. Linked Visualization Elements

As indicated by our medical collaborator, linked visualization elements are very useful in the pre-planning step of the biopsy procedure. Most of the linked navigation used in our work relies on the spatial position of a chosen point on the needle pathway. The navigation along the needle pathway can be performed in any slice view, as well as on the needle pathway distance graph. Changing the position of the inspected point will trigger a response in all the other views which will be updated accordingly. The locations of all slice

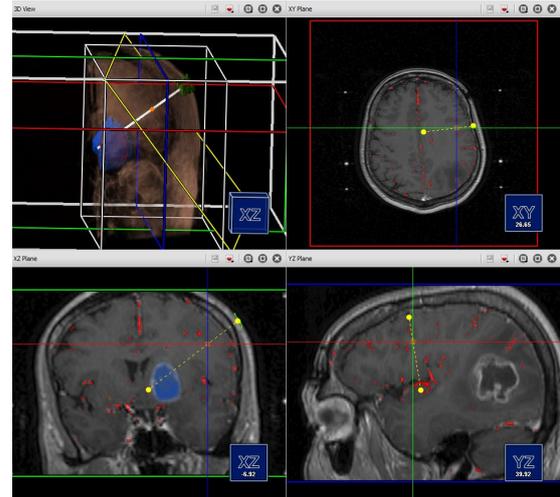


Figure 6: 3D view and 2D slice views. All views are linked together to synchronize any changes made in the position of the currently inspected point on the needle pathway. The slice positions are visible in the 3D view to provide a better spatial understanding of the biopsy procedure.

views can also be integrated into the 3D view to provide a better spatial orientation for the neurosurgeon. Figure 6 shows the three linked 2D slice views. The inspected point on the needle pathway is rendered in orange on all views. While we described all the interactions between the elements of our system, it is difficult to fully capture the interactive process from a textual description alone. For an animated demonstration of Biopsy Planner, we refer the reader to the accompanying video.

6. Implementation

Biopsy Planner is implemented in C++, with the geometry elements generated in OpenGL. The interaction elements were created using Qt libraries.

In order to obtain an interactive response to the user actions, the volumetric rendering is done on the GPU. For faster GPU processing, the data we use is saved as a four component volume, containing the scalar values of the original MRI dataset, the blood vessel mask, the tumor mask and the entry points mask. For the volumetric rendering mode, the user can choose either DVR, MIP or MIDA [BG09]. The presented system uses two transfer functions, one for the volumetric view and one for the slice views. With this we preserve the appearance of the slices to be the same as used in current medical frameworks. The application was developed and tested on a system with an i7 CPU (2.93 Ghz) and a Nvidia GeForce 9800 GT graphics card. All rendering and interaction achieves interactive performance. As the typical number of computations needed is rather low, the visualiza-

tion elements introduced in this paper can be likewise re-computed without a noticeable performance overhead.

7. Evaluation

The research presented in this paper is guided by the requirements of our medical collaborators. User feedback was acquired in order to determine the usability of our proposed methods of selecting, validating and visualizing a biopsy needle pathway in clinical practice. We also wanted to identify the areas that need further research. Based on our experiences and on the impressions of our medical collaborator, we identified the following hypotheses:

- The Biopsy Planner helps the neurosurgeons in planning the biopsy procedure faster than with a current medical workstation.
- The visualization techniques and levels of interaction introduced in this paper confer to the neurosurgeons a higher confidence in the selected biopsy needle pathway compared to current medical procedures.

The user feedback was acquired from five participants, forming two groups:

- The first group consisted of two medical experts with decades of experience in biopsy procedures.
- The second group consisted of one neurosurgeon and two neurosurgery residents with limited experience in biopsies, but with extensive experience in brain surgeries.

The evaluation protocol was slightly different for each group. The first group, consisting of the two most experienced neurosurgeons in biopsy procedures, had to perform a list of tasks with their current medical framework:

- The overall task was to find a safe biopsy needle pathway.
- For this pathway, they had to find and inspect the point that is closest to a surrounding blood vessel.
- The last task was to verify that the whole path is safe for use in the biopsy procedure.

We employed a think-aloud protocol where the users were encouraged to voice their thoughts during completion of the tasks. The goal was to gain additional information about their workflow in using the system. After task completion, we gave a short verbal introduction of how the Biopsy Planner works. A list with the system capabilities was also presented. Next, we asked the participants to perform the same tasks as before, this time using the Biopsy Planner. Different MRI datasets were used. We designed the tasks specifically to rely on the subjective judgement of the users, avoiding any bias from our side.

Because none of the two biopsy expert participants were computer specialists, it would have been very difficult for them to cope with the new interaction mode of the Biopsy Planner. Due to their limited temporal availability, they were assisted by a computer expert. Upon finishing the requested

tasks, the participants were asked to fill in a questionnaire. They had to rate 26 statements on a five-point attitude Likert scale. For completeness, we also included the ten statements of the System Usability Scale (SUS) [Bro96] in our questionnaire. The statements cover the following areas: the experience of the participant, the functionality of the Biopsy Planner, the difficulty of the required tasks and specific details about individual system components (e.g., *"I found that the volume painting algorithm and the entry points stability map were helpful in completing the tasks"*). Finally, a semi-structured interview was performed, to assess the overall impression of our system. This part of the user feedback was done individually for each of the two neurosurgeons. The questionnaire and the task list are available as accompanying material.

The second group consisting of one neurosurgeon and two neurosurgery residents specialized in brain surgeries followed a slightly different protocol. We did this mainly because they were only acquainted with the biopsy procedure, without actually having performed one. They just assisted in the biopsy needle pathway planning or procedure in their medical training. First, our medical collaborator guided them through the tasks, using a current medical workstation. Afterwards, our technical expert gave them an interactive demonstration of the Biopsy Planner by performing the same tasks. During the evaluation, we tried to keep the level of subjective thinking of the participants as high as possible. They were asked to indicate the tumor point and the entry points map. After this, they validated the chosen pathway by using all the approaches presented in this paper. Then, they individually completed the questionnaire. The interview was done in the presence of all participants of the second group, and each one expressed his opinion about the Biopsy Planner.

The result of the questionnaires verifies our hypotheses. The Biopsy Planner reduces the pre-planning time needed for the biopsy needle pathway selection. Both the experts and the second group of respondents agreed that the confidence level of the selected pathway is much higher using the Biopsy Planner than using a current medical workstation. This is due to the several possibilities of validating the needle pathway.

As expected, most of the comments came from the two experts. They were both very satisfied with the capabilities of the Biopsy Planner. They also requested more time to interact with our system, after completing the three assigned tasks. Due to the use of the think-aloud protocol, we were able to observe their way of thinking and approach for planning the biopsy needle pathway. The first task was to find and verify a safe biopsy needle pathway using their current medical workstation. They had no prior knowledge about the medical cases used for completing the tasks. Each of the participants took 25-30 minutes for planning the biopsy needle pathway for a deep seated tumor biopsy. The medical pro-

cedure they applied complies with the one described in Section 3. Afterwards, the same tasks were completed with the Biopsy Planner, using a different dataset. The time required for finding a safe biopsy pathway was 2-3 minutes. This does not include the preprocessing times for acquiring the various segmentation masks.

One expert rated our system to be very rapid and easy to use. He also stated he would use this system in the planning of the needle pathway for deep seated brain tumors. The second expert was enthusiastic about the Biopsy Planner, pointing out that the introduced validation techniques make the identification of the critical areas and the blood vessels in those regions very intuitive and easy. The major stated problem is the interaction mode, which differs from the one currently used in their medical workstation. Another concern was expressed about the necessity of segmenting the blood vessels in an automated manner on MR Angiography data.

All the participants agreed that the levels of interaction introduced by the Biopsy Planner are easy to understand and to use. They also agreed on the helpfulness of the validation techniques for the biopsy needle pathway in completing the tasks. There were no major differences in the answers from the different groups, although each respondent had different impressions about the system. From a functional point of view, most subjects agreed that our system is useful and beneficial for their work (four agreed, one neutral). The neutral response was about the easiness of integrating the Biopsy Planner into the current medical workflow. The tasks were considered to be relevant for assessing the system. Most subjects found that the tasks were easier to complete using the Biopsy Planner than using their current medical workstation (four agreed, one neutral). Concerning the interaction levels and the visualization techniques used, all subjects agreed that they are helpful in assisting them in planning a biopsy needle pathway.

From the second group of participants, one stated that it would be helpful to integrate in all 2D views information about how close the nearest blood vessel is for a point along the needle pathway. For example, if a user prefers just the 2D slice views, currently it is still necessary to look at the augmented 2D slice view to see exactly how close the nearest blood vessel is. This could lead to a hard to follow validation procedure. Also, participants indicated that the color coding scheme works for the entry points mask, but for the augmented 2D slice it would be helpful to give distances quantitatively in millimetres directly on the slice. They do not want to just see if a blood vessel is at a safe distance from the currently viewed point along the pathway, but would like to know exactly the distance without having to switch the view.

While this initial expert review only had a limited number of participants, we received very encouraging feedback as well as several interesting suggestions for improvements.

8. Conclusion

When performing a biopsy on a deep seated brain tumor, hitting a blood vessel with the biopsy needle might result in serious neurological lesions. Current medical frameworks do not provide visualization tools to assist the neurosurgeon in identifying the regions where the biopsy needle is close to a neighboring blood vessel. The techniques introduced in this paper help the physicians to minimize the risk of hitting a blood vessel with the biopsy needle.

The main scientific contributions of this work are:

- the introduction of the Biopsy Planner - an integrated system for planning and validating a biopsy needle pathway for a deep seated brain tumor;
- the presentation of a semi-automated way to select a safe biopsy needle pathway using the entry points stability map;
- the needle pathway distance graph showing the distances to the closest blood vessel for all the points along the pathway;
- the augmented 2D slice view displaying the slice normal to the needle direction, together with information regarding the distance to and position of the closest blood vessel.

Our implementation is focused on brain tumor biopsies. It may be applicable to other types of similar procedures, that involve the insertion of a needle, and where the tissue deformations caused by the insertion process are negligible. We have also presented an evaluation indicating that our system is appreciated both by the neurosurgeons and the neurosurgery residents. Our medical collaborators even stated that they are willing to add an angiography scan to the MRI scanning procedures. This would facilitate the cerebral vasculature segmentation, which is currently the major bottleneck in the preprocessing stage. The Biopsy Planner provides the neurosurgeons with a complete system for assisting them in identifying, visualizing, analyzing and validating biopsy needle pathways.

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