REALISTIC METHOD FOR GENERATING A HEXAHEDRAL FEM MESH FROM BIOLOGICAL SOFT TISSUE

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Abstract. *As part of a study on the development of a simulator for detachment of the retina operation on a human eyeball, the mechanical properties of the eyeball have been measured and a detailed solid structure constructed to reflect the many component organizations and lack of symmetry. This present work describes an FEM mesh model based on the actual shape of the eyeball taken from images by 3D-ISM. After segmenting the eyeball into its component parts, the image data were converted into numerical data. Two FEM mesh patterns were created for evaluation, a mapped mesh and voxel mesh, the mapped mesh data proving more suitable for our simulation.*

1. INTRODUCTION

A study is underway on the development of a simulator for the detachment of the retina operation on a human eyeball. Simulating the operation requires a dynamic model of the eyeball. The mechanical properties of the eyeball have already been measured and a detailed solid structure constructed. Figure 1 shows that an eyeball consists of many organizations, one of the thinnest being the retina with a 100-μm thickness. It can also be seen that the optic nerve position and attached musculature are asymmetrical [1]. An eyeball is therefore not simple sphere, and an FEM analysis of the eyeball requires an accurate and realistic numerical model.

We have already developed the 3D-ISM method [2, 3] for digitizing the detailed internal structure of the eyeball and examined a method for generating the FEM mesh from the real shape of the living body. However, the image does not incorporate data for the coordinate values, point of contact number, etc. which are necessary for a finite element analysis. To generate the most suitable mesh from the image data, we examine in this present work the method for passing image data to the mesh generator and create the mesh from the data obtained by the method.

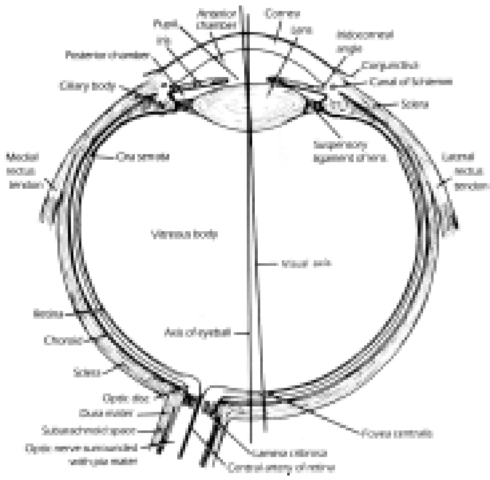


Fig. 1 Component Tissues of the Eyeball

2. EXPERIMENTATION

Image data for a pig eyeball obtained by 3D-ISM was used in the experiment. The eyeball was fixed with a 2.5% formalin and 1% glutaraldehyde mixture in a phosphate-buffered saline (PBS) solution within 3 hours of being removed from the animal. Liquid red dye was injected into the anterior chamber to distinguish each part of the eyeball, after which the dye was replaced by the PBS solution. The eyeball was then embedded in a blue OCT compound and finally frozen at –35ºC.

The frozen sample was cut into 30-μm slices by a knife rotating at 90rpm, and images of each slice were taken by 3D-ISM to a resolution of 127μm. Images of 800 slices were taken in a time of about ten minutes each and recorded on a laser disc which was loaded into a PC. The images were converted into continuous sectional images and some are shown in Figure 2, in which the cornea, lens, retina, optic nerve, and sclera can be seen.

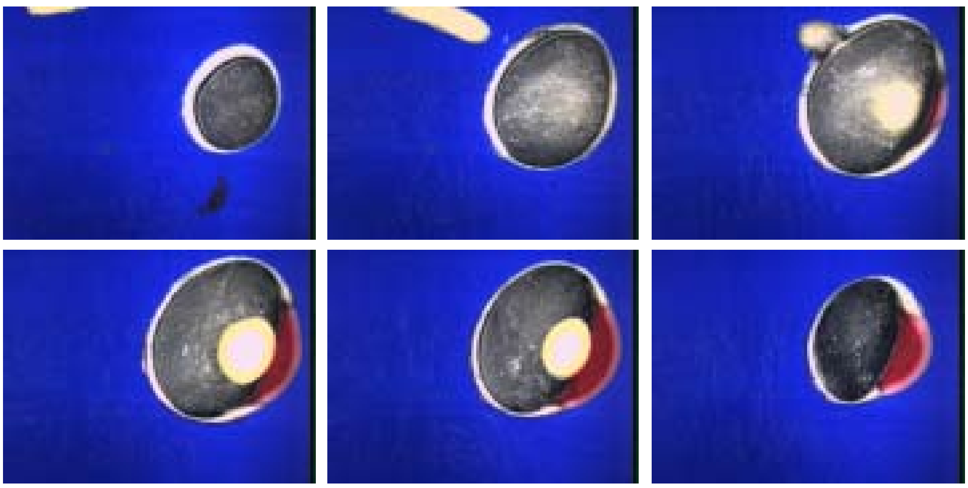


Fig. 2 Cross-sectional Images of the Eyeball

3. IMAGE PROCESSING

We created hexahedral meshes from the images of the sample sections after segmenting into each part of the eyeball. The flow chart in Figure 3 illustrates the procedure from segmentation to mesh generation.

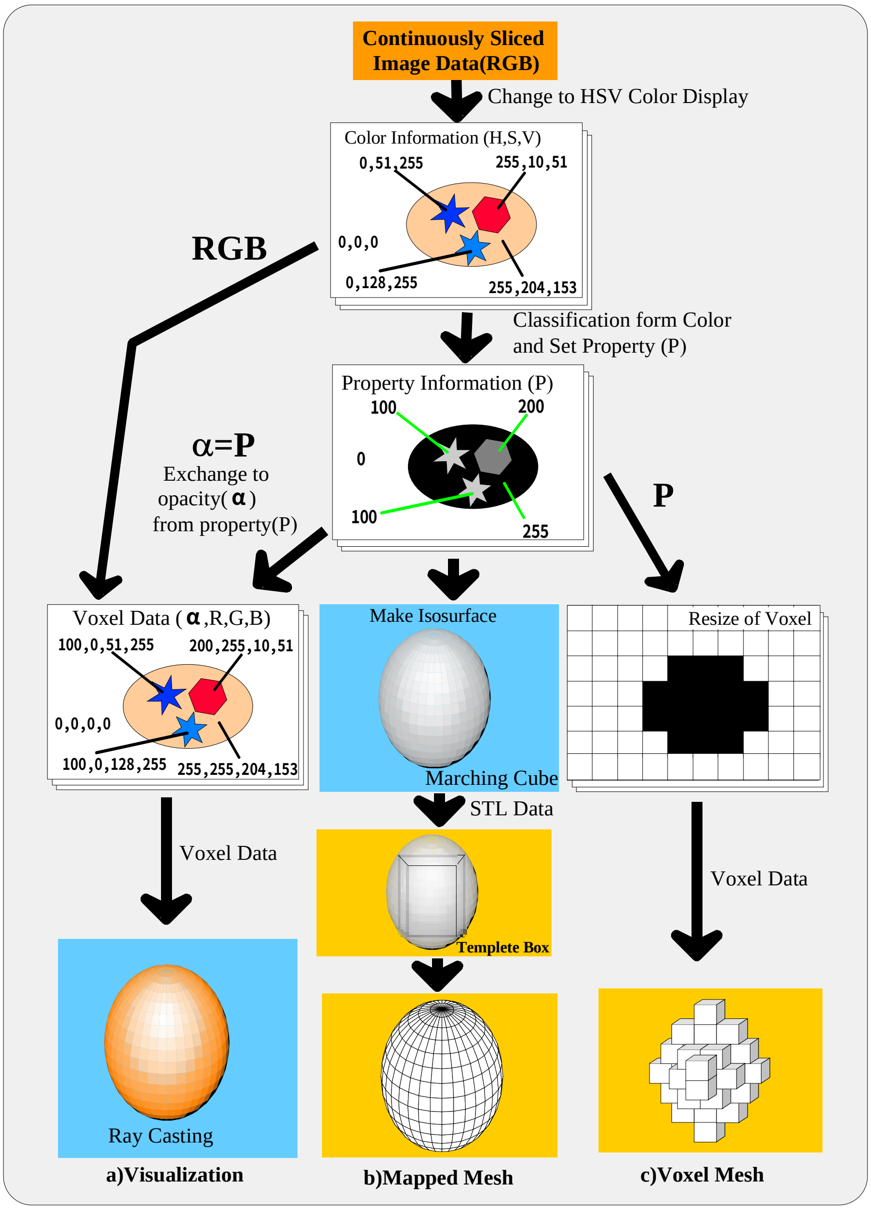


Fig. 3 Flow Chart from Segmentation to Mesh Generation

The cornea, lens, and whole eye could be distinguished in the sample images, and we segmented each part of the eyeball by using these images. The continuous cross-sectional images provide information in full color, and we classified several parts by using this color information. The property value (P) was set for the pixels in each part, the same part being set to the same property value in each image. We subsequently visualized the image and verified the set property value (α=P). The result is displayed by AVS5.3 software (AVS Inc.) which displays the image by using a module. We applied existing modules and self-made modules. The multiple cross- sectional image is formed into a 3-D image by Ray casting, this being one of the methods for volume rendering. Non-display parts are made transparent according to the property value information. The surface of the extracted part is then displayed. We also visualized the cross-sectional image that had not been actually cut and confirmed the range for the extraction of the image [4]. 3-D images of parts of the eyeball are presented in Figure 4.

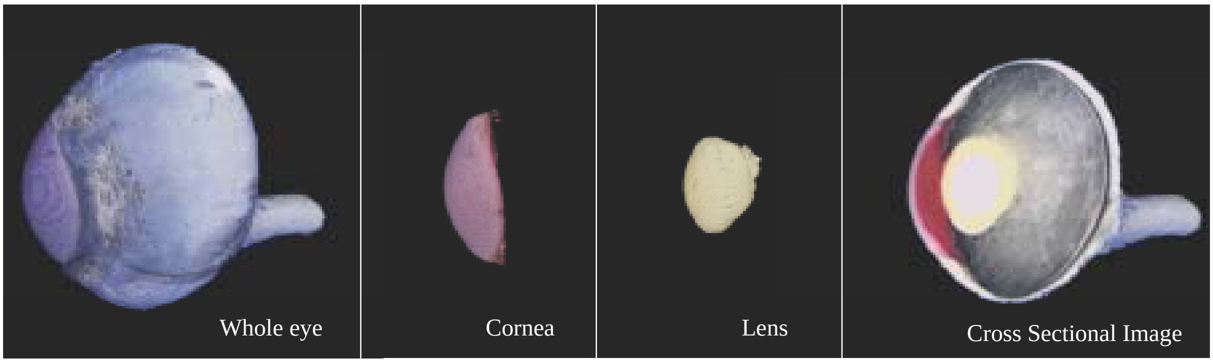


Fig. 4 3-D Images of the Eyeball

4. MESH GENERATION

We could produce 3-D images of each part of the eyeball. In this study, we produced images of the whole eye, lens and cornea, although these 3D images had neither the coordinate values nor the point of contact number. It was therefore necessary to convert the image data into numerical data. We first created the surface data based on the Marching Cube method which creates a cube to represent a voxel that has 8 corners [5]. The pixel property value at each voxel corner is read into the cube. Each corner of the cube is next determined to be either inside or outside the surface. If one or more pixels of a cube have a value less than the property value, the corner is considered to be inside the surface. On the other hand, one or more have a value greater than the property value, the corner is considered to be outside the surface. This indicates that the voxel must contribute some component of the isosurface. By determining which edges of the cube intersect the isosurface, we can create triangular patches which divide the cube between regions within the isosurface and regions outside. In this case, if we change the property value, we can make each part of the eyeball. Connecting the patches from all cubes on the isosurface boundary gives a surface representation. In addition, this surface has a polygonal patch composed of algebraic data which makes it possible to generate a mesh. The method also applies linear interpolation to process the data so that the reconstructed data gives a smoother shape than the voxel data. So we converted the voxel data into surface data that smoothed the edge of voxel.

We next reduced the polygon of the isosurface data to remove the data noise and rearranged the shape of the polygon. This surface data was output to an STL file which expresses the surface of the solid model as a group of small triangles. In this case, each polygon corresponded to an STL triangle; STL data for the whole eye comprised 1,912,512 triangles, with 198,522 triangles for the lens and 53,184 triangles for the cornea. This data has surface coordinates, so it can be used in a mesh generator (ICEM CFD/HEXA, ICEM Inc.). The ICEM CFD program applies the mapped mesh method to create the mesh [6-7]. Mapped mesh generation proceeds by identifying regions which are isomorphic to a cube. ICEM CFD/HEXA automatically generates a global block around the STL data that describe the space to be meshed. We can cut out the desired shape by subdividing this block into smaller blocks and assigning different materials. The block structure can be interactively adjusted to the underlying STL geometry to reflect the characteristic features of the geometry to be meshed. We delimit a global block which arbitrarily adjusts the number of meshes, and create a voxel mesh from the image data (VOXCELCON, Quint). The underlying principle is to define a voxel by the pixel values at the voxel. The mesh is generated in voxel units, the number of voxels being arbitrarily adjusted by the voxel size.

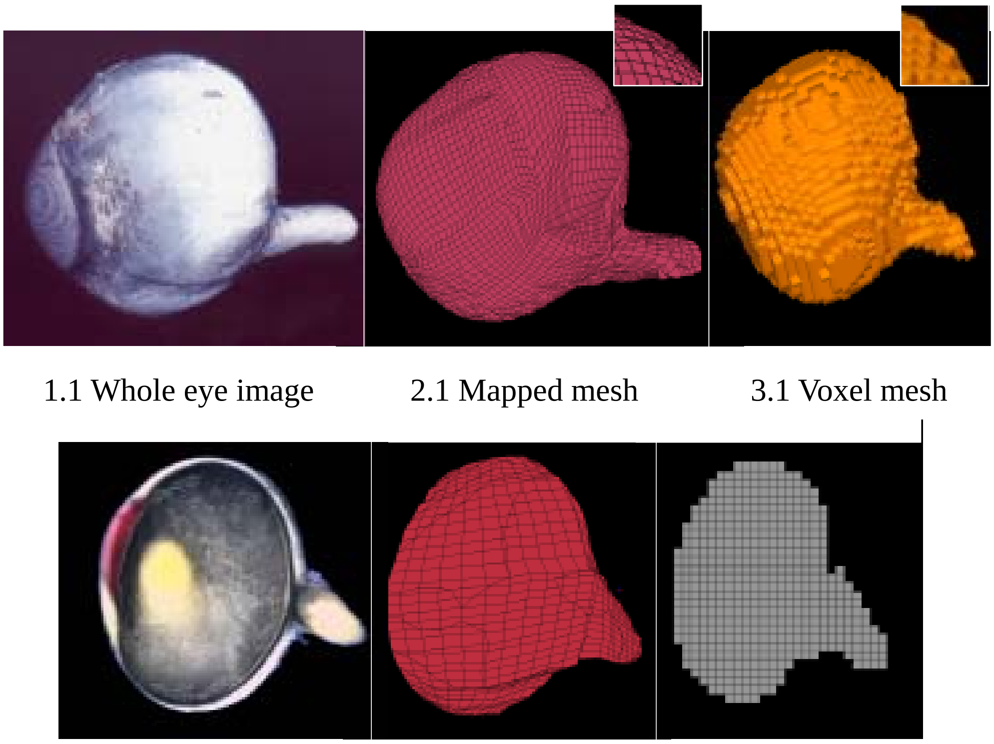
5. RESULTS AND DISCUSSION

We examined and compared the images created by the mapped and voxel mesh methods. The 3-D image data from 3D-ISM is shown to confirm the shape (Figure 5 a, b, c-1). The resolution of the image was XY: 127μm, Z: 90μm, and the size were 172x182x268 VOXEL. Figures 5 a-2, b-2 and c-2 show the hexahedral mesh generated by the mapped mesh method, the mesh being composed of hexahedral elements. It took about thirty minutes to make the mesh: the first three minutes to read the surface data, next twenty-five minutes to make the global block, and remaining time to generate the mesh. A shape comparison between the image data and mesh data shows good agreement. Figures 5 a-3, b-3 and c-3 shows the generated voxel mesh, this mesh consisting of cubic voxels. It took only about eight minutes to create this mesh, the first five minutes to read image data and the next three minutes to generate the mesh. The voxel mesh could be created more quickly than the mapped mesh.

Table 1 shows the number of elements used for the lens, cornea, and whole eye. In the case of the whole eye, the mapped mesh has 14,700 elements, and the voxel mesh has 14,296 elements, the number of elements being similar. However, the mapped mesh created a truer and smoother shape than the voxel mesh. Moreover the surface of the voxel mesh image is blurred by the mapped mesh data. It follows from this that if each model has a similar number of elements, the mapped mesh model better resembles the shape than the voxel mesh model.

Table 1 Number of Elements for Each Part

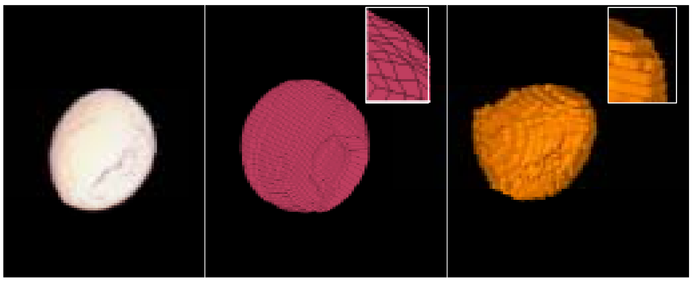
	Number of Triangles (Polygon)	Number of Elements (Mapped)	Number of Elements (Voxel)
Whole eye	1,912,512	14,700	14,296
Lens	198,522	4,782	5,196
Cornea	53,184	4,682	5,012



1.1 Whole eye image   2.1 Mapped mesh   3.1 Voxel mesh

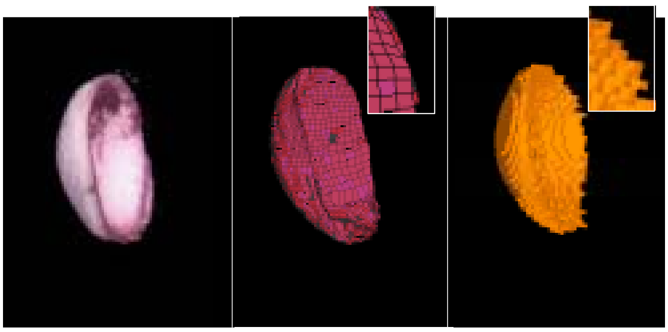
1.2 Cross-sectional image   2.2 Mapped mesh   3.2 Voxel mesh

a) Whole eye



1 Lens image   2 Mapped mesh   3 Voxel mesh

b) Lens

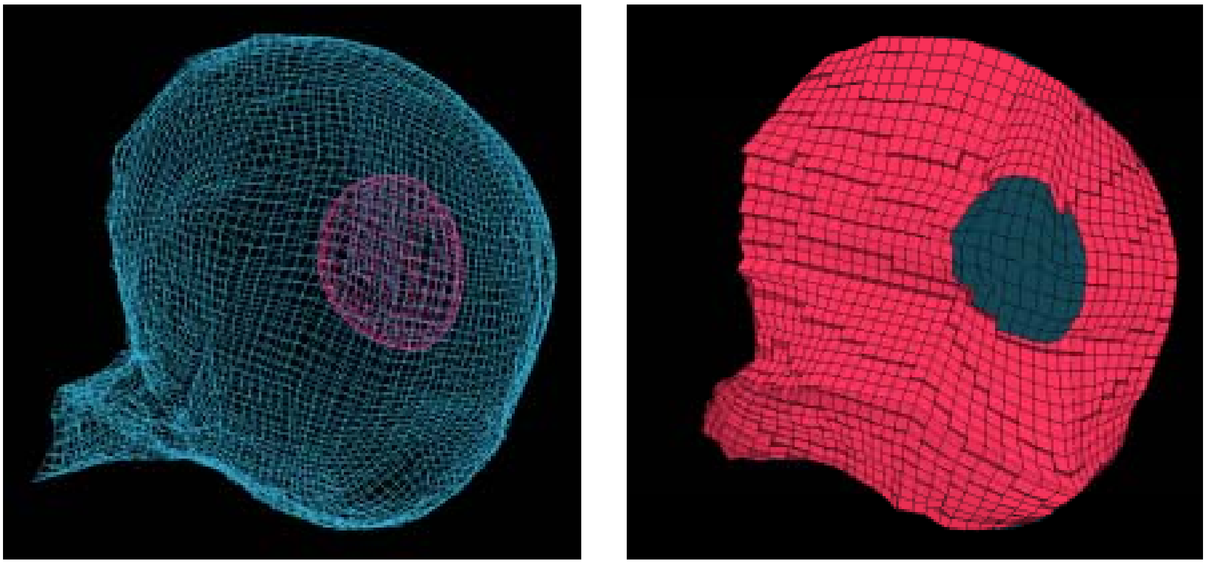


1 Cornea image   2 Mapped mesh   3 Voxel mesh

c) Cornea

Fig. 5 Mesh Images of the Eye Parts

Figure 6 shows the lens featured in the whole eye, indicating that the method can distinguish the lens from another part. This image has been created from a subdivided block and the whole eye and lens materials are assigned. The image has 32,260 elements, include 560 elements for the lens. All the element points of contact are connected and also connected tissue boundary, the lens and whole eye part. This result shows that it is possible to generate an FEM eyeball model and segment each part of the eyeball.



a) Whole view b) Cross-sectional image

Fig. 6 Lens in Whole Eye

If the model contains a membrane like the retina of the eyeball and has a complex shape, the FEM model requires a huge number of elements and a correspondingly long calculation time. In the case of the voxel mesh, for example, we accommodate the eyeball in a 3-cm-edge cube and form the mesh with a by 50-μm voxel size. This model has 300 million elements. On the other hand, if we generate the model by the mapped mesh method from the same image data, we can estimate the number of elements as 100 thousand. This is a much more compact data size than the voxel mesh model and the calculation time for analysis is shorter too. It follows from this that it is better to use the mapped mesh method than the voxel method to create the mesh for a sample which has a membrane tissue and a shape as complicated as the eyeball.

6. CONCLUSIONS

We studied the generation of a mesh from continuous sectional images that have full-color information by applying the mapped mesh method and voxel mesh method. After processing the image data, we used this data to generate a mesh. The mapped mesh method applied to data defining a small number of elements created a shape resembling the real image.

The mapped mesh data's all the element points of contact are connected and also the tissue boundary element points of contact are connected. The mapped mesh method is therefore considered effective for generating a mesh that reflects the real shape. In contrast, the voxel mesh image was blurred. Since a realistic model shape of the eyeball was required and a short analysis time is desirable for use in medical practice, we selected the mapped mesh method for our analysis.

7. FUTURE WORK

We will create a mesh from continuous sectional images of the human eye. And we'll also create all parts in one mesh data. Finally, a mesh quality will be improved to use our analysis.

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