Color Rapid Prototyping for Diffusion-Tensor MRI Visualization

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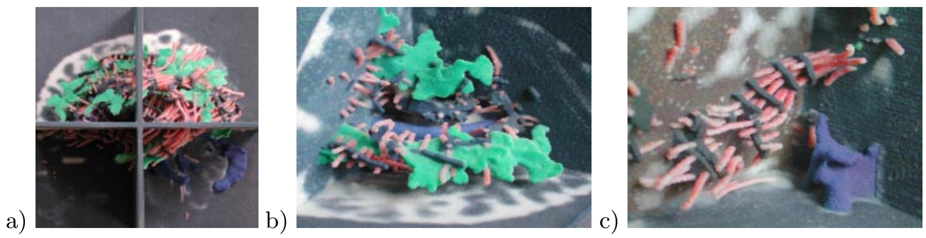

Fig. 1. (a,b) A plaster model showing areas of linear and planar water self-diffusion obtained from DT-MR images. (c) Detail of support structures (dark gray surfaces around tubes) for the streamtubes; these surfaces are created using the second and third eigenvectors of the tensors that produce the tubes.

We describe work toward creating color rapid prototyping (RP) plaster models as visualization tools to support scientific research in diffusion-tensor (DT) MRI analysis. We currently give surgeons and neurologists virtual-reality (VR) applications to visualize different aspects of their brain data, but having physical representations of those virtual models allows them to review the data with a very robust, natural, and fast haptic interface: their own hands. Our initial results are encouraging, and end users are excited about the possibilities of this technique. For example, using these models in conjunction with digital models on the computer screen or VR environment provides a static frame of reference that helps keep users oriented during their analysis tasks.

RP has been used in visualization largely for building molecular models to test assembly possibilities [1]. Nadeau et al. [4] created models of the human brain surface with the same RP techniques we use. Our approach, however, enables us to build inner brain structures.

1 Method

We examine the geometric models generated from a DTI dataset using tractography [5,2,6]. In our models, red streamtubes represent the diffusion in regions of linear anisotropy, where water diffuses primarily in one direction [6]. The streamtube direction represents the principal direction of diffusion along the tube. Studies show a correlation between the structures of neural fibers in white matter and the tracts derived from the principal direction of diffusion in linear anisotropy regions [3]. Green streamsurfaces are generated in regions of planar anisotropy, where water diffuses primarily in a small plane at any given point. These planar structures could result from crossing fibers or laminar structures [6]. In addition to tubes and surfaces, we show anatomical features for context: blue surfaces show ventricles, and the images on the three orthogonal planes show slices of T2-weighted images collected with DTI.

To create our color models we use Z-Corp's Z406 printer. The digital model, in VRML format, is subdivided into horizontal layers by the printer software. These layers are then manufactured by putting down a thin layer of plaster powder and dropping colored binder at the boundaries of the model at that level. Once all the layers are built, the powder outside the boundaries of the model is vacuumed out and loose powder is removed using a fine blower. Finally, the piece is bathed in hot wax to strengthen it and enhance its colors.

The structures in the DT-MRI models require very careful treatment. Because the long thin streamtubes often fail to support themselves during powder removal, we inserted some supporting surfaces that interconnect neighboring streamtubes without occluding interesting features. These supports are created from the second and third eigenvectors of the diffusion tensor that creates the streamtubes, so they are perpendicular by definition (see Figure 1(c)). We arrived at this methodology after several tests, including building thicker tubes and increasing their number so they supported one another. Using information already present in the DT-MRI data, we have been able to create models with better structural stability.

2 Results and Conclusions

These early stages of development have highlighted some important issues. For example, our visualizations involve organic, free-form shapes, whereas current RP technology is designed for models with more regular shapes, such as mechanical parts and molecular models. Also, the printing and cleaning process can take as much as 12 hours for complicated brain models measuring up to $8'' \times 8'' \times 10''$. However, our initial experiments suggest that this technology has the great advantage of exploiting users' familiarity with physical models: they recognize the utility of holding them in their hands when studying them. Providing scientists with these models enhances the use and analysis of their digital counterparts. To quote one of the doctors who experimented with these models: *"These physical models complement displays in digital format by providing a hard-copy frame of reference that can be touched and manipulated with optimum hand-eye coordination and immediate results."* We believe this type of physical model can be very useful in preoperative planning when used as a quick reference for structure identification.

3 Acknowledgments

DT-MRI data provided by Dr. Susumu Mori (Johns Hopkins U.) Support from NSF (CCR-0086065, CCR-0093238) and Human Brain Project (NIDA, NIMH).

4 References

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[5] R. Xue et al. MR in Medicine, 42:1123-1127, 1999.
[6] S. Zhang et al. IEEE TVCG, 9(4), 2003.

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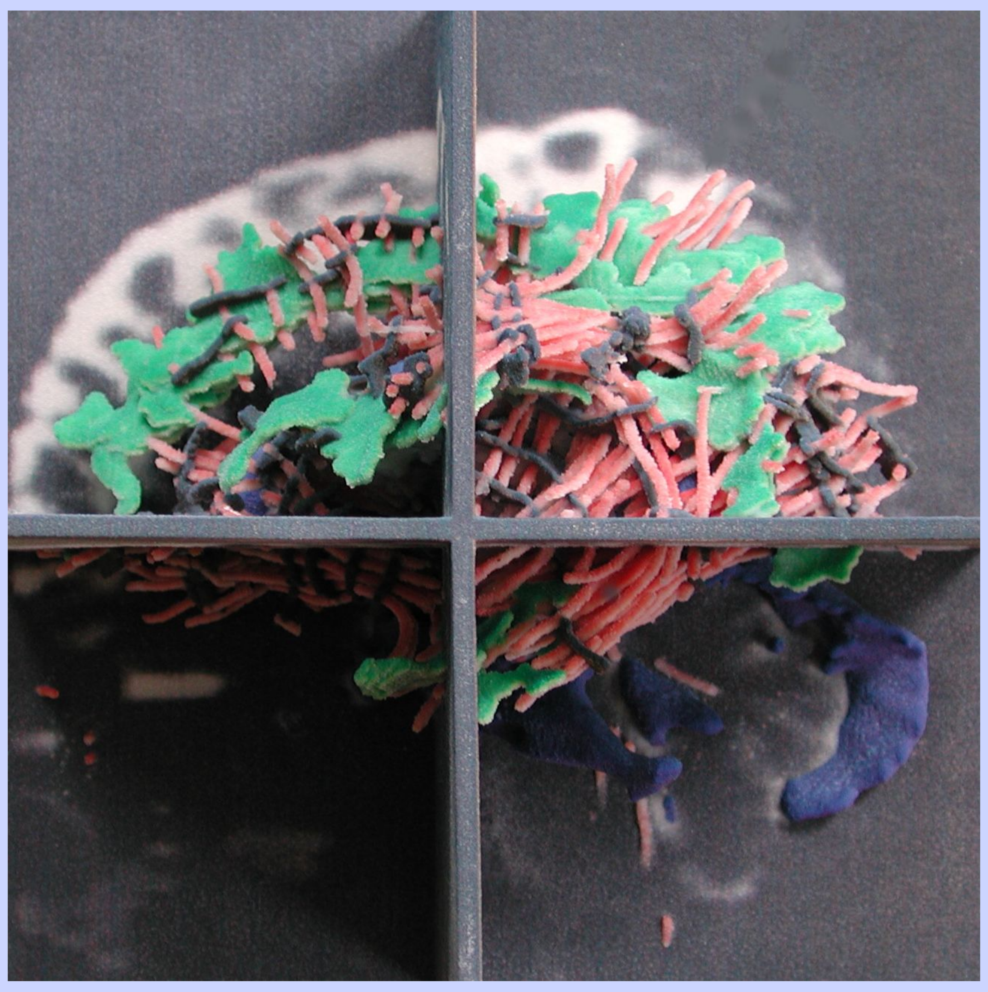
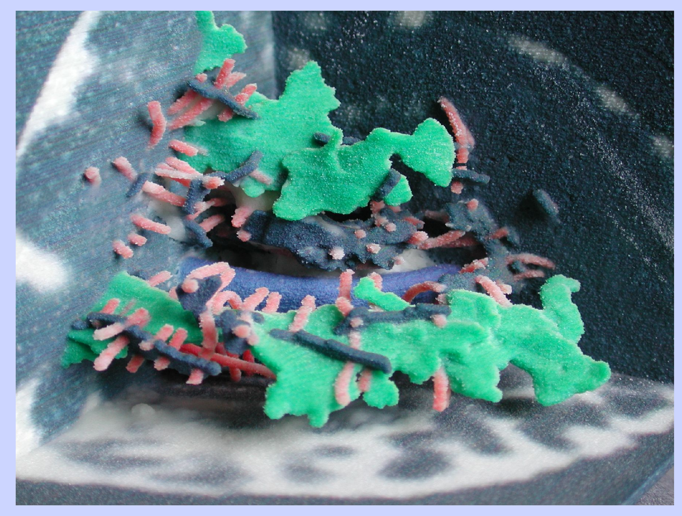
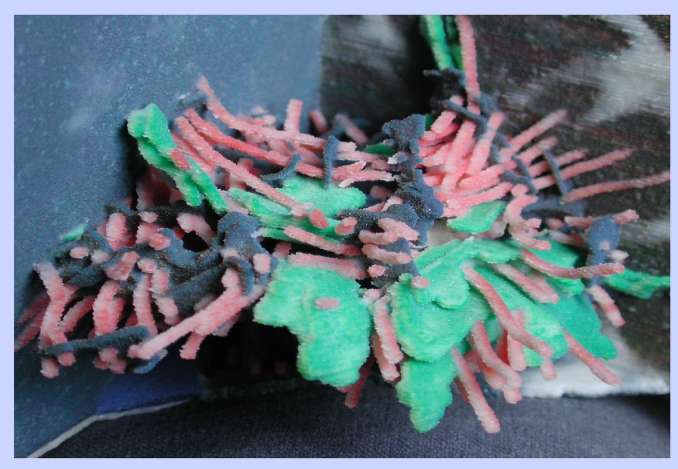
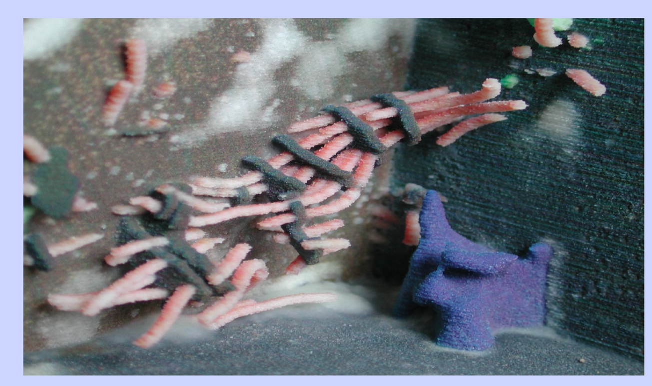






Overview

We examine the tractography-generated [5,2,6] geometric models derived from a DTI dataset. In our models, red streamtubes represent the diffusion in regions of linear anisotropy, where water diffuses primarily in one direction. The streamtube direction represents the principal direction of diffusion along the tube. Studies show a correlation between the structures of neural fibers in white matter and the tracts derived from the principal direction of diffusion in linear anisotropy regions [3]. Green streamsurfaces are generated in regions of planar anisotropy, where water diffuses primarily in a small plane at any given point. These planar structures could result from crossing fibers or laminar structures. In addition, we show anatomical features for context: blue surfaces show ventricles, and the images on the three orthogonal planes show slices of T2-weighted images collected with DTI. Because the long skinny streamtubes often fail to support themselves during the dust-removing process, we also insert some supporting surfaces that connect neighboring streamtubes together, shown as gray surfaces in the model.



Color Rapid Prototyping Strengths

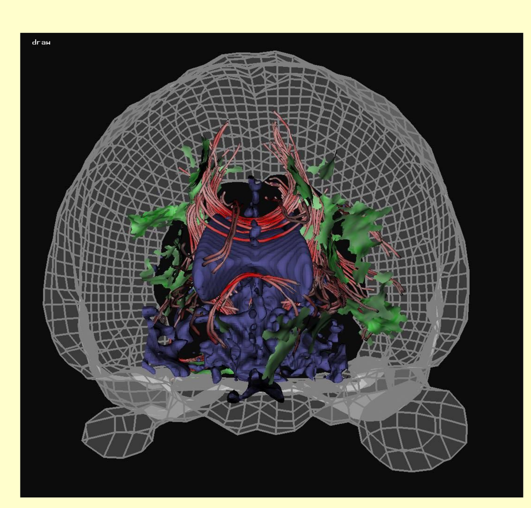
- Users are familiar with physical models and recognize the usefulness of being able to use the sense of touch in studying them.
- The data visualization is not dependent on computing power. The frame rate does not drop for more complex models.
- The use of color in these models enables us to provide scientists with more complete representations of their multi-variate data, compared with more common monochrome rapid prototyping.
- Providing scientists with these models leads to a better usage and analysis of their digital counterparts. One researcher said: "*These physical models complement displays in digital format by providing a hard-copy frame of reference that can be touched and manipulated with optimum hand-eye coordination and immediate results.*"

Issues using Rapid Prototyping

- We are using machines designed for other types of models, and we are building more organic, free-form shapes. The technology was not developed for these models and current materials don't support fragile structures very well [1,4].
- Since the pieces need to be structurally sound, the extra support needed might obstruct the view of the real data being visualized. Balancing these two factors takes many iterations of the printing process.
- One printout takes up to 12 hours for a complicated model of the brain.
- Texture mapping is not well implemented in the printing software.
- The maximum size of the models can only be 8"x8"x10". Larger models require tiling and assembling the pieces afterwards.
- Scaled models require extra cues to convey the correct scale.
- Changes in the data being visualized require a whole new model to be created.
- Color reproducibility is very hard with current technology. It does not always provide the same results when creating multiple copies of the same model.

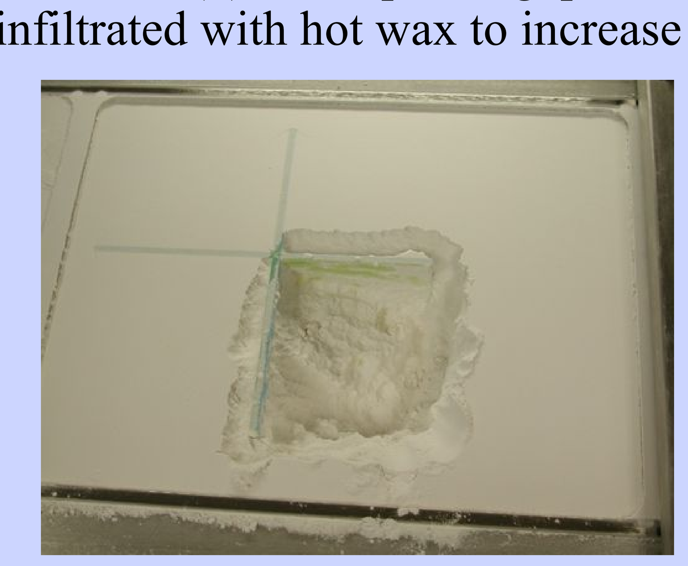
Contributions and Lessons Learned

- We have built physical three-dimensional color models as visualization tools to support scientific research in DT-MRI visualization.
- Due to the structure of the brain models we are building, extra support structures were needed to avoid their general collapse. These structures were built by using the 2^{nd} and 3^{rd} eigenvectors in linear diffusion regions.
- Scientists expressed interest in using the brain printouts as orientation aids when exploring digital models on the desktop and in the CAVE virtual reality environment (see pictures below).
- We have identified important issues in the application of rapid prototyping technology for building scientific models (see sidebar).



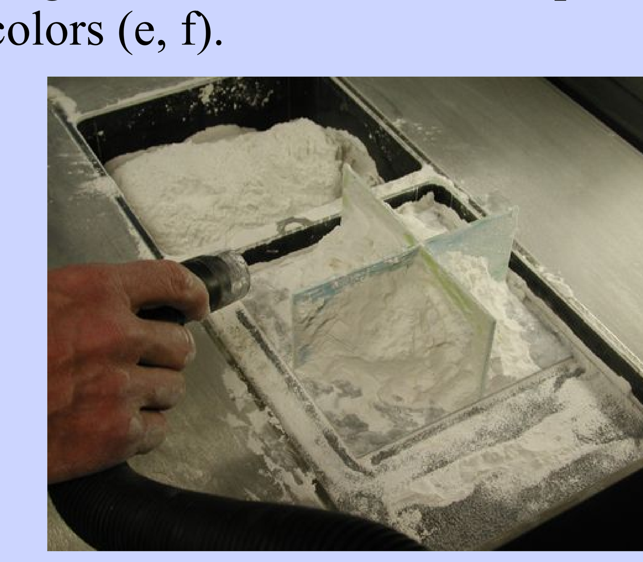
Our Printing Process

We are using Zcorp's Z406 printer. The digital model, in VRML format, is sliced into horizontal layers. The solid model is formed by putting down successive paper-thin layers of plaster powder and printing colored binder in the area described by the slice at that level (a). After the model is finished, the powder outside the model is vacuumed out (b,c). Then, using a fine blower, the loose powder in-between the final model is removed (d). The printing process takes about twelve hours. The cleaning takes two hours. The piece is infiltrated with hot wax to increase its structural resistance and enhance its colors (e, f).



a

b



c

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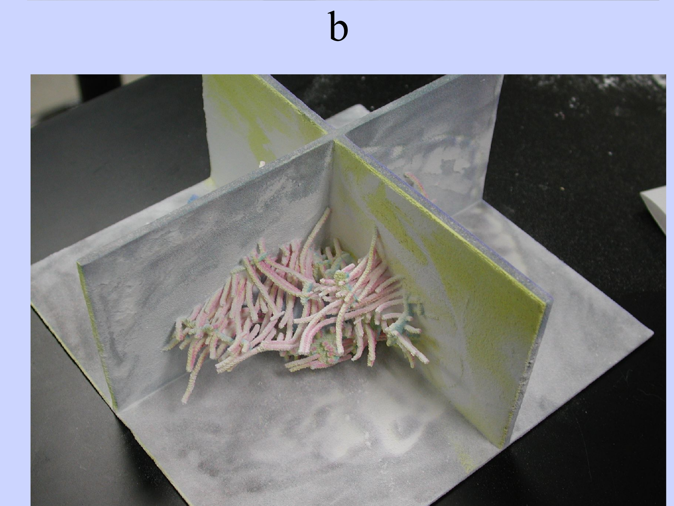
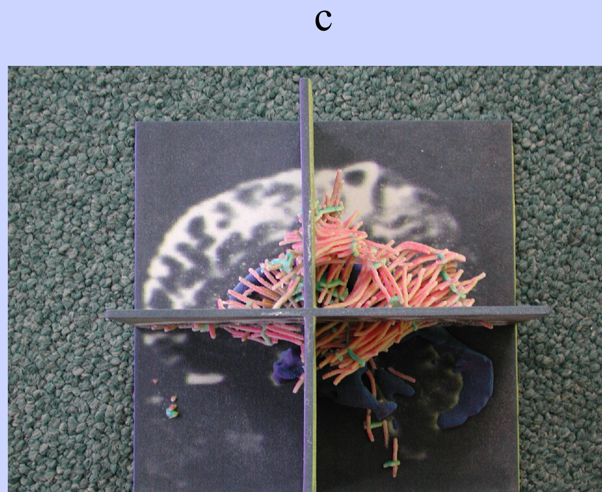


e



f

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Acknowledgments

DT-MRI data provided by Dr. Susumu Mori, from Johns Hopkins University.
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