Needle-Stability Maps for Brain-Tumor Biopsies

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Abstract—**Minimally invasive surgical procedures like biopsies require the insertion of a needle to reach a specific tissue from where samples are taken. This process is affected by a number of errors that can lead to a different needle pathway than originally planned. In the case of brain-tumor biopsies, these errors can be caused by the brain shifting when the skull is drilled, measurement errors due to the physical framework that supports the biopsy needle or some other human errors. To provide support for preoperative planning, we introduce the concept of a biopsy-needle stability-map. This map provides information on how stable a biopsy-needle pathway is. We also introduce an algorithm for finding the reachable points on the tumor border from one specific entry point. A technique for automatically selecting the needle pathway that offers the biggest minimal distance to any blood vessel is also presented. A 3D representation of the regions of interest (tumor, blood vessels) together with the needle pathway and the reachable points of the tumor has also been implemented. The resulting stability map visually represents, using color-coding, how close to any blood vessel the pathways surrounding the main one are.**

I. INTRODUCTION

BIOPSIES are a common medical procedure mainly used for a better pathology diagnosis. They represent a medical test that involves collecting tissue from a living human body structure using a biopsy needle. When dealing with brain tumors, a biopsy represents a mandatory step before more advanced treatment plans are developed. The tests run on the samples taken by biopsies will determine the type of the tumor, if a resection should be considered, if the tumor growth can be stopped by gamma rays or, if it is filled with fluid, which properties this fluid does have. The first step the physician has to perform after scanning the patient is to establish a possible needle pathway. MRI (Magnetic Resonance Imaging) is the most commonly used scanning technique for this type of pathologies as it offers high contrast images for soft tissues. For defining the biopsy needle pathway, the currently used procedures involve the manual inspection of the MRI slices for establishing the ending and the entry point of the needle. This process requires a sensitive manual adjustment of the needle

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pathway so that it will not hit any blood vessel. After completing these laborious steps, the used medical framework will provide the position data that accurately describes the needle pathway. These data have to be manually correlated with the physical framework that supports the needle insertion process. The described process is prone to human errors as well as measurement errors. Our work helps the physician by computing the best needle pathway and provides a visual representation of the pathway stability with respect to specific errors.

In order to better understand the 3D shape of a structure or for locating it more easily, a segmentation algorithm that separates regions of interest in the volume is usually implemented. We use the brain-tumor segmentation for computing the possible ending points reachable by the biopsy needle in an automated manner. The segmented cerebral vasculature will provide the input data for computing the distances from any point in the volume to the closest blood vessel. For this, we use a distance-transform algorithm that produces a volume of the same size as the original one, where the voxel values represent the distances to the closest blood vessel.

The lack of a 3D representation of the tumor or of the needle direction further increases the possibility that errors might occur in the process of defining the pathway. A visual representation of how stable this pathway is with respect to the errors that can occur (measurements errors, computational errors or human errors) can help the physicians in understanding the risks of not reaching the ending point of the biopsy needle. We introduce a visual representation for the stability of the pathway, called biopsy-needle stability-map. Our algorithm also creates a hierarchy of the possible needle pathways that provides an automatic computation and visualization of the best pathway. The quality of the pathways is given by the minimum distance to any surrounding blood vessel, considering all the points of the pathway.

This paper is organized as follows. Section II provides an overview of existing techniques in the field of tumor segmentation, distance transform computation, and stability maps. Section III contains the detailed description of the used segmentation algorithm. Section IV presents the technique used for computing the distance transform. Section V describes the approach used for finding the reachable tumor points. Section VI presents the concept of the biopsy-needle stability-map. Section VII concludes the paper.

II. RELATED WORK

The computation of a distance transform (DT) represents an important part of many computer vision or image processing applications. A DT algorithm applied on a binary image will provide as output another image of the same size. Each pixel represents the distance to the region of interest (non-zero pixel). The DT is an important operator in shape analysis [1], with numerous applications in research areas like separation of overlapping objects in microscopic images [2], computing morphological operations (erosion, dilation) [3], extracting the medial axis (skeletonisation) [4], segmentation of structures in medical images [5], analysis of three-dimensional interactions between biological structures [6].

Stability maps are commonly introduced in applications for providing visual support and guidelines for human decision making. They do not aim to replace the humans in the decision making. Stability maps are used in various research fields such as visualizing classified structures prone to large computational errors coming for example from an automatic classification algorithm [7]. Such a visualization system focuses the user onto the structures that require manual correction. Another application is the stability analysis of 3DCT scan positions, guiding the user on how to position objects during scanning. The goal is to reduce scanning artifacts [8].

Various methods for simulating the insertion of a biopsy needle were developed. A technique for simulating the insertion in deformable tissues was introduced by Alterovitz et al. [9]. They compute the error as Euclidian distance, and only consider the error that result from inserting the needle. Also a stability measurement for the simulation process is presented. A needle-path planning for breast biopsies was developed [10]. The errors considered are due to inserting the needle through soft tissue. This approach is not suitable in our situation with the brain tumor. Brain tissue behaves differently from muscular tissue. Thus the needle insertion will not change the position of the tumor and of the blood vessels.

III. TUMOR SEGMENTATION

In order to extract useful information from volumetric data, segmentation methods had to be implemented. The segmentation algorithm classifies the voxels of a volume as belonging to either a region of interest, or to less important background data. We have segmented the brain tumor using the watershed algorithm [11]. The algorithm uses the variation of the gradient to classify voxels. It provides good results in segmenting homogeneous regions that have well defined border areas (ridges). A brain tumor in MRI T1 weighted sequence has such properties. The gradient input image is treated as a height function, with the assumption that higher intensity values in the image indicate border areas. The watershed algorithm works by "flooding" this height field and by assigning an unique value for each lower intensity area.

Two parameters control the output of the segmentation algorithm: threshold and level. Threshold sets the absolute minimum height value used in the segmenting process. In other words, it discards the voxels with values below the threshold. A high value for the threshold will lead to a segmentation result with fewer regions. The level parameter controls the depth of the flooding. A value of 1.0 will provide the result of flooding the entire image resulting only one segmented region. A value of 0.0 will produce a basic segmentation, with a lot of oversegmented areas. Fig. 1 shows the result of applying the watershed algorithm on an MRI T1 weighted contrast enhanced volume. The used threshold is 0.06 and the level value is 0.5. These values worked for all tested MRI T1 weighted volumes.

As the result of the watershed algorithm is represented by various regions for areas bounded by ridges, an additional operation for selecting the tumor points is needed. We used a simple interval threshold filter to discard all the points that are not belonging to the region of interest, outputting only the tumor mask. As the watershed algorithm assigns different values for each segmented region, the simple inspection of the segmented volume is needed for selecting the value corresponding to the tumor. The approach of using the watershed algorithm followed by an interval threshold filter is suited when dealing with multiple brain tumors in the same dataset. Multiple brain tumors are commonly encountered in metastatic diseases.
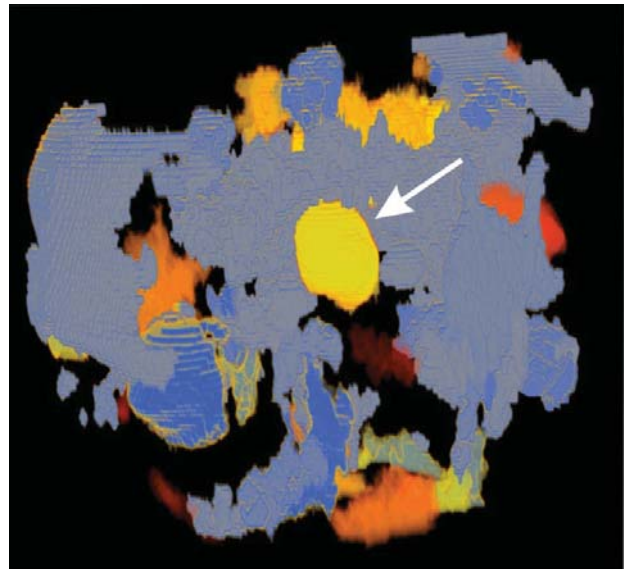

Fig. 1. 3D view of the watershed segmentation algorithm applied for segmenting a brain tumor. The arrow is pointing to the tumor.

IV. DISTANCE TRANSFORM

Computing a DT was mainly done in for 2D [1], but it can be easily extended to 3D. In the 3D case, the DT determines the distance of each voxel of the volume to a given subset of it, in our case the blood vessels. The blood vessel mask was obtained by a manual segmentation. Let $Vol: \Omega \subset \mathbb{Z}^3 \rightarrow$

{0,1} be a binary volume where the Ω domain is convex. An object $\mathcal{O}$ will be represented by all the white voxels of the volume:

$$\mathcal{O} = \{p \in \Omega \mid Vol(p) = 1\}$$

The voxels of $\mathcal{O}$ are referred as foreground, and its compliment, $\mathcal{O}^c$ is called background and consists of black voxels of Ω. The distance map of volume Vol (or the distance map of $\mathcal{O}$) is given by the following definition:

$$D(p) = min\{d(p,q) \mid q \in \mathcal{O}^c\}$$

where $d(p,q)$ is the distance between p and q, usually taken as the Euclidian distance.

In this paper, we used a distance transform algorithm introduced by Felzenszwalb [12]. We choose this algorithm because it is easy to reproduce and provides satisfactory speed and results. When dealing with non-isotropic voxels, as usually encountered in medical imaging techniques, a correction of the Euclidian distance computation has to be applied. In our dataset, the pixel spacing on x, y, z axes are 0.54mm, 0.54mm and respectively 1.5mm. Computations performed on the z axis had to be corrected by multiplying the result with 1.5/0.54=2.77. Fig. 2 presents a slice of the DT volume. The darker areas correspond to areas closer to a blood vessel while the brighter areas denote a bigger distance to any surrounding blood vessel.
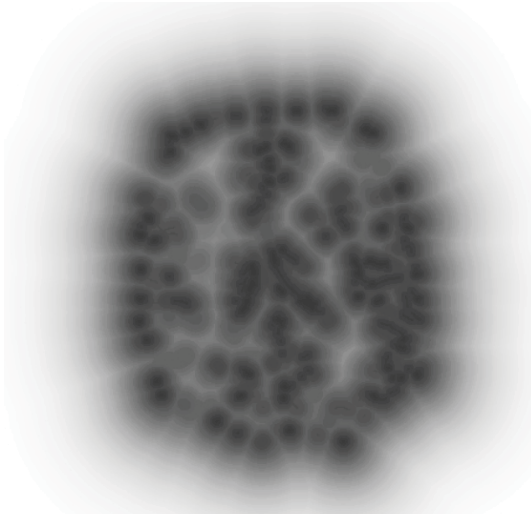

Fig. 2. Slice of the DT volume computed from the blood vessels mask. A darker region indicates the presence of a blood vessel in the neighboring area.

V. TUMOR ENDING POINTS

We define the reachable points of the biopsy needle as the tumor points that are reachable from one fixed entry point and the pathways to these points have the property of hitting directly and only the tumor reachable point. We use the segmented tumor data as input for computing the reachable
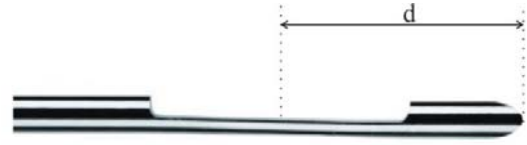

Fig. 3. Tip of a biopsy needle. The gap can be opened or closed by an inner layer controlled by the physician.

points of the biopsy needle. We propose a straightforward and easy to implement algorithm for finding the reachable tumor points for one fixed entry point. Because the biopsy needle does not take tissue samples from the tip and features an opening at one side close to the tip (see Fig. 3), the computed reachable points need to have specific characteristics to fit the physical model of the needle.

The automated computation of the reachable points helps the physician in seeing what tumor points can be reached by the biopsy needle, for one specified entry point. The position of the blood vessels does not influence this algorithm, as the computation of all reachable tumor points is desired. The pseudocode for computing the possible reachable points for the biopsy needle is provided as Algorithm 1.

Algorithm 1 DetermineReachablePoints

```
For the entry point EP
    For every tumor point TP
        If (The previous voxel of TP on the line
            given by EP and TP is a non-tumor point)
            AND
            (The next n voxels after TP on the line
            given by EP and TP are tumor points)
        Then
            Add TP to reachable tumor points set
```

The number *n* is given by the physical specification of the needle, namely the distance from the tip of the biopsy needle to the middle of the sample taking gap (distance *d* in Fig. 3). The computed reachable tumor points from one specific entry point EP are presented in Fig. 4 as a white mesh covering the tumor.
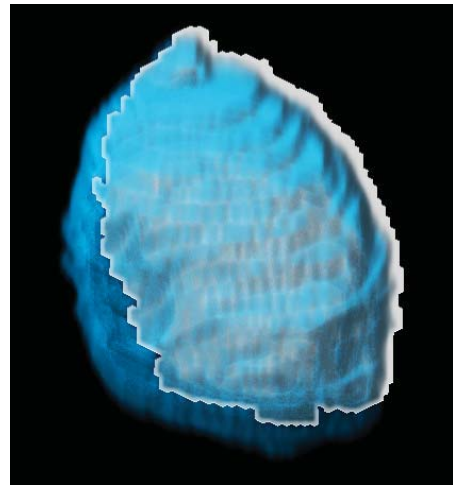

Fig 4. Reachable tumor points (white) from one specific entry point (side view). The tumor points are colored in blue.

VI. BIOPSY-NEEDLE STABILITY-MAP

For creating the stability map, we first create a disk Ds in the normal plane to the needle pathway (NP), with the centre in the chosen reachable tumor point (RTP). This disk projected along the needle direction will serve as a proxy object for the stability map.

An example of one needle pathway starting from the entry point EP, along with the disk created in the normal plane of NP with the center in one chosen RTP is shown in Fig. 5.
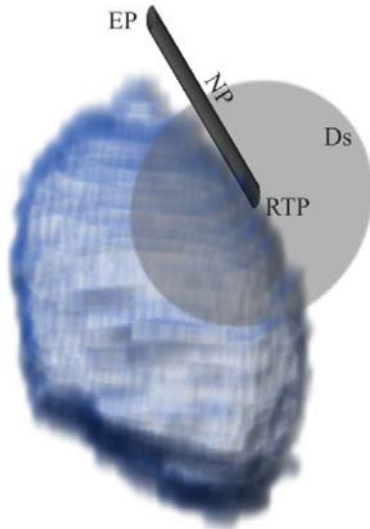

Fig 5. A disk Ds created in the normal plane of one biopsy needle pathway NP, with the centre in the considered reachable tumor point RTP.

We consider the cost of each needle pathway given by the minimum distance from any point belonging to the pathway to any blood vessel, using the previously calculated distance transform. As presented in Section IV, the DT volume stores the distances to the closest blood vessel for each voxel of the volume. For determining the cost of which rays will be represented in the stability map, we first determine the needle pathways that will correspond to the points of the stability-map. The directions of these pathways are determined by the entry point EP and by the voxels of the disk Ds. Depending on the disk orientation and position, the pathway might hit the tumor in a point situated in front or in back of the disk. In some cases, it is also possible that the pathway will not hit the tumor. The pseudocode for assigning a color to each point of the stability map is given by Algorithm 2.

Algorithm 2 CreateStabilityMap:

```
For each voxel V ∈ disk Ds
    Try to find a tumor point (TP) on the
    direction defined by V and EP
    If (TP was found as belonging to the tumor)
    Then
        Compute the cost of the pathway defined by
         EP and TP
        Assign a color according to the cost of
         the pathway
        Draw the corresponding points on the
        stability map
    Else
        Draw the corresponding points on the
        stability map in white, as the
        corresponding needle pathway is not
        reaching the tumor
```

According to the computed cost of each considered pathway, a color coding scheme was implemented (Fig. 6). White indicates areas where the direction given by the entry point and the corresponding disk point does not intersect the tumor. The green color indicates that the corresponding direction has a large distance to any blood vessel. The red color indicates the region where the direction is hitting a blood vessel. In particular case represented in Fig. 6, even if the considered pathway ensures a large distance to any blood vessels, the physician might opt for another needle pathway, as the biopsy needle might not hit the tumor (areas in white) if any error will occur. By sorting the directions according to the cost described above, we can represent in an automated manner the pathway with the best cost. The physician can then inspect the stability-map of the pathway and decide if it suits the medical requests.
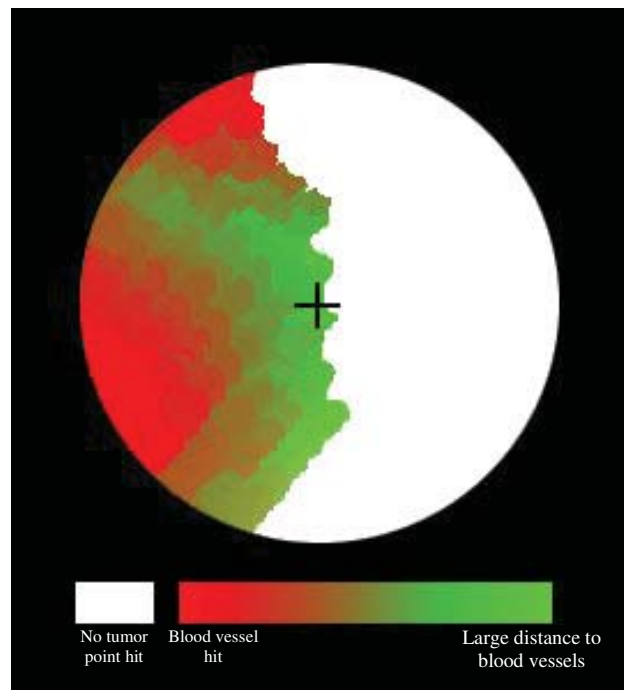

Fig 6. Biopsy-needle stability-map for a needle pathway. Green regions indicate a needle direction that is further away from a blood vessel and red regions indicates that the pathway is hitting a blood vessel. White areas indicate that the tumor is not hit.

The presented work was implemented as a VolumeShop [13] plugin, with a 3D volume renderer implemented in GLSL, an OpenGl geometry renderer and a stability-map editor implemented using Qt libraries.

VII. Conclusions

In this paper, we presented an application for creating a stability map for the needle in brain tumor biopsies. We presented the algorithms used for segmenting the brain tumor and for computing the distance transform of the blood vessels volume. The created stability map guides the physician in visualizing the needle pathways that are most stable. If errors happen in the needle insertion process, the patient will not sustain damage due to punctuated blood vessels. The introduced stability map also provides information on which needle pathways close to the considered one will not hit the tumor. The application can also suggest a needle pathway in an automated manner according to the minimum distance from any point belonging to the pathway to any blood vessel. The work described in this paper received good feedbacks from the neurosurgeons it was presented to. Future work will include integration into current medical frameworks, so the users will not need to learn two interfaces.

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