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Medial & Medical: A Good Match for Image Analysis

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MIDAG at UNC is, at over 100 members, the largest and among the oldest medical image display and analysis research groups in the world. Our history and philosophy can be found in our guest editorial in IEEE *Transactions on Medical Imaging* [2003]. Around 30 of our members are graduate students, around 50 are faculty, and the remainder are postdocs, undergrads, and staff. We come from a half-dozen or so departments in the sciences and a half-dozen or so departments in the Medical School, collaborating in a scientifically and administratively seamless way. Our success derives from this collaboration of computer scientists, mathematicians, statisticians, physicists, and engineers with medical doctors from a variety of disciplines and biomedical scientists. We help physicians plan and deliver therapy, such as radiotherapy of tumors and both minimally invasive and open surgery. We help them provide diagnoses. We help biomedical scientists understand the processes of disease.

We develop and use methods across the gamut of image analysis and computer graphics: statistical pattern recognition, nonlinear diffusion, height ridge following, posterior optimization for deformable models segmentation, rendering, augmented reality, etc. We are concerned with images, whether using image analysis to understand them and make measurements in them or using computer graphics to produce them, and we place no boundary between these interrelated subdisciplines. We are driven by problems from mental disease understanding, neurosurgery, breast and abdominal surgery, radiation oncology, interventional radiology, radiological diagnosis, trauma care, and medical education. But perhaps what we are best known for in the *IJCV* community is analysis via medial models, whether it be of blood vessel trees, of anatomical objects of a well comprehended shape such as livers, kidneys, or hippocampi, or of ensembles of such objects, such as those forming the male pelvis, the abdomen, the subcortical brain, or the heart.

The one-letter difference in the words "medial" and "medical" has caused certain typographical confusions in the writings of MIDAG scientists. Their closeness ironically foreshadows the benefits of applying the medial form of object analysis to medical images (and other images, as well). In this editorial I will discuss the great advantages of medial models for problems of medical image analysis that UNC-MIDAG faces, as well as for non-medical applications.

This issue of *IJCV* is made up of 5 recent papers on medial image analysis. We in MIDAG have been doing research on medial geometry, medial representations, and medial algorithm development since around 1980. Our group's medial research began [Nackman 1985] with methods to extract medial representations from object boundaries. These were the approaches stimulated by Blum's pioneering work [1967] in medial shape analysis. The best of these methods, I judge, are described and compared in the final paper in this issue, by Kaleem Siddiqi from McGill University, Gabor Székely from ETH Zürich, and Steven Zucker from Yale University, together with two members of MIDAG, James Damon and me. I am honored that these accomplished scientists from other universities were willing that our paper appear in a special issue focused on work at UNC.

MIDAG's medial research moved from methods for transforming boundaries to medial representations to methods for extraction of medial representations directly from images by following height ridges of medial strength measures to produce *cores* (see the final paper in this issue). Though we are still working on cores [Aylward 2002, Fridman 2003], in the last seven years we have featured methods in which a medial representation was deformed into image data.

This change of focus resulted from a realization that it is constructive for researchers in *image analysis* to consider this name a misnomer: we should see ourselves as being in *real world analysis* with images as evidence. Certainly in medicine, we are about helping patients' health, not about analyzing images for their own sake. That is, we are helping the physicians or biomedical scientists understand the biological real world of the patient's anatomy or physiology. To do real world analysis, we need models of the real world, and that is where medial models are so useful. Images are evidence about the anatomy or physiology, and this spatial evidence needs to be taken in relation to the spatial layout of the anatomy of the particular patient, i.e., relative to our models of the world. Medial models have special strengths in providing object-relative coordinates in which to consider these image intensities. Besides the information in an image, information on the objects is available on the prevalence of certain geometric conformations in the real world, within a class, e.g., healthy patients or patients with a particular disease. Medical real world analysis from images thus depends on both descriptions of the real world geometry and probability functions on these geometric descriptions. Medial representations have a special role in describing this geometry and its probability. To explain this role, we chose to use the word *figure* to describe the solid region associated with a single, smooth, non-branching medial sheet. The discussion here is primarily in 3D, with corresponding 2D properties sometimes included in parentheses.

From the beginning discussion of medial models for image analysis by Harry Blum, it was intuitively obvious that they provided important opportunities of subdividing objects into positive (protrusion) and subtractive (indentation and hole) figures and of dividing geometric transformations on these objects into widening/narrowing, bending/twisting, and elongation. However, over time medial analysis got a bad name among image analysts for a number of reasons. First and foremost, when starting from a boundary and trying to achieve a full medial description at all levels of scale, it is distressingly sensitive to boundary details and thus to image noise. Second, and related to the first, much of each branch of the medial locus describing protrusions and even quite small boundary pimples account for very little of the volume (area in 2D) of the object. Third, medial analysis had a sensitivity in locating the important positions of object boundary crests (vertices in 2D), or equivalently, medial locus ends, due to the fact that the angle between the spokes from the medial point to the two associated sphere bitangent points on the boundary moves to zero with infinite speed as that medial endpoint is approached. Fourth, it was not understood how to correctly derive the object boundary from a discrete representation of the medial locus. Fifth, the 2D medial sheets from a 3D object degenerated into 1D loci for a tube and even a 0D locus for spheres, and as objects transformed in a 1-or-more parameter family, they might pass through such singular cases.

Rather than give up the apparent advantages of the medial representation, we believe that we have solved these problems, provided some mathematical understanding of this representation, and extended the opportunities by the following additions to the medial apparatus:

1) **Medial atoms: hubs with spokes.** What Harry Blum saw intuitively, that geometric transformations on objects could be decomposed into widening/narrowing, bending/twisting, and elongation, we made real (see Fig.1) by adding to the medial hub and the associated radius of the bitangent sphere, the spokes from the hub to the boundary bitangent points; thus we associated a frame and a metric to the medial origin to produce a medial atom and transformed the medial locus into a manifold (with boundary) of medial atoms, and we saw the atom as producing a full local coordinate system for points in and near the figure. They described the relation between atoms not only in terms of position but also in terms of orientation and size. Moreover, these atoms swept out the volume of the object; they modeled the object interior, not just the boundary. The object descriptions using medial atom meshes easily extend to topologies other than branching slabs, such as branching tubes, cyclic topologies such as bagels, etc.

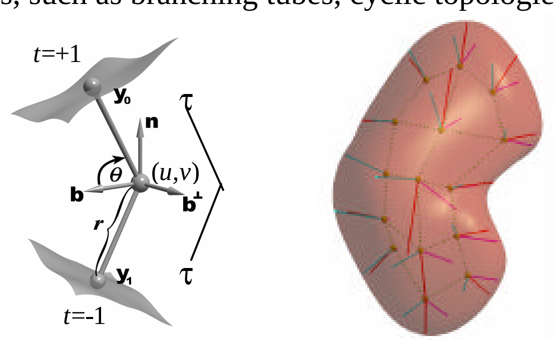

Fig. 1. Left: a medial atom with its figural coordinates and implied boundary section. Right: a kidney represented by a discrete grid of medial atoms, sampling a continuous sheet of medial atoms.

2) **Medial primitives imply a boundary.** It was clear to all that extracting the medial locus from the primitive boundary was an unstable transformation at small scale. We noted that it followed that the inverse operation had to be extraordinarily stable. Thus, while in stable situations of high contrast going from the boundary to the medial manifold was possible, as realized most effectively by Kimia, Zucker, and Siddiqi, going from the medial manifold to the boundary was the preferred transformation. Consequently, one wished to describe geometry by a base medial locus that should be deformed to produce a boundary. As a result, the wonderful singularity theory of the transformation from the boundary to the medial locus culminating in the work of Giblin et al. required an addition of the mathematics of the transformation from a locus of medial atoms to the object interior and thence to the boundary. James Damon of UNC-MIDAG, a noted singularity theorist in his own right, produced that mathematics [2002, 2003]. All this allowed fitting a medial description into an image, just as others using deformable boundary models fit their models into images.
3) **Boundary-attached subfigures.** We saw the instability of subfigures interrupting main figures' medial loci as an impediment. Others had noted that major medial locus sections of these subfigures were responsible for little volume, and we associated this fact with the instability. Thus we redescribed protrusion and indentation subfigures as additive and subtractive figures riding on the implied boundary of a host figure. This description required developing a means of

blending the seam of a subfigure with its host figure [Thall 2003], an idea that we inherited from computer graphics.

4) **End atoms.** We saw the importance of figural ends, which correspond to crests on the implied boundary. But we noted not only their instability as the end was approached but also the instability of deriving them from but a point of the image information on which they depended. Thus we invented a new representation called *end atoms* for figural ends that was designed to be stable in both of these senses. To be stable, this description needed to avoid the infinitely fast collapse to zero of the angle between the medial spokes, so it could allow only a subset of the types of ends generally allowed. At the same time, it needed to be consistent with the description used for the interior portion of the medial manifold. We therefore cut off the interior description while there was still a significant angle between the spokes and insisted that the Blum medial axis of the end portion continue straight from the place where the interior description stopped. We provided the end atom with a parameter of crest sharpness additional to the parameters of the interior medial atoms, thus allowing crests of arbitrary sharpness and even corners.
5) **A figural coordinate system.** Figures with interior medial atoms and special end atoms yielded a natural medially based coordinate system for the whole interior and near exterior of figures. We also designed a coordinate system for the blend region between a host figure and its subfigure that was consistent with the two figural coordinate systems of the respective figures. This medially based coordinate system supported transformations of subfigures while remaining attached to their hosts, by considering the transformation in the host's figural coordinate system. It also allowed considering the relation between nearby and possibly abutting figures by considering the boundary of one in the figural coordinate system of the other. Most importantly, it provided a useful positional correspondence across object or object ensemble instances that is necessary to summarize classes of individuals statistically and to describe changes within an individual across time.
6) **Multiscale object descriptions; marriage with deformations at small scale.** The sensitivity of a medial description at small scales but its important strengths at large and moderate scales made us realize that a full geometric description should be medial at large and moderate scales but needed to be combined with a nonmedial means of describing small scale spatial deformations. We call these multiscale descriptions *m-reps*. Choosing their scale levels as object ensemble, object, figure, medially described figural through-section, and small scale spatial deformation, all interrelated via a medially based coordinate system, was driven by the need to understand anatomy at many user-relevant levels of spatial scale. Inspired by the Laplacian pyramid and the wavelet, we invented the notion of medially based geometric residues at one scale from the description of a structure at the larger scale levels.
7) **Medial descriptions of object populations.** Medial descriptions were originally designed to describe a single object instance, but we have seen that they have special strengths in describing a population of objects or object ensembles that have a common medial structure of separated, branching, and interacting manifolds with boundary. The recent advance of Fletcher et al. [2003] in seeing a medial description as a point on a Lie group of geometric transformations and seeing statistics of objects by finding means and principal geodesic components of these points on this Lie group has been particularly important in providing such statistics of object or object ensemble geometry. Also important are the advances of Lu et al. [2003] in building multiscale models of objects and object ensembles via medially based residues and then deformation residues using Markov random field approaches applied to a model of fixed structure. These approaches allow coarse to fine segmentation and statistical characterization from training sets

with only tens of cases, but they beg the question of how to build a stable common medial structure from a population, even though the small-scale medial structure of the Blum medial locus varies across the members of the population. This question is dealt with in the paper of Styner et al. in this issue. The resulting probability distributions can be used not only as priors for posterior optimizing segmentation methods but also to probabilistically characterizing geometric differences between populations of objects, giving both user-intuitive descriptions of the differences and their locality. Methods for doing such description of geometric differences in populations have been developed in our group by Yushkevich [2003] and by Gerig et al. [2003], with applications to the study of the effect mental diseases have on brain structures. Since these methods are limited to populations of object ensembles that all have the same objects in the same interrelation structure and each with the same branching structure, Wang [2003] in our group began to develop statistical methods to describe populations of objects with variable branching structure.

Deforming medial models is a very effective approach when the medial branching structure is consistent or includes just a few types within a population. Accomplishing such deformation as a means of segmentation by posterior optimization is described in the first paper in this issue. Also of interest in MIDAG is deformation via finite element mechanical models with multigrid meshing based on medial models [Crouch 2003]. However, there are many cases, such as various blood vessel trees, where the structure is so variable across a population that one wishes to extract the medial structure with a less constrained medial model. In the blood vessel example, one may use the knowledge that the structure is a tree of tubes. Methods going from boundary or from an image to medial locus are applicable here. An important class of these methods for tubular trees has been developed by Aylward and Bullitt [2002] in MIDAG. The paper by Aylward et al. in this issue applies these medial segmentations to registration of images via their blood vessel trees.

When extracting a curvilinear medial model, either of a boundary in 2D or of tubes in 3D, the complex branching that can result makes one face the question of which branches are continuations of another section of object (form a “limb”) and which are the branches from the limb. This is the question addressed in the paper by Katz et al. in this issue.

I conclude this editorial by a summary of the usefulness of medial representation of objects and object ensembles and of the challenges left to be dealt with. Medial representations augmented by a small scale deformation are a powerful alternative to other useful object representations: landmark sets; boundary representations, whether as a set of points, a tiled surface, or an orthogonal function decomposition; and displacement vector fields from an object-labeled atlas of voxels. In the forms described earlier what are the relative strengths of medial representations? They directly represent the object interior and allow an efficient calculation of the object boundary. They provide rather good correspondences in and near that interior via their figural coordinate system. They support a multiscale representation, thus providing efficient segmentation, statistical characterization with locality based on limited training sets, and object descriptions at any of a choice of spatial scales: global scale down to small scale. And, augmented by small scale deformations of the boundary or of the object interior, they describe object geometry in terms intuitive to users of image analysis; for medical applications this means objects are described in terms of figures that have anatomic names and through deformations that correspond to anatomically reasonable changes.

There is much more research to do to make medial models achieve their great potential. The following lists many of these challenges:

1) To do more validations of medical image analysis applications of our medial models. For MIDAG the measure of success of a technical development lies in its medical usefulness. While we have shown the effectiveness of medial modeling for certain segmentation, registration, and statistical shape characterization tasks for medical application, much more validation in terms of these uses remains to be done.
2) To improve the figural coordinate system a) to reflect the shape of the medial sheet, b) to improve the correspondences across objects to produce effective statistical descriptions, and c) to extend the coordinate systems of individual objects to the space between objects.
3) To use these coordinate systems in studying probabilities on images, i.e., on image intensity distributions.
4) To provide the multiple medial scale levels that are probably necessary to adequately characterize figural shape.
5) To provide a method to generate probabilities on populations of objects with variable medial branching structure, by themselves and in combinations with objects of fixed branching structure. This will allow the combined analysis of organs and the blood vessels that course within them.
6) To provide a method to generate probabilities on populations of objects with multiple modes.
7) To describe objects as they vary in time, i.e., to produce spatiotemporal medial geometry.
8) To deal with families of objects or object deformations that pass through singular cases of tubes or spheres.
9) To build the dense atlases of various parts of the human body, describing means and variabilities of geometric residues at many scales, that will provide many uses: segmentation, statistical characterization of the geometric effects of disease, and education, among others.
10) To build statistical descriptions of image intensities in multiscale residue terms consistent with the multiscale geometric residue descriptions based on medial models and small-scale deformation.
11) To combine figural geometry and Euclidean geometry to describe heavily folded objects in the human, such as the cerebral cortex and the intestine.
12) To use probability distributions on complexes of medial atoms for object recognition.
13) To apply m-reps to non-medical applications. Medial models have been shown useful for a variety of objectives, and extending the improved medial models to such image analysis objectives as segmentation of manufactured objects, their statistical geometric characterization, their mechanical modeling, and their object recognition and to such applications as morphing for animation, image-based rendering, and design of manufacturable objects and art objects seems very promising.

References

Aylward, SR, E Bullitt (2002). Initialization, Noise, Singularities, and Scale in Height Ridge Traversal for Tubular Object Centerline Extraction. IEEE Transactions on Medical Imaging, **21**(2): 61-75.

Blum, H (1967). A Transformation for Extracting New Descriptors of Shape. In W Wathen-Dunn, ed., *Models for the Perception of Speech and Visual Form*. MIT Press, Cambridge, MA: 363-380.

Crouch, JR, SM Pizer, EL Chaney, and M Zaider (2003). Medially Based Meshing with Finite Element Analysis of Prostate Deformation. Proc. MICCAI 2003, to appear.

Damon, JN (2002). Determining the Geometry of Boundaries of Object from Medial Data. UNC Mathematics Department Technical Report.

Damon, JN (2003). Global Geometry of Regions and Boundaries via Skeletal and Medial Integrals. UNC Mathematics Department Technical Report.

Fletcher, PT, C Lu, S Joshi (2003). Statistics of Shape via Principal Geodesic Analysis on Lie Groups. CVPR 2003, **I**: 95-101.

Fridman, Y, SM Pizer, S Aylward, E Bullitt (2003). Segmenting 3D Branching Tubular Structures Using Cores. Proc. MICCAI 2003, to appear.

Gerig, G, KE Muller, EO Kistner, Y-Y Chi, M Chakos, M Styner, JA Lieberman (2003). Age and treatment related local hippocampal changes in schizophrenia explained by a novel shape analysis method. Proc. MICCAI 2003, to appear.

Lu, C, S Pizer, S Joshi (2003). A Markov Random Field Approach to Multi-scale Shape Analysis. Scale Space Methods in Computer Vision (Scale Space 2003). LD Griffin and M Lillholm, eds. Lecture Notes in Computer Science **2695**: 416-431.

Nackman, LR, SM Pizer (1985). Three-dimensional Shape Description Using the Symmetric Axis Transform, I: Theory. *IEEE Trans. PAMI*, **7**(2):187-202.

Pizer, SM, G Gerig, S Joshi, SR Aylward (2003). Multiscale Medial Shape-Based Analysis of Image Objects. Invited Proc. IEEE paper, to appear.

Pizer, SM (2003). The Medical Image Display and Analysis Group at the University of North Carolina: Reminiscences and Philosophy. IEEE Transactions on Medical Imaging, **22**(1): 2-10.

Thall, A (2003). Deformable Solid Modeling via Medial Sampling and Displacement Subdivision. UNC Computer Science Dept, Dissertation to be defended August 2003.

Wang, H (2003). Functional Data Analysis of Populations of Tree-Structured Objects. UNC Statistics Dept, Dissertation.

Yushkevich, PA (2003). Statistical Shape Characterization Using the Medial Representation. UNC Computer Science Dept, Dissertation.