COHERENT UNWRAPPING AND SEGMENTATION OF THE SPIRAL COCHLEA

A Thesis

by

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MASTER OF SCIENCE

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ABSTRACT

Volumetric Optical Coherence Tomography and Vibrometry (VOCTV) were recently developed to record very sensitive spatially resolved vibratory measurements in the unopened mouse cochlea. It is a challenge to do quantitative analysis and segmentation of the volumetric data with the spiral structure of the cochlea. Here I present a newly developed technique to label the soft tissues, including the Reissner's membrane, tectorial membrane, and basilar membrane by unwrapping the spiral cochlea coherently thus "linearizing" the volume image. The acquired volume is rotated by hand so that the cochlea has an axis parallel to the z-axis of the Cartesian coordinate system. The 3D spiral is used to estimate the location of the spiral limbus by calculating the spiral's radius and height. The parameters of the model are determined by the given points from the actual vertices of the spiral limbus. Then, the frame is resampled around the estimated point and stacked to generate a new linearized cochlea. The linearized cochlea is segmented and points are selected from the segmented mask by algorithm. With the selected points, polygons are generated for labeling. Selecting points, however, can be challenging if the SNR is low or the segmentation result is not suitable to automatically select points. In this case, linearization is beneficial since the regions to be labeled can be found by interpolating points. After labeling, the labeled regions are rewrapped to observe the region at the original volume image. Since the frames are not continuously extracted, the rewrapped volume is made to be continuous by closing operation. This

algorithm can be further developed by segmenting and labeling the organ of Corti with detail, and automatizing the rotation and the model production.

ACKNOWLEDGEMENTS

I would like to express my appreciation to my advisor, Dr. Applegate who motivated me with valuable ideas to complete this work. I would also like to thank my committee members, Dr. Ji, Dr. Righetti, and Dr. Cui, for their guidance and support.

Thanks to my colleagues and friends for their assistance and suggestions throughout my research.

Finally, thanks to family for their encouragement and support.

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1. INTRODUCTION

As it is widely known, we can hear sound because it causes vibration that stimulates cochlea, specifically the auditory receptor [1, 2]. In the inner ear, there is an organ called cochlea which is filled with fluids and surrounded by a bone. When the sound wave reaches the inner ear, the auditory ossicles move the oval window. It causes the fluids inside of the cochlea to move and the movement causes the vibration around the organ of Corti. Then, the vibration is changed into electrical signal and it is carried to our brain. The organ of Corti is stimulated by specific frequency. At the apex, it is vibrated by low frequency and, at the basal end, it is vibrated by high frequency. The region where we observe the vibration is Reissner's membrane, basilar membrane and tectorial membrane.

Recently, a device called Volumetric Optical Coherence Tomography and Vibrometry(VOCTV) [3] was developed. It measures the vibration of the tectorial membrane and the basilar membrane within the unopened mouse cochlea. The result of this device can be used to compare the vibrating location of a normal mouse's cochlea with an abnormal mouse's cochlea that was genetically modified to have malfunctioning cochlea. Due to the nonlinear structure of cochlea, it is challenging to analyze the volume images without proper processing. In this study, we present a newly developed algorithm that simplifies labeling Reissner's membrane, tectorial membrane, and basilar membrane by linearizing the cochlea based on the helico-spiral model.

Unwrapping the cochlea implants was proposed by Wang *et al.* [4]. Wang's algorithm found the electrode array at a volumetric CT image of the implants by implementing two algorithms: Karhunen-Loeve transform and direct estimation of the next point along the local direction. The starting and end points are defined by user, and the structure can be traced with either algorithm. In this study, the unwrapping process is completed utilizing the helico-spiral model.

With the geometrical model, the path of cochlea spiral can be estimated. The model was first suggested by Fowler *et al.* to model sea shells [5]. Yoo *et al.* modeled the central path with the helico-spiral model [6]. Yoo's method was used after applying segmentation to the cochlea. His model approximates the location of the central path curve which provides the location of the electrode array which was implanted for the patient. In this paper, however, the initial model provides the location of the spiral limbus with selected points and frames are obtained around the spiral limbus to label components around the organ of Corti.

By stacking the resampled frames, the internal structure around the scala media is linearized. To label components within the cochlea, the frames are segmented by thresholding and masks are generated. Since the internal structure of the linearized cochlea does not change radically, we can interpolate the vertices of the masks to generate masks when the SNR is too low to analyze or when the segmentation does not give a reasonable result for labeling. By interpolating the internal structure of the linearized cochlea, the Reissner’s membrane and the organ of Corti can be labeled. The organ of Corti mask is divided based on the cochlea anatomy to label the tectorial membrane and the basilar membrane. The three masks can provide the location of the target region at the linearized cochlea, while our goal is to observe the labeled region at the original volume image. Therefore, the linearized cochlea is rewrapped with the labeled region. The model that was used at linearizing can give the information for rewrapping by providing the location of resampled frames. With the rewrapped segmented volumes, the Reissner’s membrane, tectorial membrane and basilar membrane can be labeled at the original image.

2. METHOD

2.1 Helico-spiral model

To linearize the cochlea, the helico-spiral model [5, 6] is used, which stretches the logarithmic spiral model along the z-axis. It is defined by

$$\mathrm{R} = \mathrm{a}\, e^{b\theta}, \qquad \mathrm{z} = \mathrm{c}\, e^{d\theta}$$

where a and c are the parameters that decide the initial point, b and d are the parameters that decide the rate of change of radius and height, R is the radius of the spiral, and z is the height of the spiral. The equation on the left is the logarithmic spiral which is represented at Figure 1(b). By stretching it along the z-axis with the equation on the right, the spiral can be represented as Figure 1-(a).

2.2 Morphological operation

Morphological operation [8] transforms binary images based on a structuring element (SE): a small binary image with an origin used to probe the target binary image. By moving the SE, the origin of the SE visits every element of the target image and an operation yields a new resulting set. In this study, two basic operations called erosion and dilation are used to extract the boundary and close a gap in an image.

2.2.1 Dilation

The dilation of A by B, denoted by $A \oplus B$, is defined as

$$A \oplus B = \left\{ (u, v) \in Z^2 \middle| \left(\hat{B}\right)_{(u,v)} \cap A \neq \emptyset \right\}$$

where A and B are sets in Z^2, A is a target image, B is a structuring element, $\hat{B}$ is an operator reflected B about its origin. It means, while visiting every element of A with the origin of B, the dilated image is a set of all elements that $\hat{B}$ was overlapped on the target image and share at least one element in common. By dilating an image, the target image becomes bigger. The shape and the size of the dilated image depend on the structuring element. Figure 2-(b) shows the dilated image of Figure 2-(a).

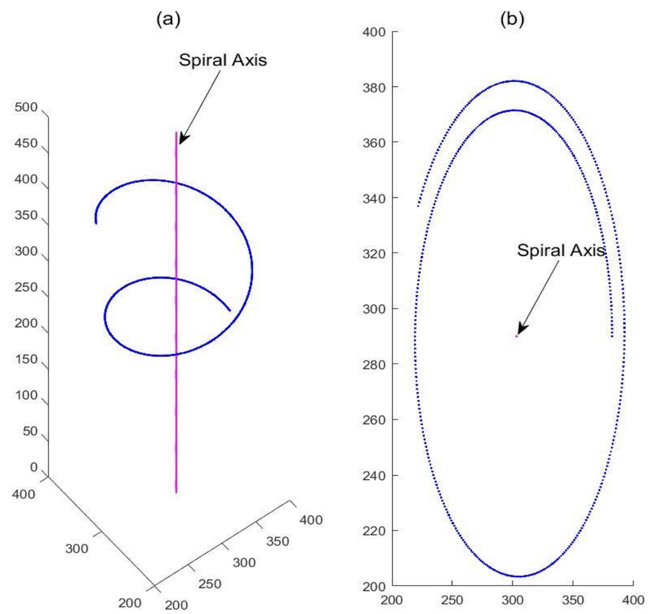


Figure 1: Example of spirals. (a) helico-spiral example; (b) logarithmic spiral example.

2.2.2 Erosion

The erosion of A by B, denoted by A $\ominus$ B, is defined as

$$A \ominus B = \{(u, v) \in Z^2 | (B)_{(u,v)} \cap A^c = \emptyset\}$$

where A and B sets in Z^2, A is a target image and B is a structuring element. It means, while visiting every element of A with the origin of B, B should not share any element in common with the background of A and every element of B should be overlapped in A. By eroding, the resulting image is smaller than the original image and the size of the resulting image depends on the size of the SE. Figure 2-(c) shows the result of the eroded image of Figure 2-(a).

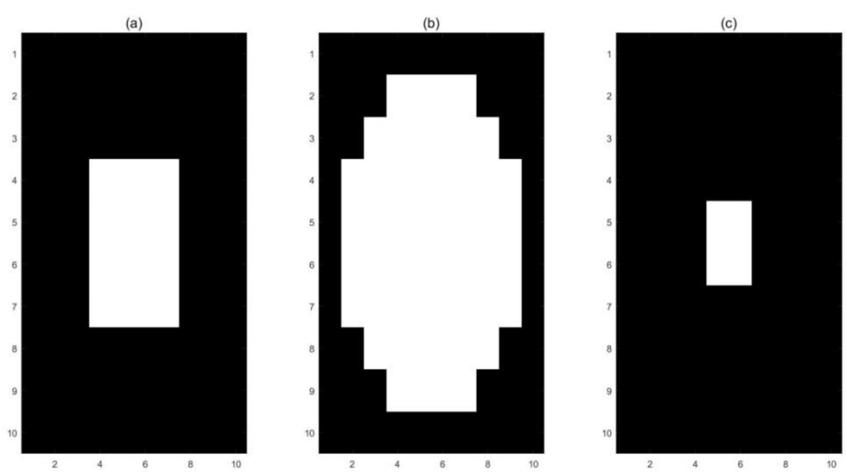


Figure 2: Examples of morphological operations-1. (a) target image; (b) dilated image of (a); (c) eroded image of (a).

2.2.3 Boundary extraction

The boundary extraction, denoted by $\beta(A)$, is defined as

$$\beta(A) = A - (A \ominus B)$$

where A is a target image and B is a structuring element. The image A is eroded by B, and then all common elements of A and the eroded image are eliminated from A. Thus, the resulting image only has elements that A dos not share with the eroded image, which is the boundary of A. To yield the result in Figure 3-(b), the structuring element with disk size 2 is used and the thickness of the boundary is, therefore, at least two pixels.

2.2.4 Closing operation

The closing operation, denoted by A • B, is defined as

$$A \bullet B = (A \oplus B) \ominus B$$

where A is a target image and B is a structuring element. By dilating an image, small holes or gaps are filled. Then, the dilated image is eroded. The holes or gaps are remained filled even after the erosion since there are no holes or gaps inside of the dilated binary image. To yield result of Figure 3-(c) from Figure 3-(b), a disk with radius 15 is used as the structuring element.

2.3 Mask with line equation

A line equation can be implemented to make a mask based on the ratio of the structure. F or example, when a line passes p1 = (x_1, y_1) and p2 = (x_2, y_2), a line equation can be ge nerated as

$$f(x,y) = (y - y1) - \frac{y_2 - y_1}{x_2 - x_1} \cdot (x - x1), \text{ where } \begin{cases} f(x,y) = 0, & \text{if } (x,y) \text{ is on the line} \\ f(x,y) \neq 0, & \text{otherwise} \end{cases} .$$

With this, the right or the left region of the line can be selected and it is represented at Figure 4-(b). By multiplying with another region generated from a different line equation, a new region is selected as Figure 4-(d). With these masks, the region of interest can be obtained as Figure 4-(c) and (e).

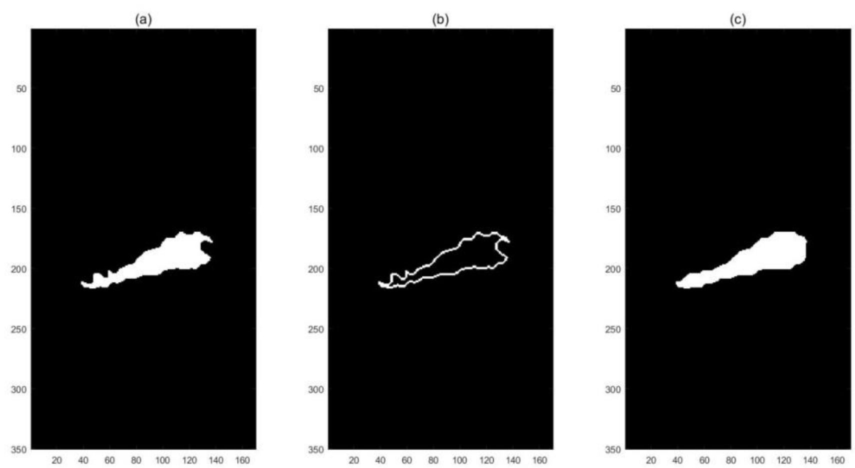


Figure 3: Example of morphological operations-2. (a) an example image; (b) boundary extraction; (c) closing operation

2.4 Saturation artifact

When imaging with OCT, saturation artifacts can appear due to the detector's limited dy namic range. At the data acquired from VOCTV, it appears at random A-lines along the volume as it is shown Figure 5-(c). To reduce saturation artifact, a method that is used in the retinal scan is implemented [7]. In the retinal scan, the A-lines with saturation artifac t are detected by finding unexpected peaks among average intensities of each A-line.

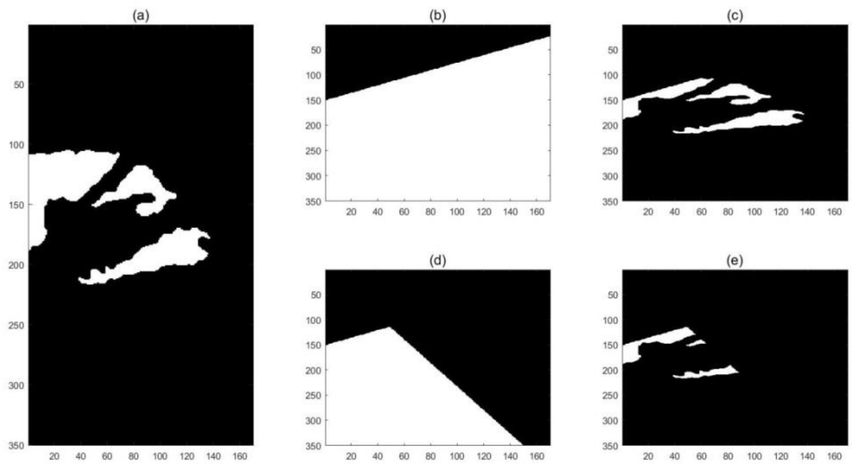


Figure 4: Generated mask from line equations. (a) example image; (b) mask generated from one line equation; (c) (a) masked by (b); (d) mask generated from two line equations; (e) (a) masked by (d).

In the volumetric cochlea scan, the method is expanded to consider the whole volume instead of single 2-D image. The artifacts are reduced by

$$\widehat{V}(x,y,z) = \begin{cases} V(x,y,z) + \left(avg(V) - \mu(z)\right), & \text{if } |\mu(z) - avg(V)| > T \\ V(x,y,z), & \text{otherwise} \end{cases}$$

where V is the volume image, avg(V) is the average intensity of the whole volume, $\mu(z)$ is the average intensity of each A-line, and T is the threshold value which is set to 500. In Figure 5-(b), the blue line is the average intensity of each A-line of Figure 5-(c) and the red line is the threshold. If the blue line is above the red line, it means that there are saturation artifacts. With this detected location, the artifact reduced image is shown in Figure 5-(d).

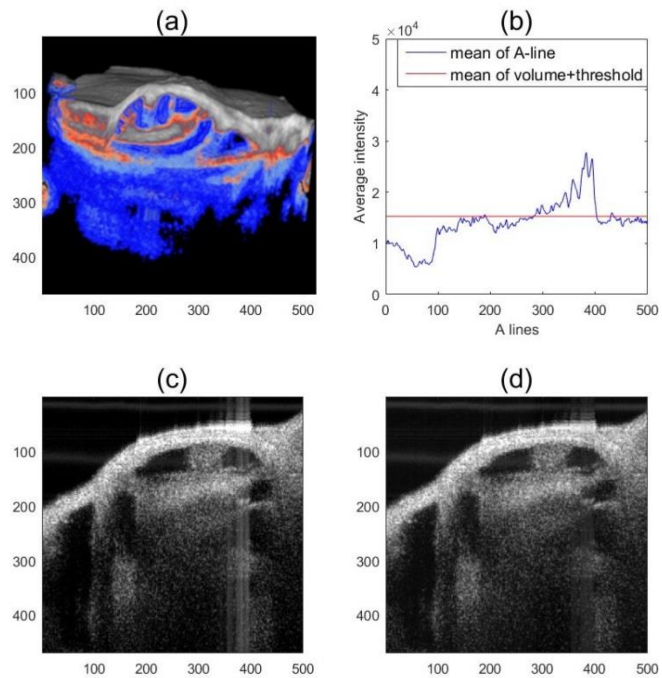


Figure 5: Reducing saturation artifact. (a) original volume image; (b) saturation artifact detection; (c) example image with saturation artifact; (d) example image with reduced saturation artifact.

3. RESULT

3.1 Rotating the volume

After the saturation artifact is reduced, the cochlea is rotated by hand to apply the helico-spiral model. The rotation angle is determined by iteration. At first, two planes are selected by hand that are parallel to the xz plane and yz plane of the Cartesian coordinate system and, at the same time, have the longest distance between two upper chambers. Then, a line is drawn in each plane from a point in the middle of the two upper chambers to a point in the middle of the two lower chambers. The volume is rotated with the angles between the lines and the xy plane so that both lines are perpendicular to the xy plane. If the angle of the line in the rotated volume is not close to the right angle in both planes, it is repeated. Otherwise, the iteration stops. The axis of the cochlea is now parallel to the z-axis of the Cartesian coordinate system of the volume image. Figure 6-(a) and (b) show the frames that includes the spiral axis.

3.2 Linearizing and resampling

Due to the spiral structure of the cochlea, labeling the Reissner's membrane, tectorial membrane, and basilar membrane is challenging without proper processing. Linearizing the cochlea will simplify the segmentation process by allowing the estimation of a specific location when the SNR is low making it difficult even for naked eyes to identify the target.

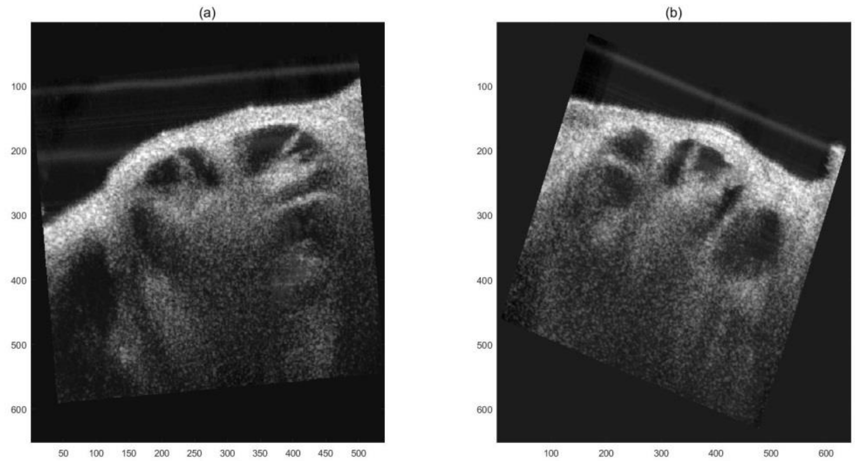


Figure 6: Result of rotation. (a) (b) rotated images.

The helico-spiral model is utilized to linearize the cochlea. Since the cochlea having a spiral structure with increasing rate of radius change, modeling the cochlea based on a fixed rate of radius change will not provide an accurate estimation. To compensate this issue, modeling the cochlea is achieved by combining two spirals with different parameters. These two spirals are generated with points which are selected by the user on the spiral limbus when θ = 0, 250 and 500. The upper spiral is determined by θ from 0 to 250, while the lower spiral around the basal end is determined by θ from 250 to 500. As you can see from Figure 7, unlike the example from Figure 1, the radius of the spiral increases faster after theta = 250.

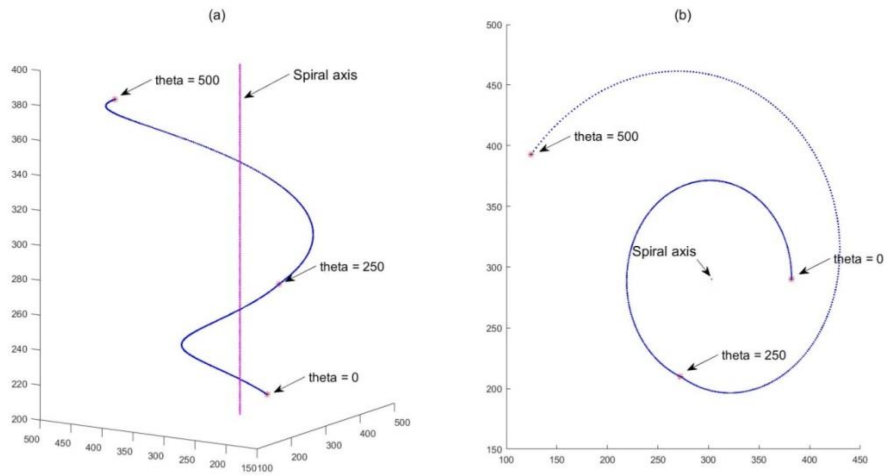


Figure 7: Initial helico-spiral model. (a) spiral stretched along z-axis; (b) spiral when z=0.

Then, frames are extracted by rotating a window with $\Delta\theta = 1$, while one side of the window includes the spiral axis. The way frames are extracted is visualized in Figure 8. The squares with dotted lines within the volume are the frames to be extracted. In each frame, the model approximates the location of the spiral limbus. Based on the given location, the frame is resampled to contain the region around the scala media. Finally, they are stacked and a new volume of the linearized cochlea is generated. Figure 9 shows an example of the extracted frames setting the $\Delta\theta$ as 90, and Figure 9-(b) through (f) are stacked to generate a linearized volume.

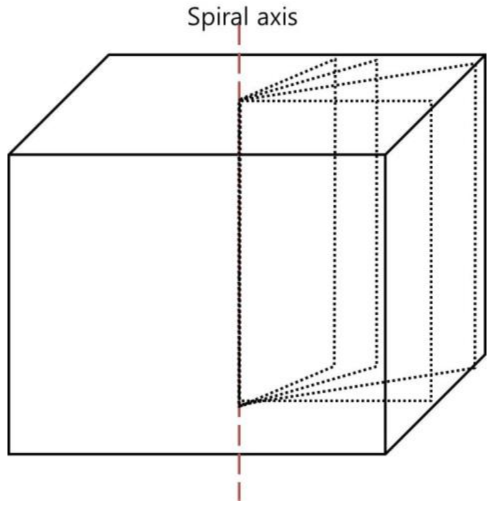


Figure 8: Frame extraction.

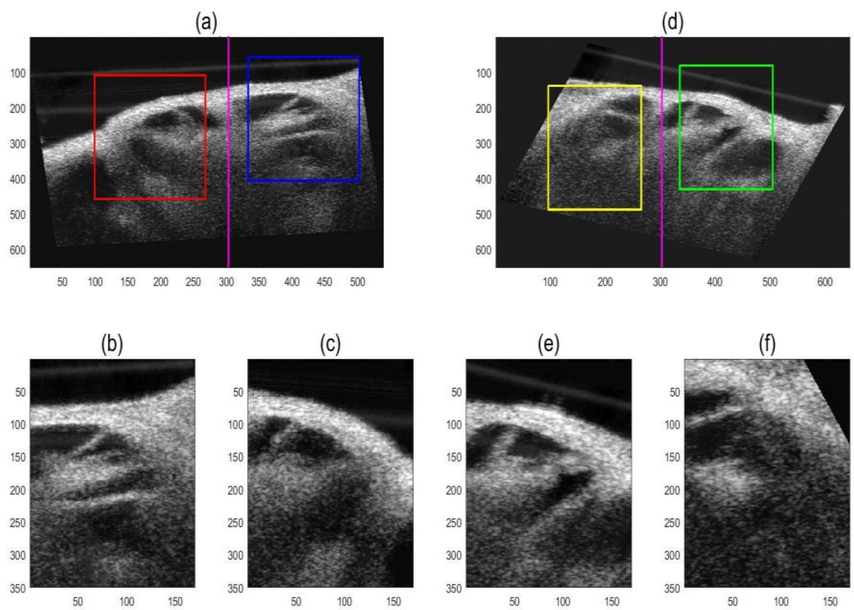


Figure 9: Linearizing and resampling. (a),(d) images that frames are extracted when θ = 0, 90, 180, 270; (b) θ=0(blue square on (a)); (c) θ=90(green square on (d)); (e) θ=180(red square on (a)); (d) θ=270(yellow square on (d)).

3.3 Segmentation and labeling

The objective of this step is to make three masks to label the Reissner's membrane, tectorial membrane, and basilar membrane. These masks will appear in the original volume image after the rewrapping is completed. Each mask is generated in a polygon shape by selecting points using an algorithm. At first, pixels with nonzero values in a binary segment are detected. Then, the desired points are selected by an algorithm from the coordinates of the detected pixels from the previous step. For example, the desired points can be the leftmost, the rightmost, the uppermost points in one segment, and the closest points in an adjacent segment. In this study, two polygons are generated: one for the Reissner's membrane and one for the organ of Corti. In the polygon for the organ of Corti, the tectorial membrane and the basilar membrane are labeled based on the cochlea anatomy. The indirect labeling method is employed for these two particular membranes because the basilar membrane labeling requires vibrometry information and the tectorial membrane is difficult to find in most frames.

The segmentation and labeling step begins with implementing Gaussian filter to remove noise and excluding the region that has no data caused by volume rotation. Then, the frame is segmented by thresholding. The threshold is determined by intensity values around the spiral limbus. Since the location of the spiral limbus is an estimated point, its more accurate location can be found by corner detection. The median intensity value around the enhanced spiral limbus location is used for thresholding. After the segmentation process is completed, masks for the scala vestibuli, scala media, and scala tympani are chosen based on their distances from the spiral limbus location. Figure 10-(c) shows the chosen three chambers from (b). In Figure 10-(b), segmentation results give reasonable segments to choose three chamber. In Figure 10-(d),(e), and (f), they show the frames where segmentation results are not reliable to choose three chambers due to the frame's low SNR or segmentation errors. Even with these inconsistencies, we can conclude that the model itself provides a dependable point approximates of the sprial limbus.

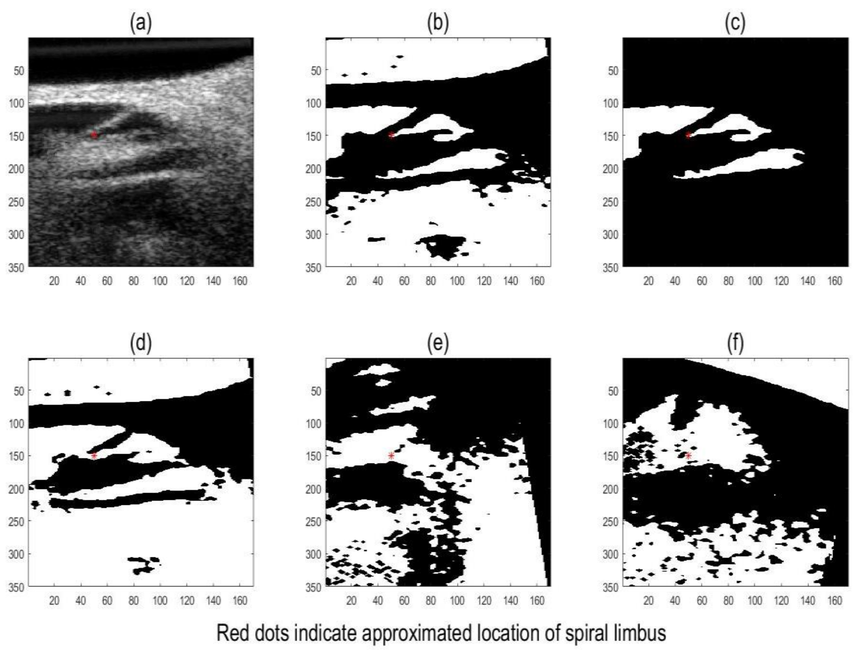


Figure 10: Result of segmentation. (a) an image to be segmented; (b) segmented (a); (c) selected masks of scala vestibule, scala media, and scala tympani; (d),(e),(f) segmentations which cause problems at labeling

To label the Riessner's membrane, which is located between the scala media and scala vestibuli, a polygon is generated by selecting four points; the points selected are the leftmost(A) and the uppermost(B) points on the mask of the scala media and two closest points(C, D) from points(A, B) on the mask of the scala vestibuli. Selected points are visualized at Figure 12. The blue polygon connecting points (A, B, C, D) is the location of the Reissner's membrane.

To label the organ of Corti, four points are selected from the boundaries of the scala media and scala tympani. From the boundary of the scala media, the leftmost(E) and the rightmost(F) point is selected, unless height difference between E and F is too significant. In that case, the location that has the greatest (column + row) value is selected for point F. From the boundary of the scala tympani, the point (G) which is closest from the point F is temporarily selected. Then, the boundary is traced to the left from point G, and the tracing stops at point H when the boundary starts to go downward. Similarly, by tracing the boundary to the right from point G, another point(I) is selected by stopping when the derivative is negative infinity. Figure 11 shows the points found to label the organ of Corti on the frame and the segmented image. Selected points are visualized at Figure 12. The blue polygon connecting the points(E,F,H,I) is the location of the organ of Corti.

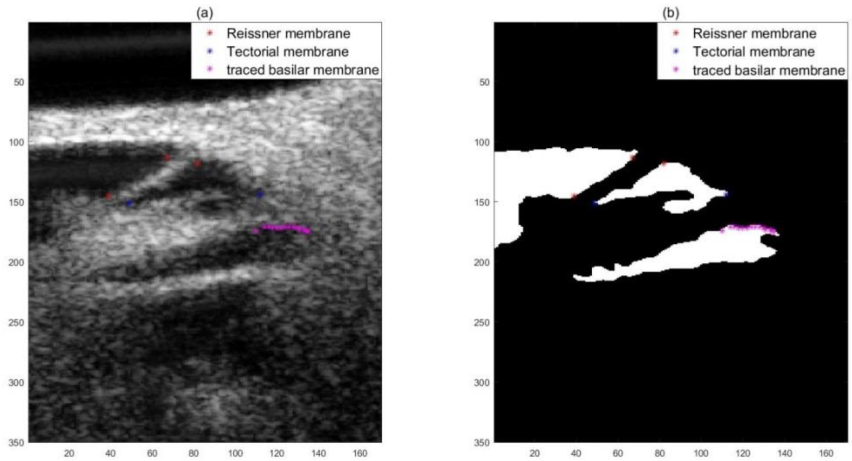


Figure 11: Labeling-1. (a) an image to be labeled with selected points; (b) selected points on the segmented (a) with selected points.

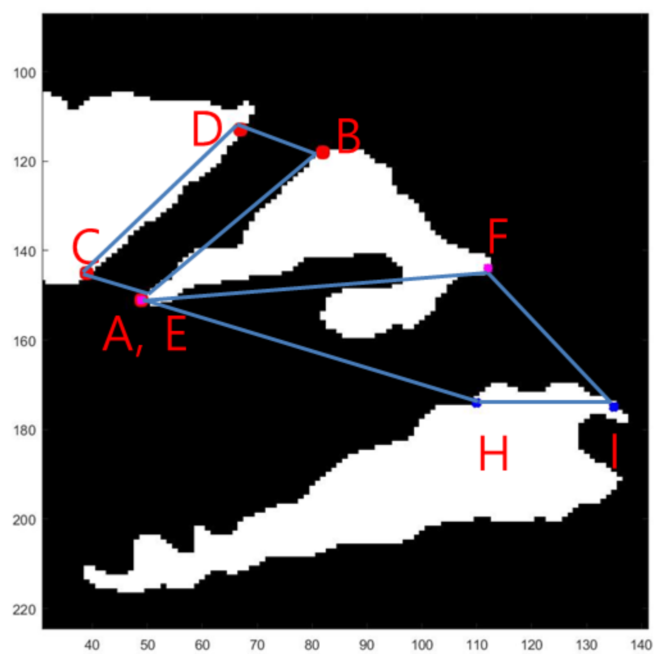


Figure 12: Example of selected points.

Then, the decision whether the chosen chambers are acceptable or not is made based on the location of the vertices, such as the distance from the points on the previous frame, height difference, the number of resulting segments, and the distance between each other. If the three chambers are correctly chosen, the points for labeling the Reissner's membrane and the organ of Corti are saved. Otherwise, their location is linearly interpolated based on the point location of the previous and subsequent frame where both frames have saved points. The result of the interpolating spiral limbus point is shown in Figure 13. Since two points are connected with a straight line when interpolating, points which are in the same line can be found near x = 30. After interpolating, almost every point is found for labeling. With the points (A, B, C, D), a polygon is generated for labeling the Reissner's membrane. With the points (E, F, H, I), it is possible that the generated polygon is not appropriate for labeling, because the upper part of the tectorial membrane might not be included in the labeled organ of Corti. In which case, further processing is required. The interpolated points on the frames are shown in Figure 14-(a) through (c). As in Figure 14-(c), even when the structure of the frame is difficult to observe, the interpolated points approximate the desired vertices.

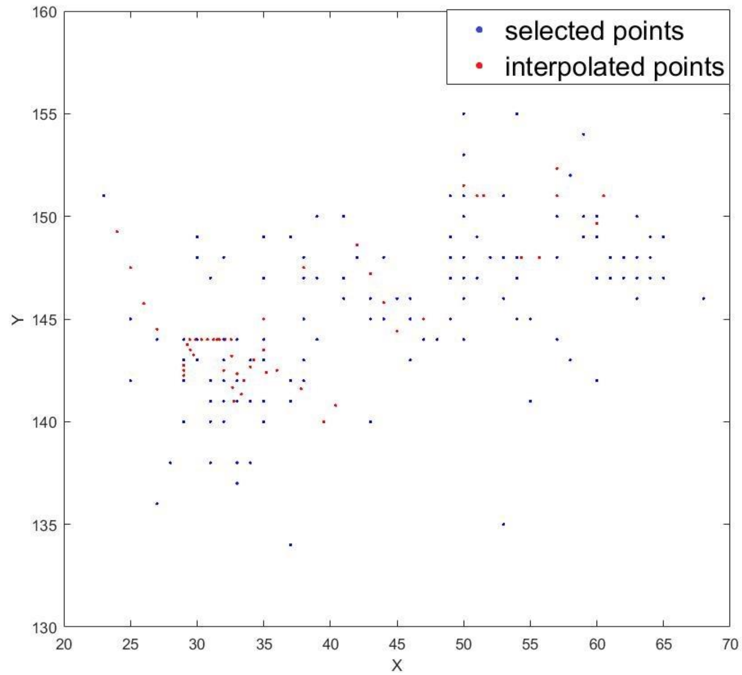


Figure 13: Result of interpolation.

When further processing is required, each frame is segmented again by setting the threshold to the intensity of the spiral limbus, which is point A. The left region of the frame from the spiral limbus is set to zero in order to prevent a problem when the scala media and scala vestibuli masks are connected after segmentation, which is shown in Figure 10-(d). Boundary of the scala media is traced again to find the upper curve of the tectorial membrane, and it stops when the row value of points starts to decrease; signifying that it passed the tip of the tectorial membrane. The boundary is traced downward from the tip of the tectorial membrane to find another point that starts to turn. Since this process is implemented to every frame, even the frames with low SNR, another boundary condition is required. To determine whether the traced boundary is correct or not, the location of the traced points are saved based on the distance from the previous frame and the relative location between each other. Then, the saved points are used for interpolating in the frames without the saved points. By comparing the height of the traced line with the line E-F, it can be determined if the line E-F is crossing the tectorial membrane. If the line E-F is crossing the tectorial membrane, a new uneven line is created and is used for producing a polygon to label the organ of Corti. As in Figure 14-(d), making a polygon around the four detected points are insufficient to label the tectorial membrane. Thus, as in Figure 14-(e), the upper part of the tectorial membrane should be traced, and the traced line should replace the original straight line.

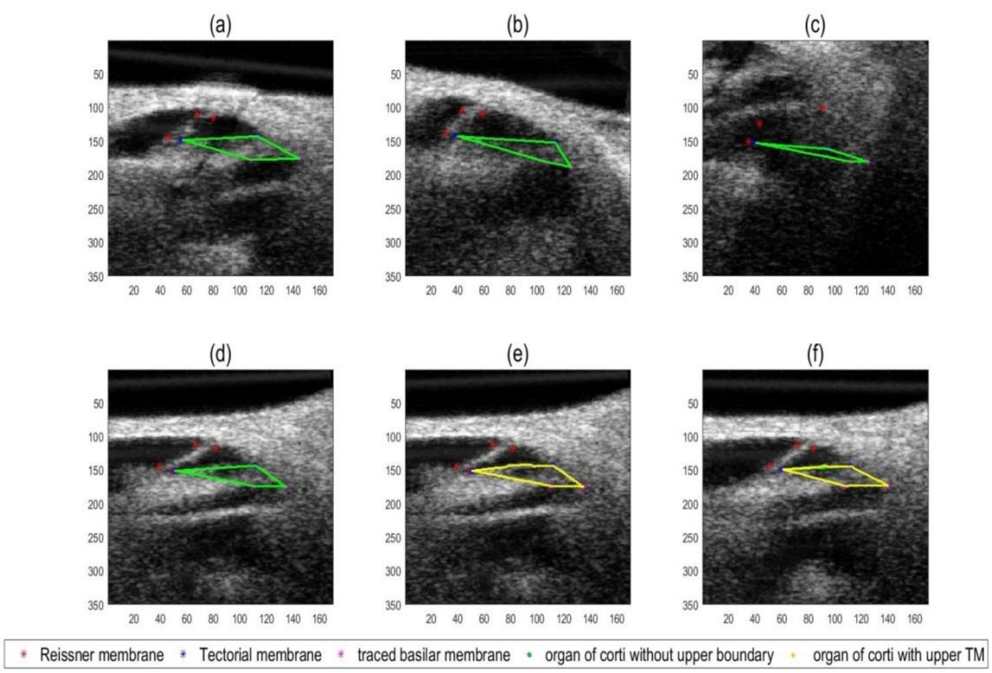


Figure 14: Labeling-2. (a)-(c) results of interpolation; (d) square mask with only four vertices of TM and BM; (e) mask with upper region of TM; (f) mask with upper region of TM overlapped with square mask.

With the labeled organ of Corti, we can approximate the location of the tectorial membrane and the basilar membrane based on the cochlea anatomy. A line is drawn between the mid-point(J) of line E-F and the midpoint(K) of line H-I to measure the thickness of the membranes. Two lines are drawn to be parallel to E-F at the point where it is the top 30 percent of J-K, and parallel to H-I at the point where it is the bottom 20 percent of J-K. With line equations, we can make a mask to extract the membranes with the desired thickness. To label the tectorial membrane more accurately, additional processing is required due to its length. For this, another line is drawn which is perpendicular to line E-F at the point where it is the left 80 percent of line E-F. Again, the mask for the tectorial membrane is modified with another line equation. With these masks, labeling the tectorial and basilar membrane is completed by multiplying them with the labeled organ of Corti. The division is visualized at Figure 15. In Figure 16-(a), the organ of Corti mask is the entire colored region: the tectorial membrane is in the magenta colored region, and the basilar membrane is in the yellow colored region. Also, the labeled result is shown in Figure 16 from (b) to (f).

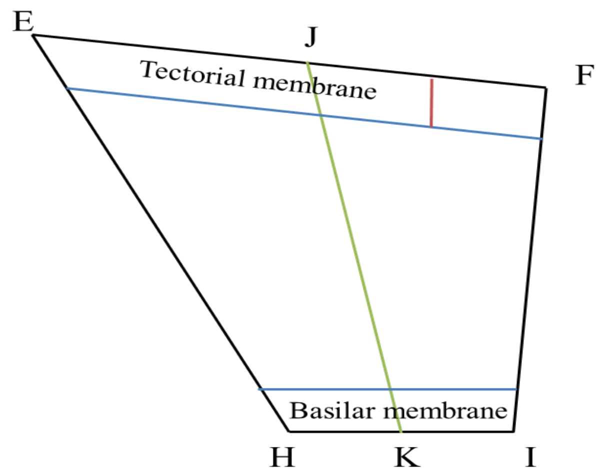
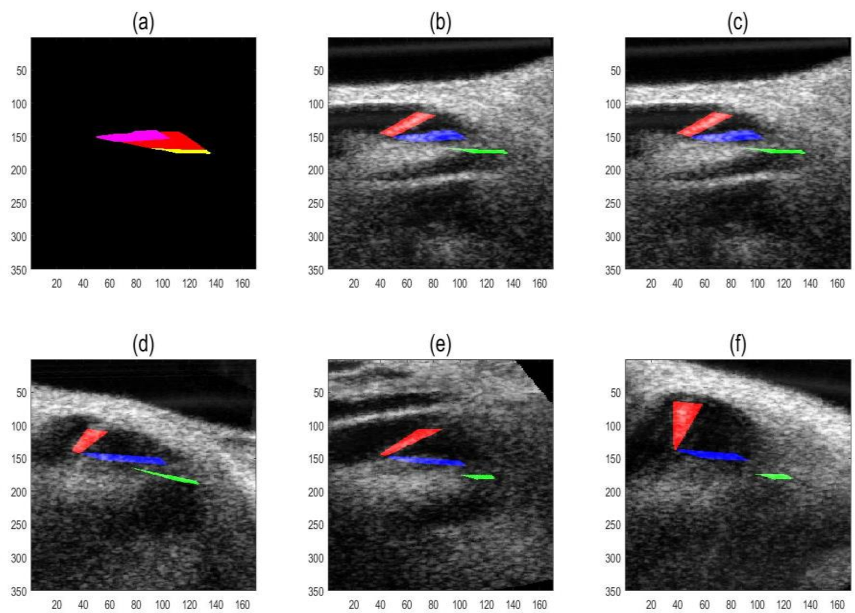


Figure 15: Dividing the organ of Corti based on line equations.



Red region: Reissner's membrane, Blue region: Tectorial membrane, Green region: Basilar membrane

Figure 16: Labeling-3. (a) line equation is applied for labeling at organ of Corti; (b)-(f) labeled frames.

3.4 Rewrapping

Since the goal of this algorithm is to make segmented regions observable at the non-linear shape of the cochlea, rewrapping the unwrapped cochela is required and it can be achieved based on the initial spiral model. Then, the rewrapped cochlea is now rerotated based on the rotated angle. When extracting frames, however, the frames are not continuously extracted, and it causes discontinuity at the segmented region in the rewrapped cochlea. To resolve the discontinuity, the morphological closing operation is implemented to fill the gaps in the frames parallel to x-y plane of the Cartesian coordinate system of the volume image. To show the discontinuity in Figure 17-(a), an white mask with the size of the linearized frame is used to rewrap, instead of the small segmented mask. After rewrapping it, the mask is multiplied to the original volume image, and the discontinuity between frames is shown in Figure 17-(a). The result of the closing operation when multiplied with the original volume is shown in Figure 17-(b).

By applying the closing operation at the three rewrapped masks and applying colors, segmenting and labeling the volumetric cochlea image is completed. The B-scans of colored volume is available at Figure 18.

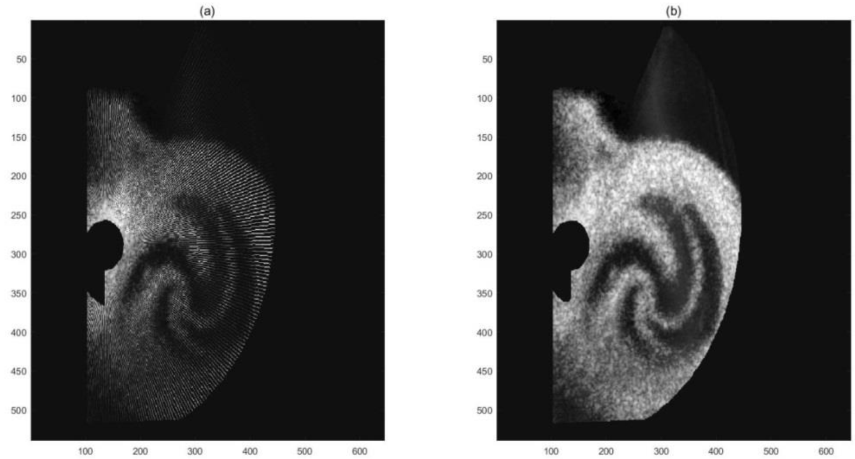


Figure 17: Rewrapping. (a) rewrapping frames without closing operation; (b) rewrapping frames with closing operation.

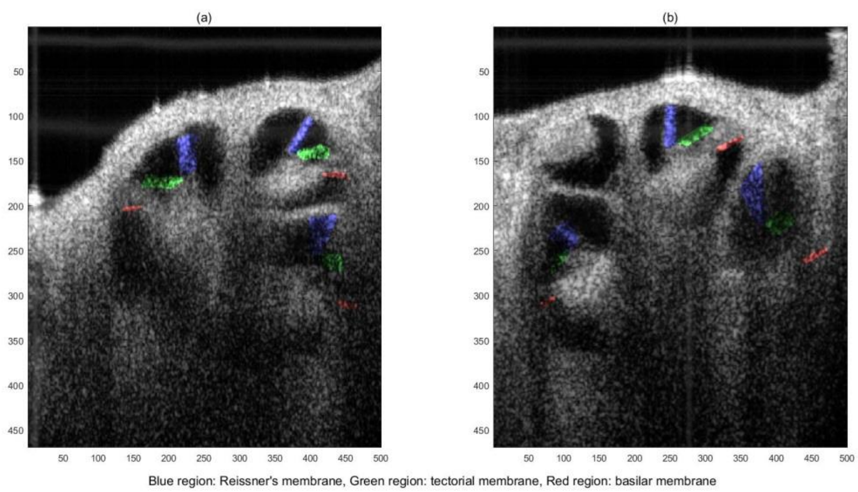


Figure 18: Final result.

3.5 Summary

The process of the presented algorithm is briefly explained in Table 1.

1. Rotate the volume by hand

1) Select two planes which have the longest distance between upper chambers

2) Draw a line of estimated axis in both planes

3) Rotate the volume so that the lines are perpendicular to the xy plane

4) Go to 1-1) to iterate or stop if both lines are perpendicular to the xy plane

↓

2. Linearizing and resampling

1) Select three points on the spiral limbus by hand and make a helico-spiral model

2) Extract frames around the estimated points of spiral limbus by rotating a square window with $\Delta\theta = 1$ while a side of a window includes the spiral axis

3) Stack the extracted frames to linearize

4) Stop rotating the window when the extracted frame is around basal end. In this case, $\theta = 510$

↓

3. Segmentation and labeling

1) Segmentation by thresholding which is determined by intensity values around the estimated point of spiral limbus

2) Select three binary segments based on their distance from the approximated spiral limbus

3) Select four points for RM and four points for the organ of corti from the selected segments

4) Check if the selected points meet the boundary condition. If it does not meet the condition, move on to 3-5). If not, save these points and move on to 3-5).

5) Repeat 3-1) to 3-4) until the last frame

6) Interpolate the points for the frames with no saved points

7) Segment the frame again to include the upper region of TM

   a. Trace the upper boundary of the tectorial membrane and make a line between the point on the spiral limbus and the rightmost point of scala media

   b. Compare the line with the trace point and replace it with the traced point if it is above the line in that column

8) Repeat 3-7) until the last frame is segmented and save the points if it meets the condition

9) Interpolate the line and generate two masks, one for RM and one for the organ of corti

10) With the mask of the organ of corti, generate two masks to label TM and BM by using line equations

↓

4. Rewrapping with segmentation

1) Rewrap linearized masks based on the model from 2-1)

2) Fill gaps between rewrapped frames by closing operation

3) Re-rotate based on the rotation angle from 1

Table 1: Flowchart

4. CONCLUSION

In this study, we have presented a newly developed algorithm, which semi-automatically labels the Reissner's membrane, tectorial membrane, and the basilar membrane within the unopened cochlea. Unwrapping the cochlea coherently is the key for the algorithm. It is linearized by extracting the frames while a square window is rotating around the spiral axis and stacking the extracted frames. After linearizing, at some images, errors caused by the low SNR and segmentation generate improper masks for labeling. In the images where the generated masks are acceptable, the selected points based on the location of pixels in the segment are saved. The beauty of this algorithm is that by linearizing, we can interpolate to estimate the desired points at the frames where the segmentation result is not reliable. With the interpolated points, masks are generated. The mask for the organ of Corti is divided into two by producing another mask with the line equation: one for the tectorial membrane and one for the basilar membrane. Based on the model that is used for the linearizing process, the segmented masks can be rewrapped. Since the frames are discontinuously extracted, the rewrapped volumes need further processing, and the discontinuity is resolved by the morphological closing operation. When the volume that is rewrapped with segmentation and is overlapped with the original volume image, we can see that the algorithm yields a reasonable result. This study can be further developed by segmenting the organ of Corti with more detail, automatizing the rotation, and generating the initial model without assistance.

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