Image-Guided Interventions: It Takes A Village…

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Legacy Constraints

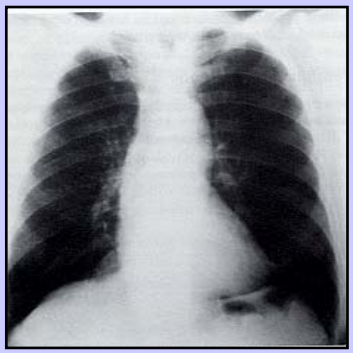
Overcoming the “mental reconstruction” dogma

3D (4-5D) images provide quantitative and essential information not available from serial 2D images alone

PICTURE, n.

“A representation in two dimensions of something wearisome in three.”

- The Devil's Dictionary by Ambrose Bierce

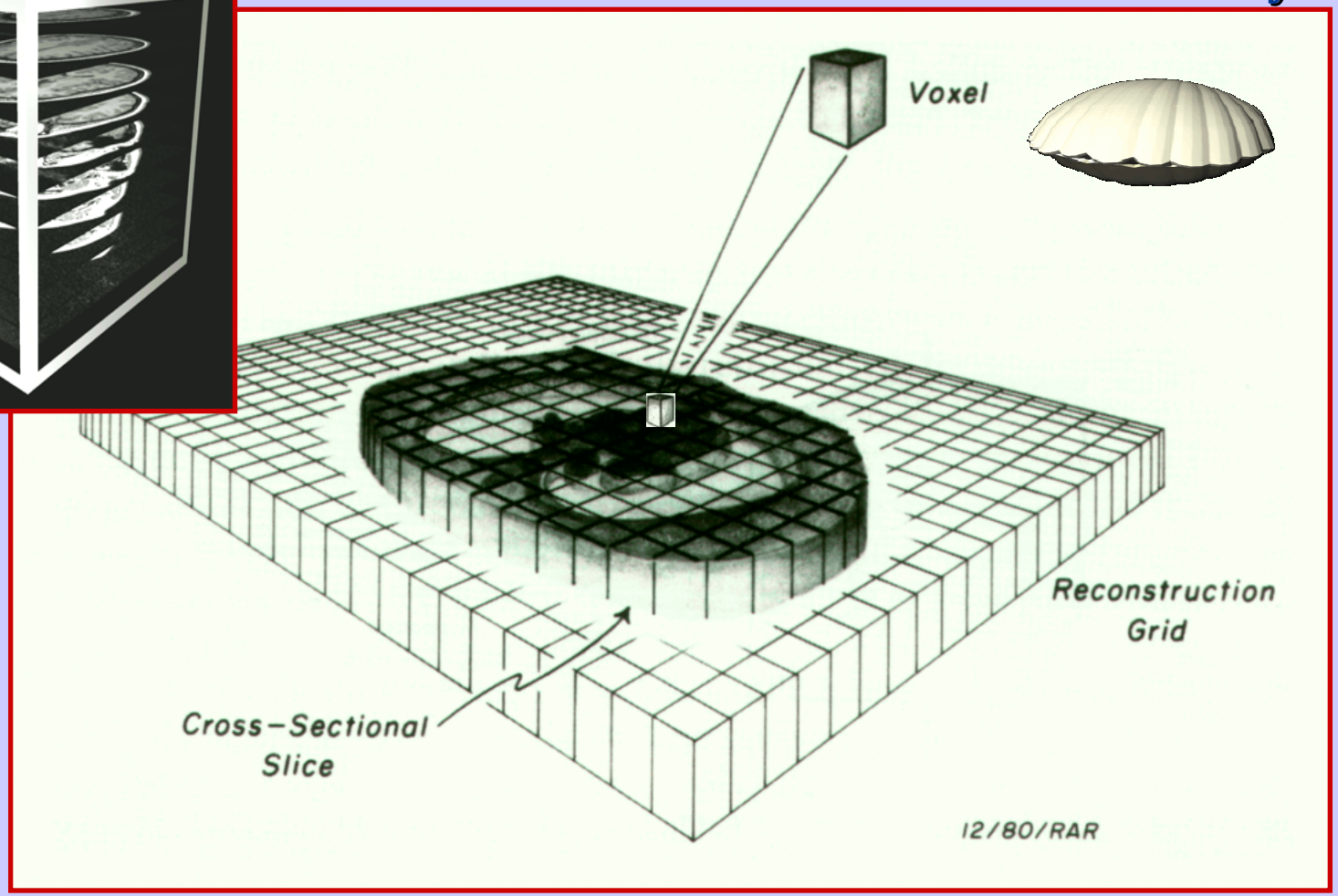


?

DON'T FORGET THE PIXEL (VOXEL) !

"Errors, like straws, upon the surface flow; He who would search for pearls must dive below."

- John Dryden



Human Imaging Challenge And Promise

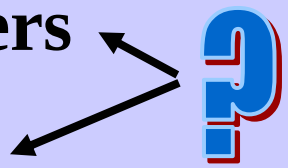
- **Body structures & functions are integrated and interdependent**
- **Body structures & functions range over orders of magnitude in size and time intervals, respectively**
- **Body structure-to-function relationships are generally continuous through scale space, but that space is sparsely sampled currently**
- **Accurately quantifying and correlating these relationships will advance biomedical knowledge and understanding, promote health and long life, enhance specificity of diagnoses and increase effectiveness of treatment**

Outline

- Definitions 101
- What's The Real Problem?
- Potential Solution Space
- How To Facilitate Multidisciplinary Collaboration
- Barriers To Interdisciplinary Collaboration
- Technology Advances Needed Next 5-10 Years
- Common Image Processing Requirements
- Clinical Examples of Image-Guided Interventions

Definitions

- **IGI: Intrinsically multi/inter-disciplinary**
  - **Image: 2D>5D, anatomy, function, chemistry…**
  - **Guide: Diagnose, Stage, Plan, Treat, Monitor**
  - **Intervention:**
    - **Invasive - e.g., open body surgery, chemotherapy?**
    - **Minimally-invasive - e.g., biopsy, laparoscopy?**
    - **Non-invasive – virtual endoscopy, radiotherapy?**
- **Village: Team science and Team practice**
- **Collaboration: Multi/Inter-Disciplinary, Synergism**
- **Facilitate: Enable, Sustain, Overcome Barriers**
- **Barrier: Block, Impede, Prevent Facilitation**
- **Technology: Machines, Methods, Models**



What Are The Problems (Challenges)?

- **Improved Outcomes: Cure, Morbidity, Errors, Cost**
  - **Sensitivity, specificity, reproducibility, false positives and negatives**
- **Status Quo: resistant to change, adoption of innovation**
  - **De facto requirement that new technology must significantly exceed/advance current practice**
- **Only successful systems are highly customized**
  - **Simple robot (laparoscopy assistant)**
  - **Image-guided radiotherapy**
  - **Stereotactic breast biopsy**
- **Ability to reuse or disseminate experience**
- **Single-center approach to high end requirements**
- **Overcoming inertia of many types**
  - **Administrative, regulatory, insurance payers, early adopters, consumer**

Some Common Tasks To Solve*

- Extraction of geometry from images; subvolume segmentation; tissue classification
- Visualization of instruments in context; multimodality registration; image to patient registration; instrument tracking
- Target definition (detection and quantification)
- First guess treatment plan
- Plan optimization
- Plan verification and validation

*Amenable to automated or semi-automated solutions

Solution Space

- Team science & practice: multi/inter-disciplinary
- Effective Communication, language syntax & semantics
- User interfaces, standards, common components
- Acceptable latency, highly interactive, near real-time
- More performance, with lower cost, less complexity, increased ease-of-use, automated as much as possible
- Open software* and middleware** foster collaboration – multiple centers should take the lead in persistent virtual infrastructure for IGI
- Focus on major effect – Detect/treat prevalent diseases in early stages, collaborative science, reduction of operator variability, minimize medical errors

*Shared source code development and **software or products that connect two otherwise separate applications or serve as the "glue" between two applications

More On The Village…

- Teams vs. teamwork (the village sleeps?)
- Allocation of work – complementary, fair, productive
- Sharing success AND failure, IP, publications
- Professional jealousy, mistrust. imperialism
- Intramural vs. extramural
  - Intramural: (-) harder (no “prophets at home”, walls- silos-turf, sufficient time); (+) history of collaboration, common goals, complementary knowledge/skills, intellectual reserve
  - Extramural: (-) communication, admin. policies, sharing, funding; (+) richer complements possible, less “competition”(?), Internet 2, Grid, teleconference

3 Issues*

1. **How Do We Facilitate Multi/Inter-Disciplinary Collaboration in IGI?**

2. **What Are The Barriers To Such Collaboration?**

3. **What Technology Developments Are Required To Advance IGI in the next 5-10 years?**

** Will include some findings relative to these issues from joint NIH-NSF Workshop on IGI held in 2002.*

1. Facilitate

- **Remove the Barriers (too easy - see next issue)!**
- **Increase and Bias Funding Toward Real Collaboration**
  - **More Team Flexibility, Variety, and Involvement**
    - **Allow/Require Joint PIs (e.g., scientist/engineer & physician\surgeon)**
    - **Unfettered discretionary funds for unforeseen needs, breakthroughs**
    - **Connect & supplement already funded R01 grants into partnership grants**
    - **More funds for inter-institutional meetings (e.g., travel, video-conferencing)**
    - **Educational workshops to inform and cross-train (focused on IGI)**
    - **Encourage consortiums by special supplements for indirect costs**
    - **Support more research-oriented clinicians and clinical-oriented engineers**
    - **Establish young investigator awards especially for cross-training**
    - **Do not fund requested TO-BE-NAMED positions**
    - **Do not fund requested individual effort under 10%**
  - **Reward Successful Past Collaborations**
    - **Past successful PPGs and BRPs, etc. (science must remain competitive)**
    - **Provide longer funding periods for successful collaborators**
  - **Restructure the SBIR/STTR programs**
    - **Fund prototypes languishing in the "valley of death"**
    - **Promote/require <u>both</u> inter-company and inter-institutional partnerships.**
- **Better Matching of Real Problems to Promising Solutions**
  - **Clinician may not need fancy device or elegant math to solve problem**
  - **Engineer must understand clinical workflow and routine tasks in practice**
  - **Both should work together to learn fundamental language of the other**

2. Barriers

- Communication (both syntactic and semantic)
  - Between/among people, institutions, systems, components
  - Education, advertising, market channels
- Lack of cooperative and/or credible champions
  - Need joint, strong clinical and engineering/science advocates
  - Insufficient time for clinicians, insufficient support for engineers
  - Personality/aspiration clashes, non-complementary knowledge/skills
  - No history, career building, publishing, sharing the credit, intellectual property
- Validation and proof of benefit
- Regulatory pipeline, administrative inertia
- Geography and time
- Cost (basic science, prototyping, clinical trials, marketing)
- Complexity of performance and use
  - operator training, variations in normal anatomy, no easy reuse of experience
- Lack of standards, normative databases, common platforms

3. Technology

- Bridge the tech transfer chasm (“valley of death”), early adoption
- Robust validation, careful calibration, clear benefit demonstration
- Adapt inter-agency advances (NIH, NSF ,NASA, DARPA)
- Manage cost, expectations and consumer education
- Standardize volume anatomy and function imaging
- Promote multimodality image fusion and integration
- Increase resolution, speed, accuracy, ease of use
- Decrease motion artifact, latency, risk, morbidity
- Friendly interfaces, automated tasks, interactivity
- FDA “lighten up a bit”, NIH “tighten up a bit”
- Integrate imaging with treatment devices
- Programmable devices and procedures (scanners, protocols)
- Smart devices navigate safely, find highly specific targets
- Match better solution to problem (“swat the flies, hammer the nails”)

Possible Next Steps

- Translate requirements into specifications
- Verify that specifications are achieved
- Clinical applications must guide new development
- Validate the new clinical applications
  - Both performance and benefit
- Establish inter-institutional collaboration within a persistent infrastructure (e.g., national grid)
- Move limited series of IGI units into test phase
- Establish an evaluation consortium; educate users
  - Common experimental platform replicated at several sites; plug ‘n play components exchanged; standard procedures followed to document benefits
- Institutional buy-in through funding incentives
- Incrementalism is rewarded by regulatory authority; include FDA in the development cycle

On Technology Transfer

Considerations For Successful Routine Applications

- Based on relevant needs & expectations
- Improves outcomes &/or reduces risk
- Computationally & procedurally safe
- Accurate, reliable, easy to use
- Modular, extensible, portable
- Maintainable & supportable
- Scientifically & clinically validated
- Cost/Benefit analysis, justification

On User Interface

- Often most neglected, least optimal component of a system, including IGI
- Should be familiar and consistent with current practice (e.g., image types)
- Tailored to application, provides needed context and relevant functions
- Present “new” real time images in context, screen real estate is valuable
- Interactivity a must, simple or automated processes desirable, user override
- Can overload the operator – KISS principle especially for busy clinicians
- Interface design must be carefully organized/managed, frequent reviews
- Needed steps:
  - Application analysis: required functions & response time, data source(s) & characteristics, user profiles, etc.
  - Dialog design: virtual world/space, interaction, metaphors, navigation, transformations, macros, etc.
  - Graphic design: screen layout, menus, color, typeface, interactive elements, sound, animation, etc.
  - Iterative prototyping: implement, test, get user feedback, evaluate, change/fix, repeat cycle
  - Usability evaluation: iterative testing, evaluate outcomes, user satisfaction, goal(s) achieved

On Validation

Objective Factors

- Sensitivity & specificity
- Reproducibility
- False positives & negatives
- Conform with standards
- Time and cost for procedure
- Outcome (survival, morbidity)

Subjective Factors

- Physician acceptance
- Patient acceptance
- Government acceptance
- Insurance company acceptance
- **Exclusivity (unique merits)**

Promising Technologies

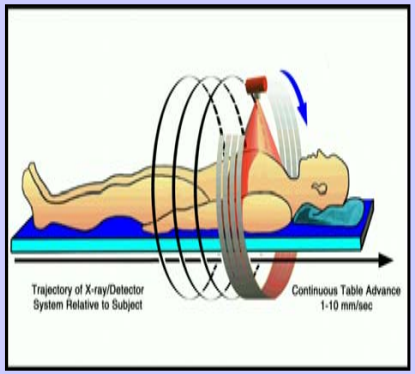
- **Optical, Nuclear, CT, MR, US**
  - **Especially combined modalities**
- **IGI treatment planning & simulation**
- **Synergistic contrast agents and instruments (sensors/effectors)**
- **Open source and collaborative science infrastructure**

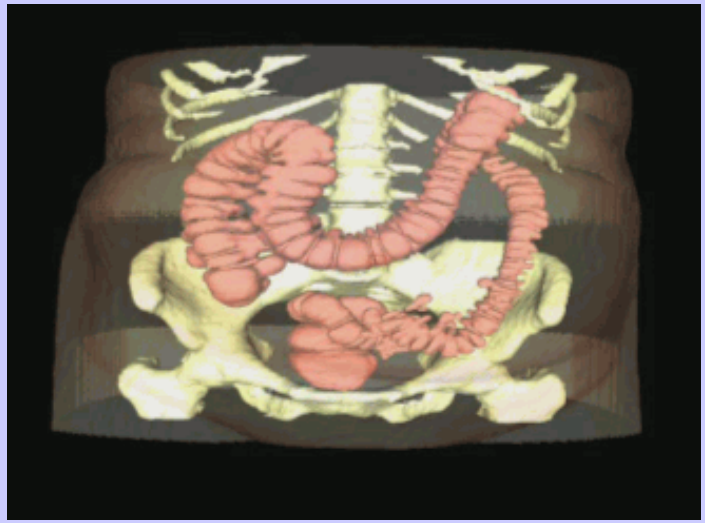
Molecular Imaging

- Biomedical imaging plus genomics
- Imaging molecular alterations that are the basis of disease rather than merely observations of pathological effects
- Imaging of selective gene expression
- New markers for early disease detection
- Specific markers for therapy assessment

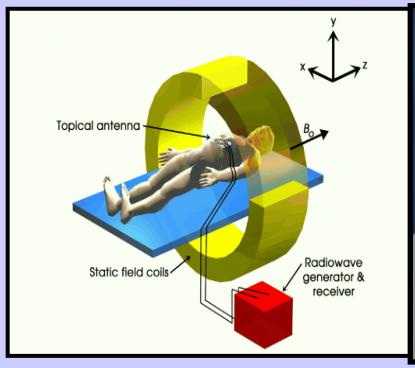
Some Current Volume Image Acquisition Systems

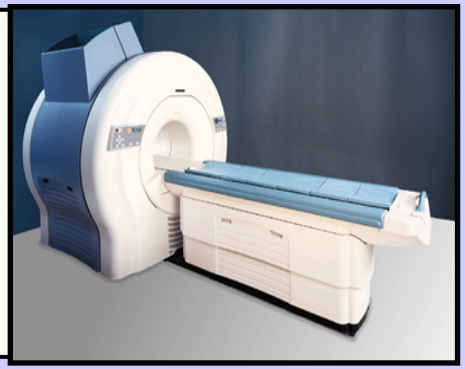
CT (spiral, multi, cine)



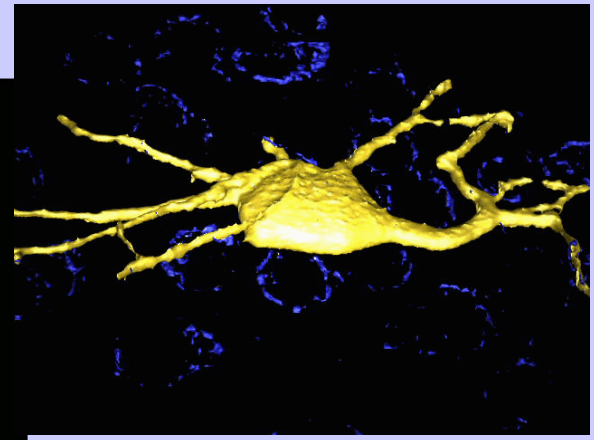


MRI (fast,open)



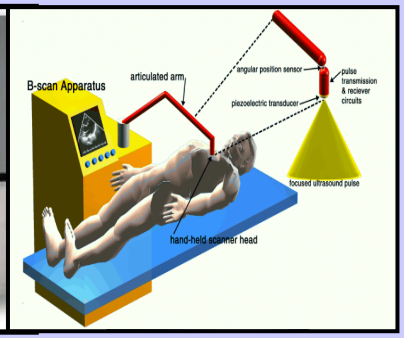


Microscopy

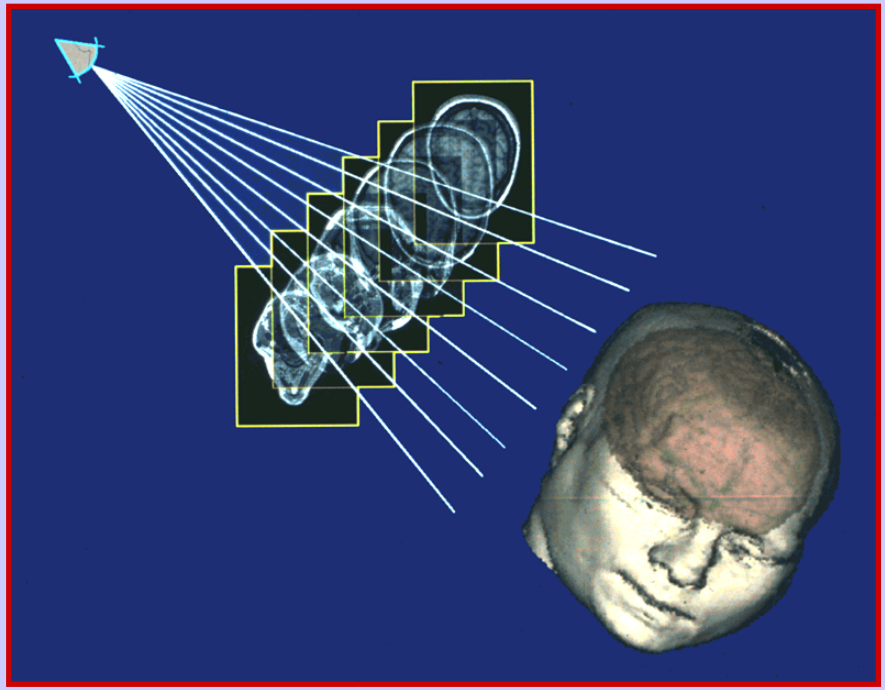


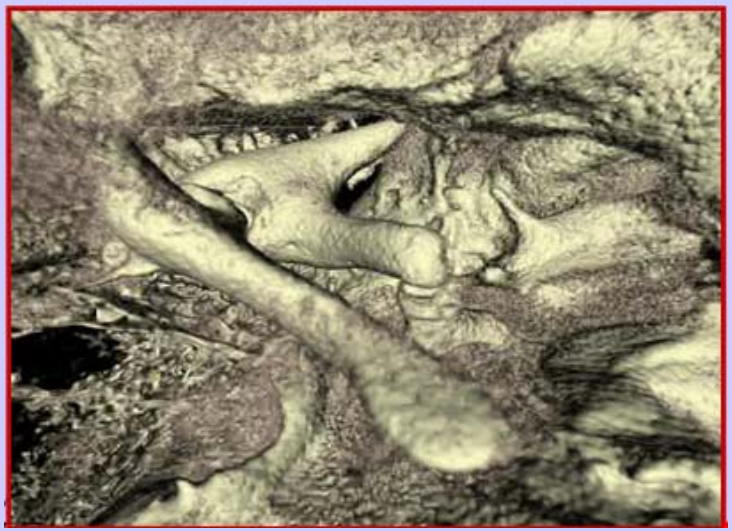
PET

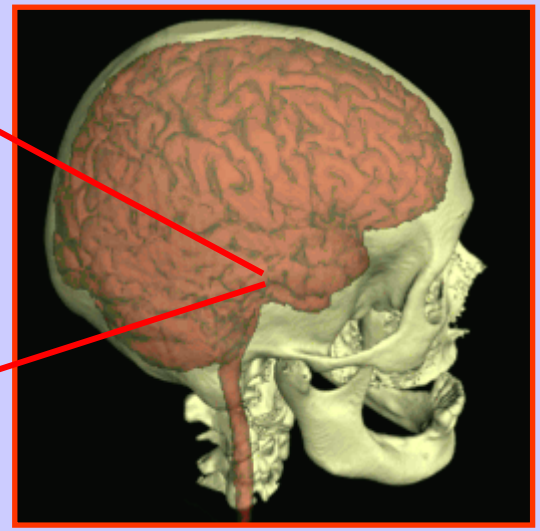
US



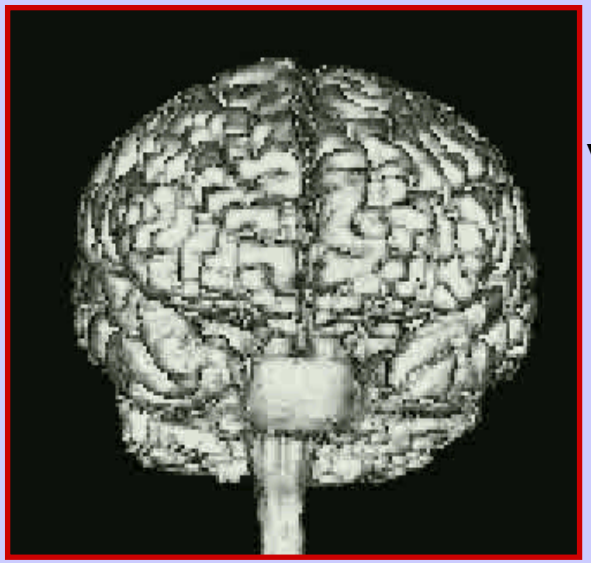
Volume Image Reconstruction & Rendering







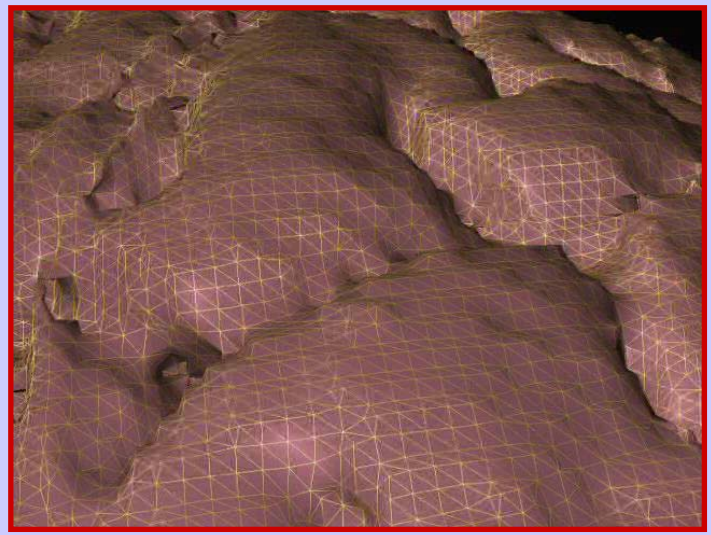
Volume Surface Tiling By Adaptive Deformation



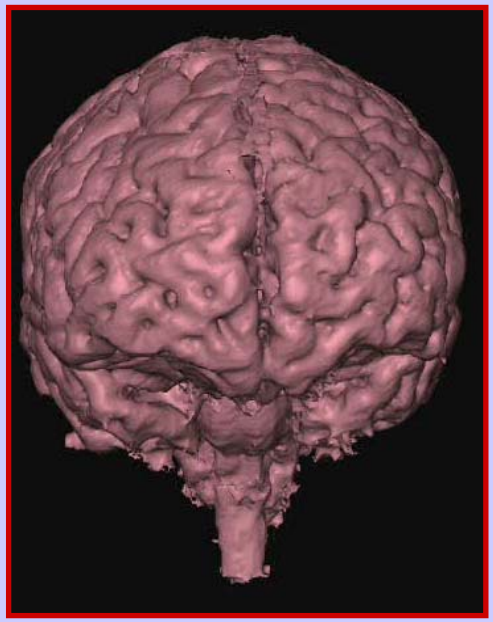
Voxels

Surface

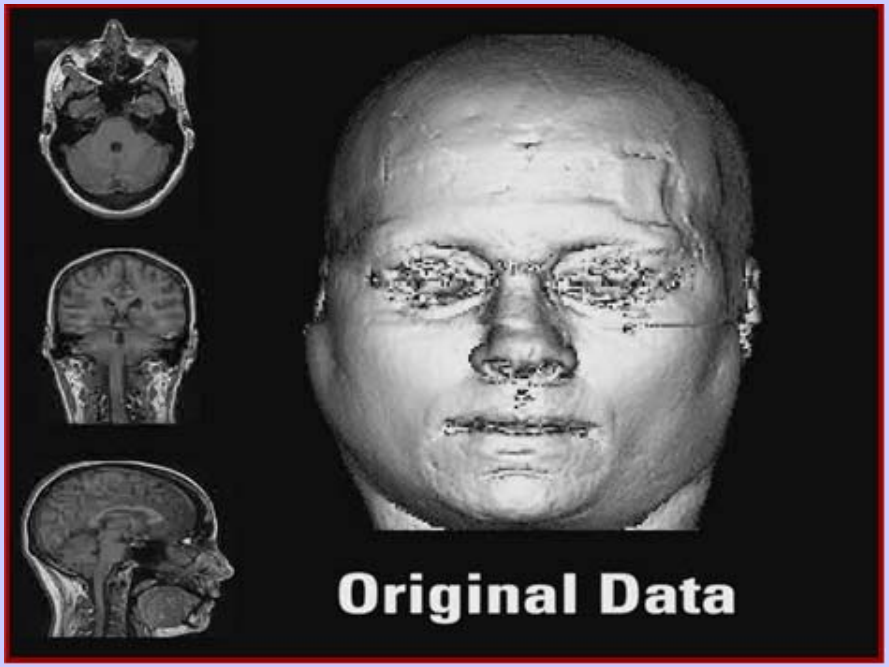
Tiling



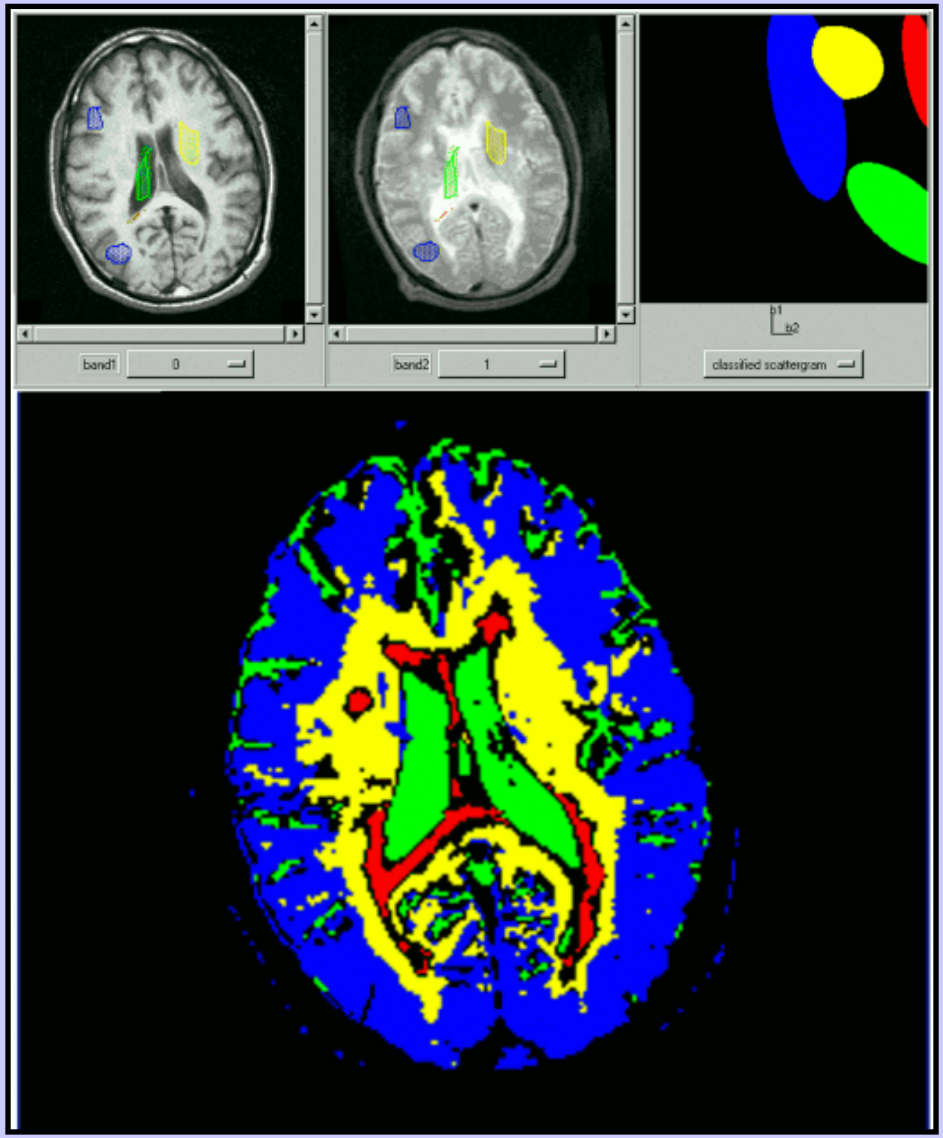
Polygons

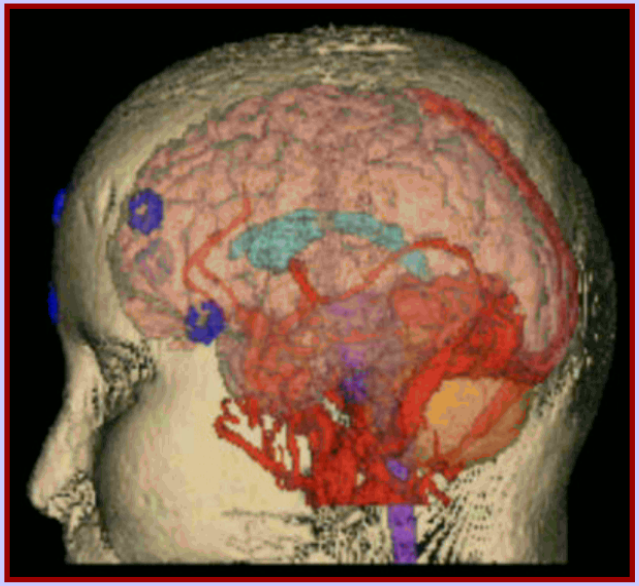


Volume Image Segmentation & Classification



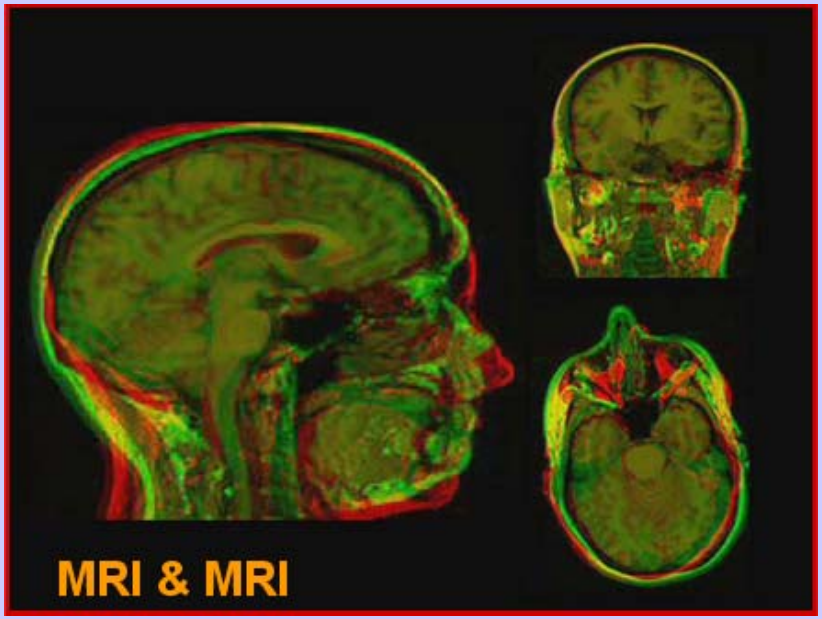
Tissue Classification



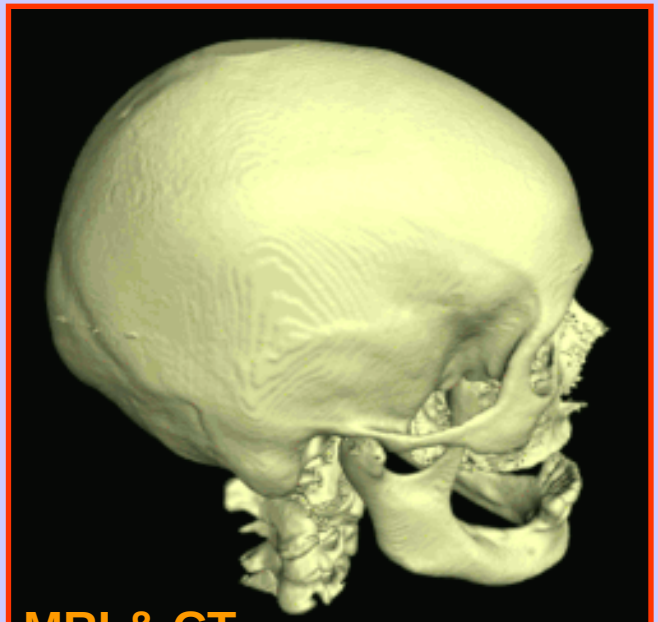


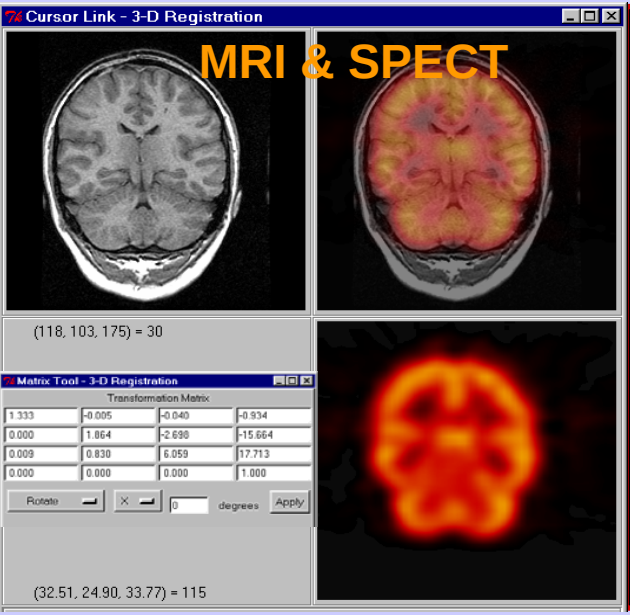
Multi-Volume Segmentation

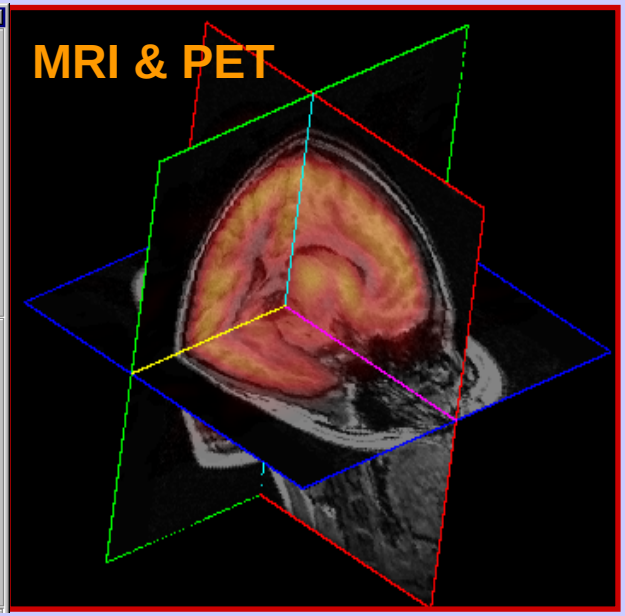
Volume Image Registration & Fusion



FUSION







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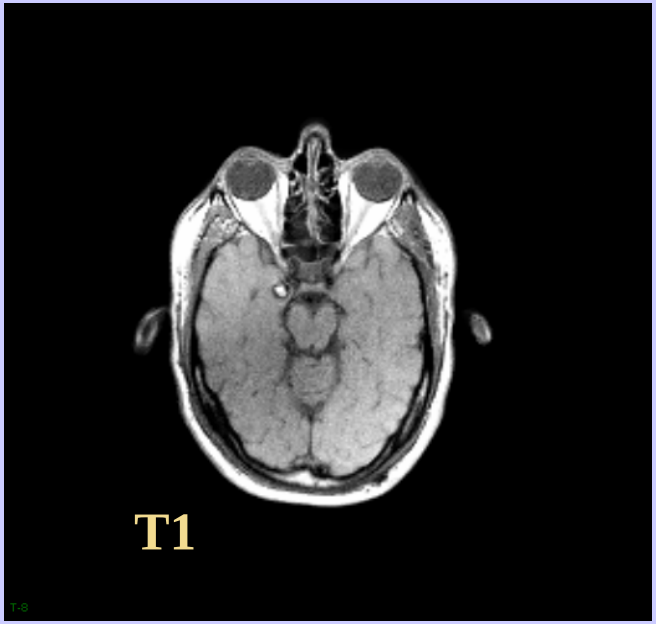
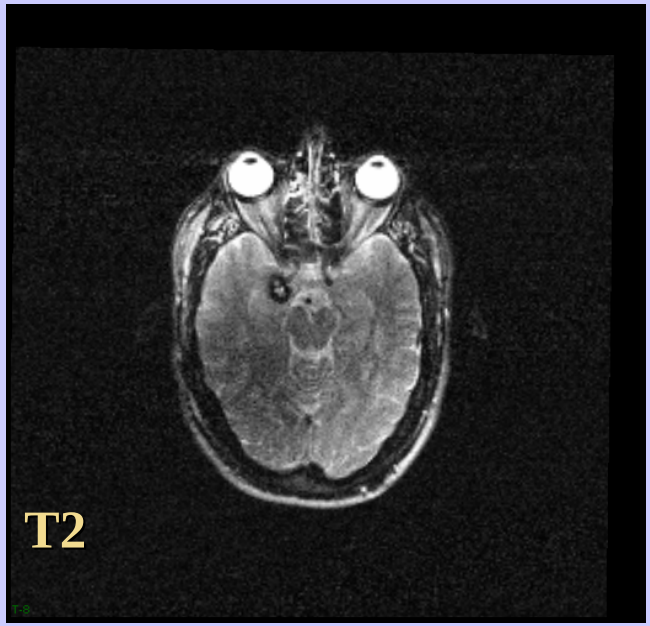
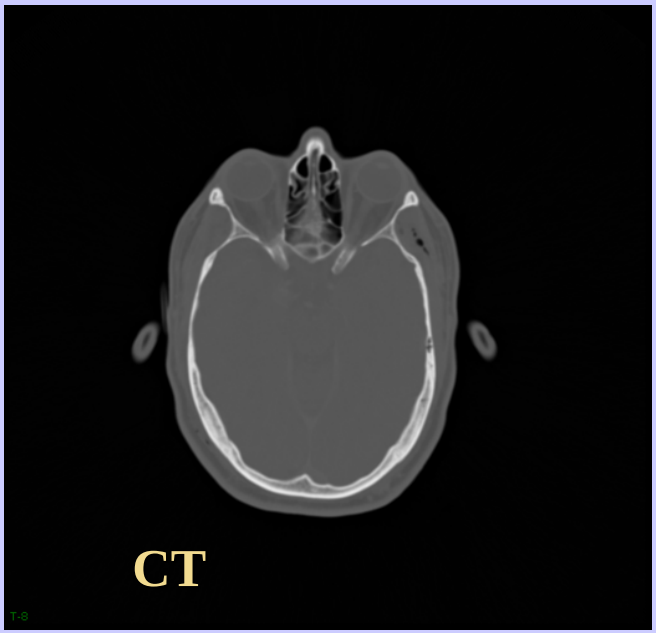
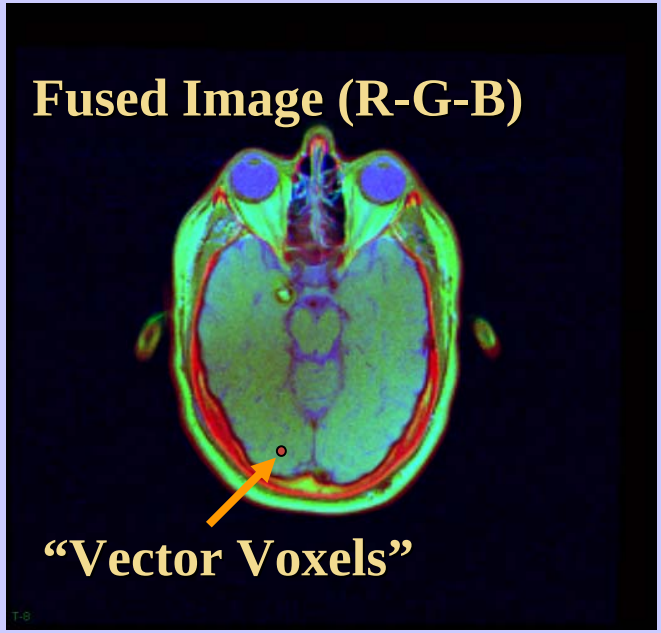
Fusion of Multi-Valued Structures









Definition:

Image Fusion is the integration of multiple scalar-voxel images into a single vector-voxel image involving correction of any position, orientation, scaling or sampling differences among component images, thus producing a coherent image of voxel vectors potentially more useful for multi-dimensional image visualization and analysis than any of the constituent images alone.

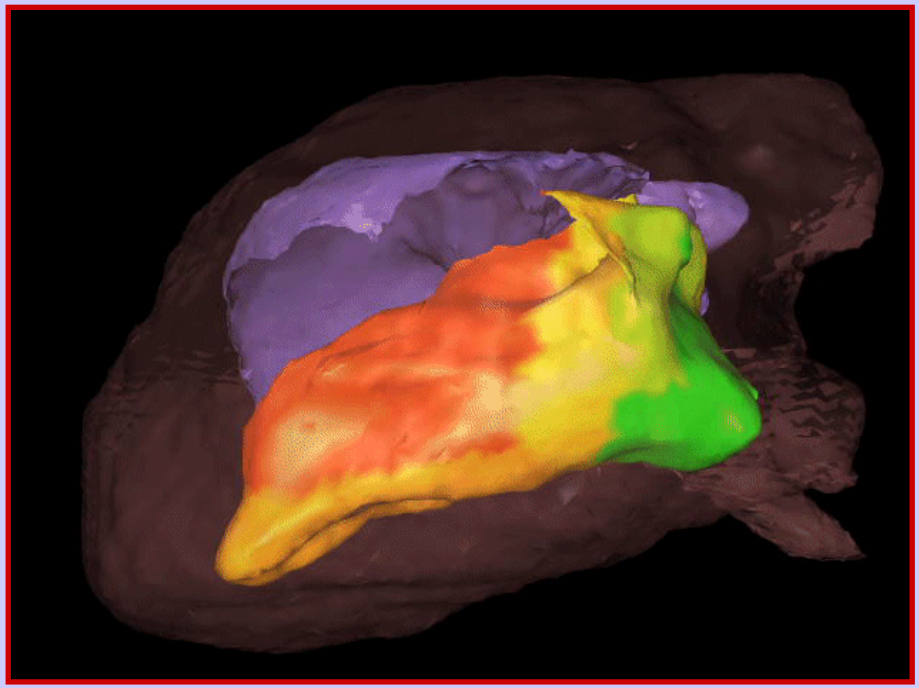
…or 1 + 1 > 2 (synergism) !

Fusion Beyond Anatomy: Add Function To Structure

- Kinetics
- Elasticity
- Electrical
- Flow
- Pressure
- Temperature
- Viscosity
- Absorption
- Diffusion
- Strain
- Etc….

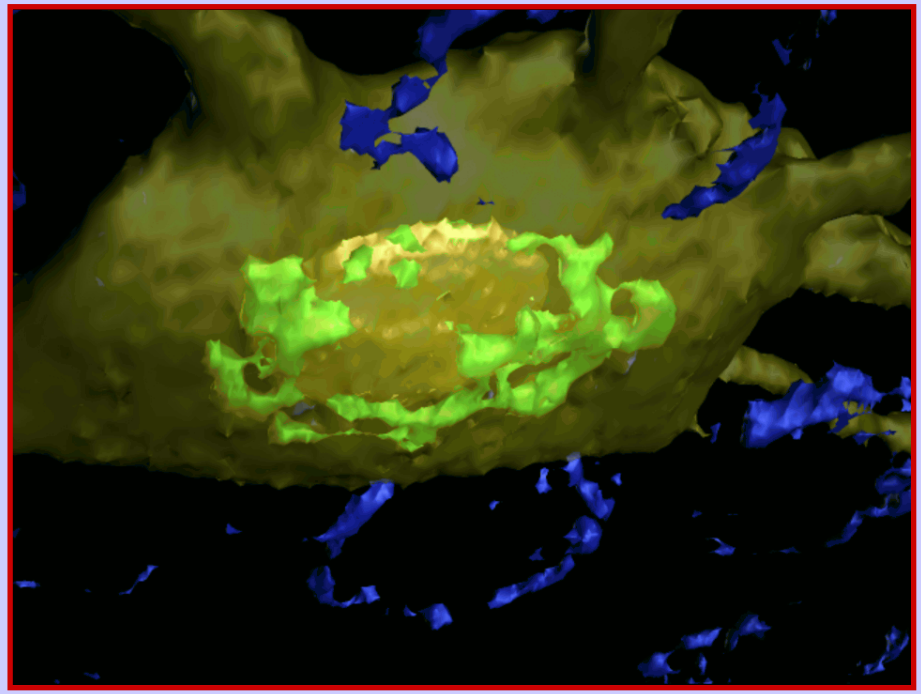
4~5 Dimensional Fusion Images (x, y, z, t, f)

Structure Function



3D heart beating with contraction pattern mapped onto surface of left ventricular endocardium (= 5D)

f=electrical activation (color pattern)



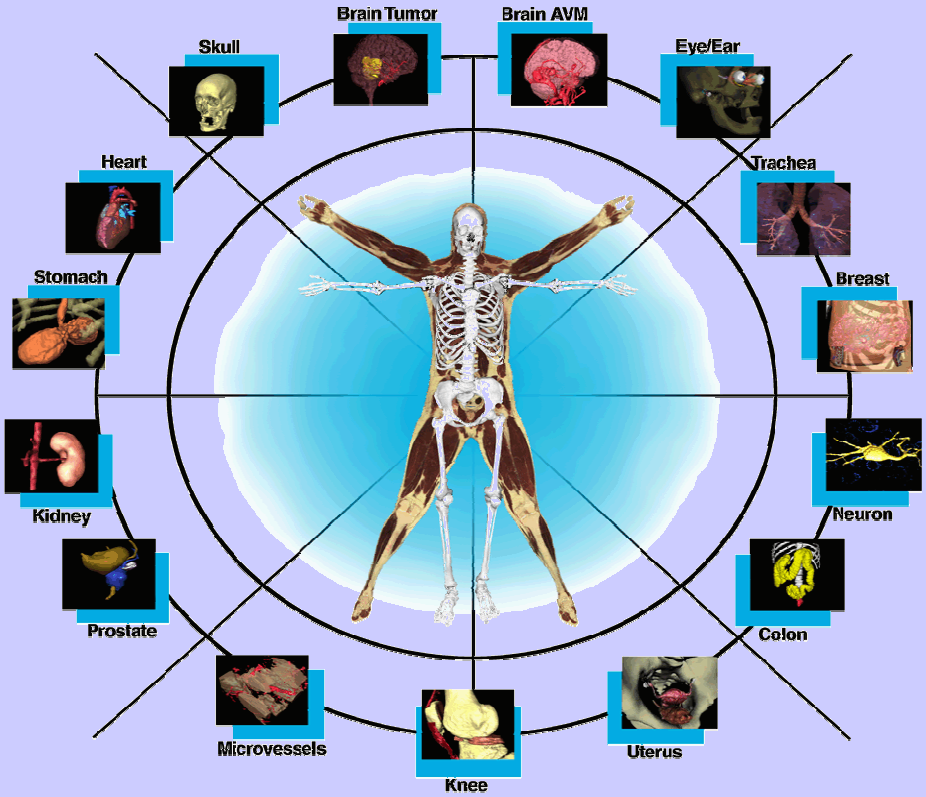
3D neuron in transparency to reveal nucleus and mapped receptor sites for selected neuro-transmitter (=4D)

f=receptor binding sites (color labeled)

Patient-Specific Anatomy/Function Imaging and Modeling

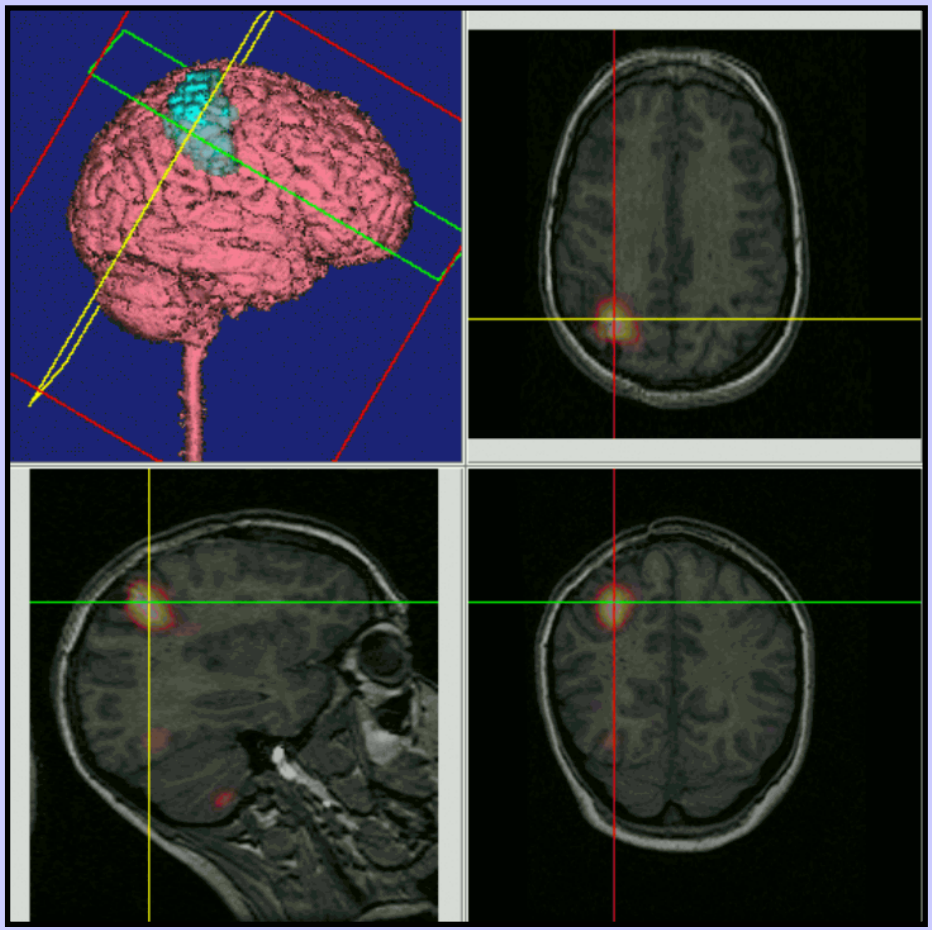
- Scan a desired volume of the body
- Segment specific anatomic sub-volumes
- Transform volumes into surface shells
- Tile with adaptive deformable polygons
- Map desired textures onto polygons
- Map desired functions onto polygons
- Render mapped surface for display & use

Examples of Image-Guided Intervention

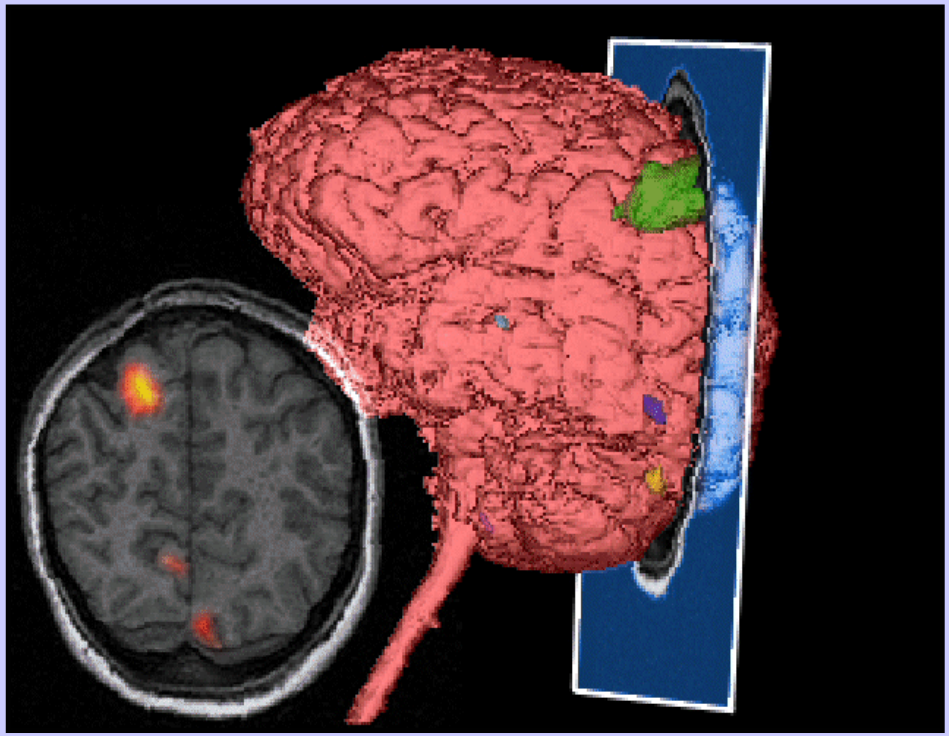


- *Brain Surgery For Epilepsy*
- *Guided Arrhythmia Ablation*
- *Virtual Colonoscopy*
- *Prostate Cancer Treatment*
- *Cochlear Implants*

Image-Guided Brain Surgery For Epilepsy



3D SPECT Subtraction And Fusion With MRI To Localize Tissue Region Causing Seizures



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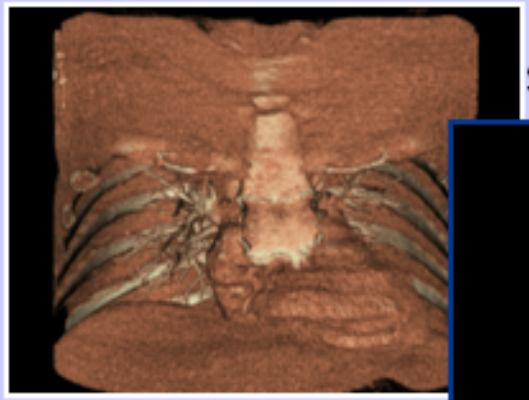
With Drs. Elson So, Brian Mullan

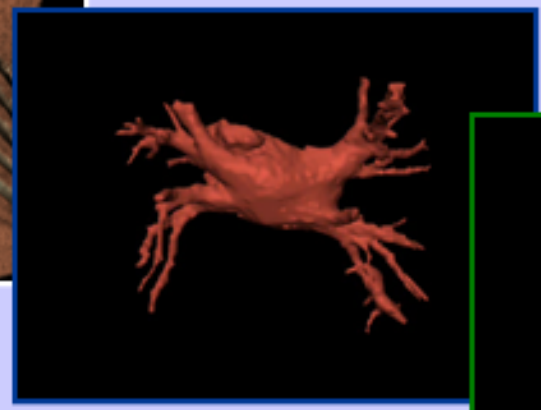
5D Image-Guided Cardiac EP Ablation

Pre-op Volume Scan

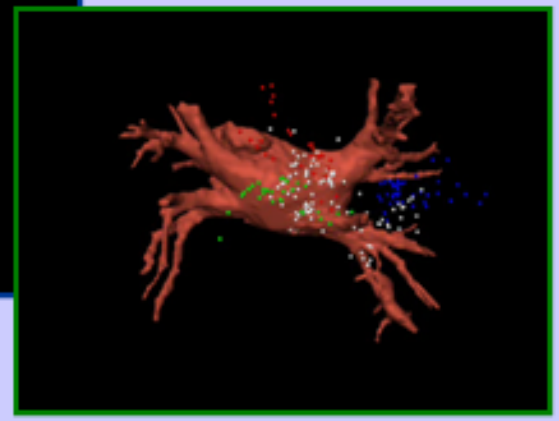
Rendered Volume Scan

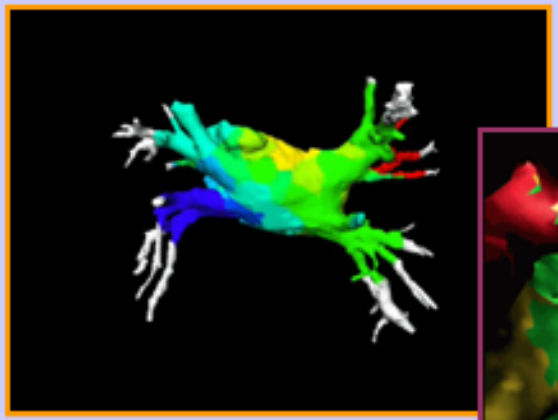


Segment & Model Atria

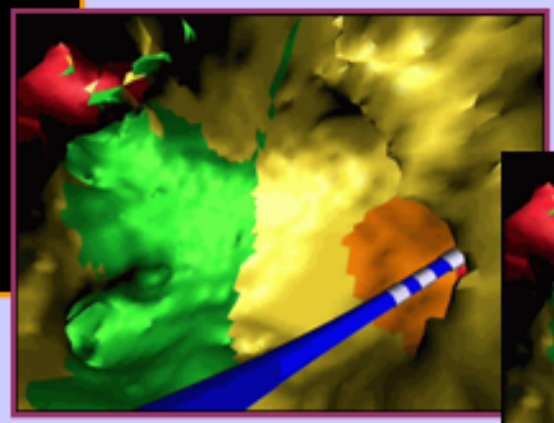


Register EP Points

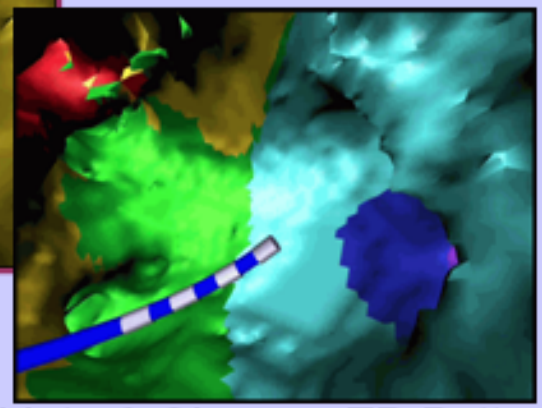




Map EP Pattern



Guide Ablation Catheter



Ablate & Observe EP Pattern

RT 3D US

Image-Guided Colonic Polyp Detection

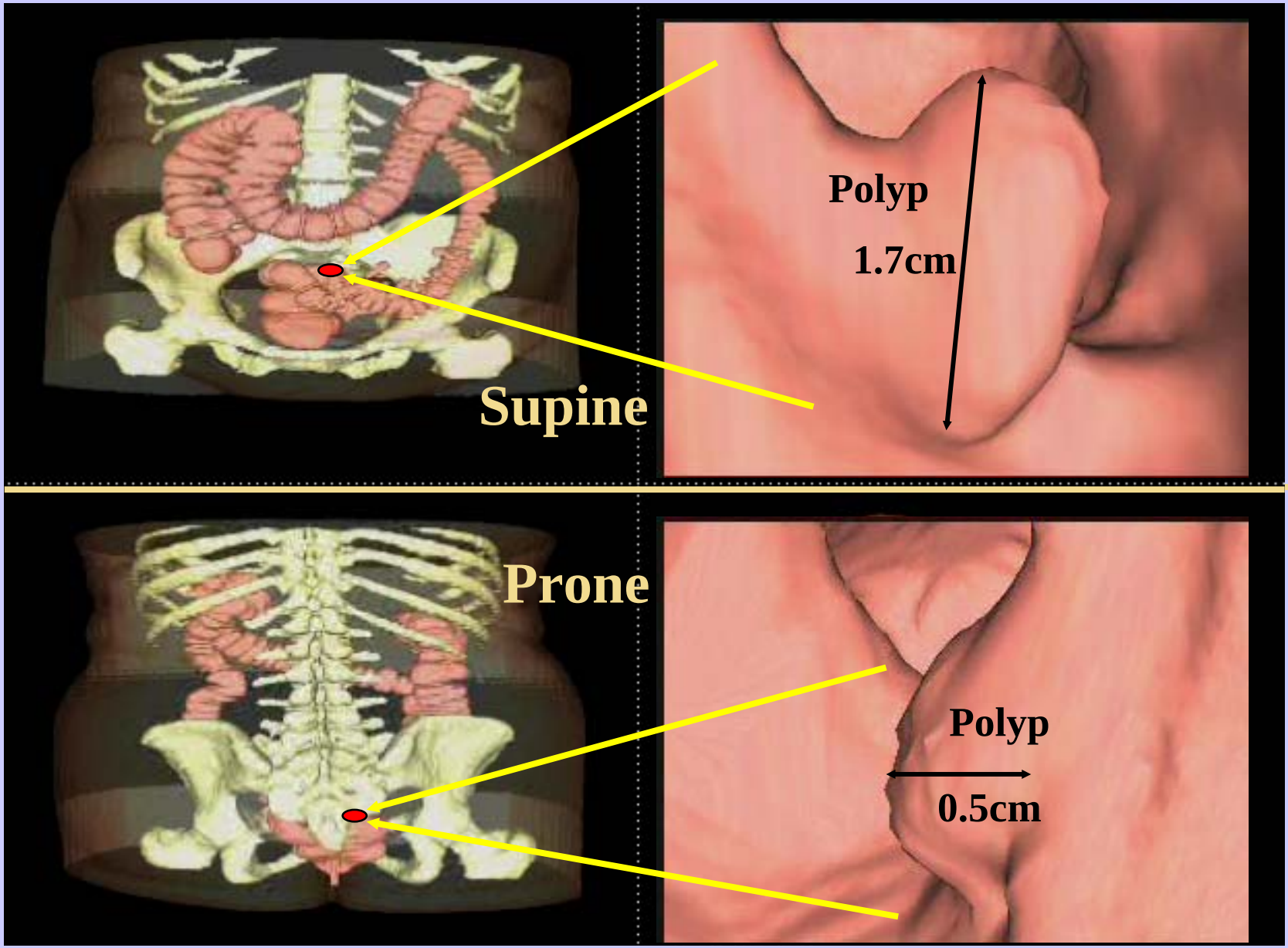
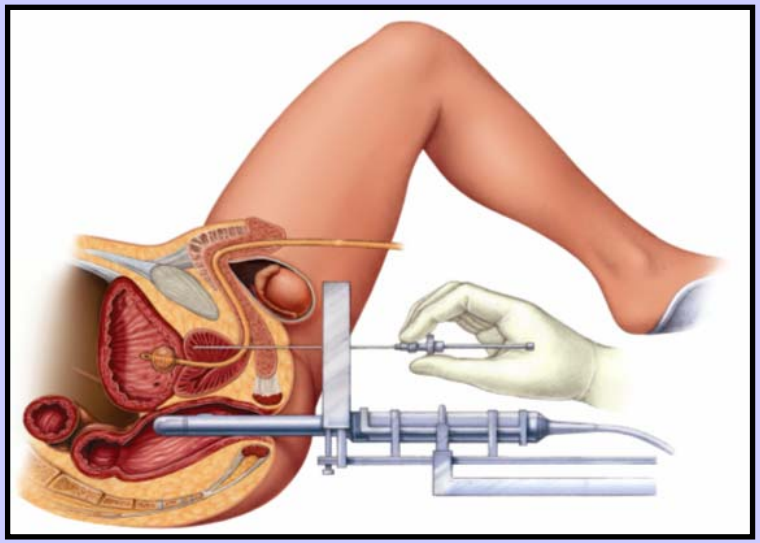
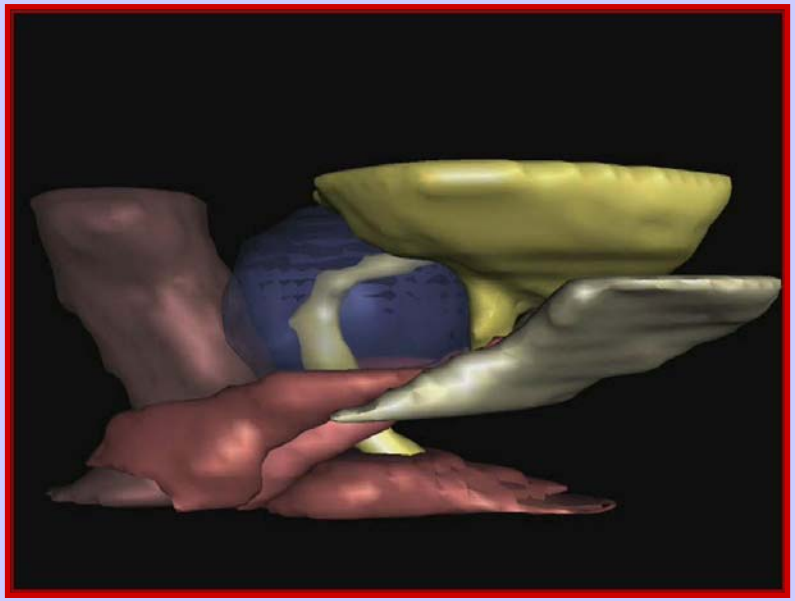


Image-Guided Prostate Cancer Brachytherapy



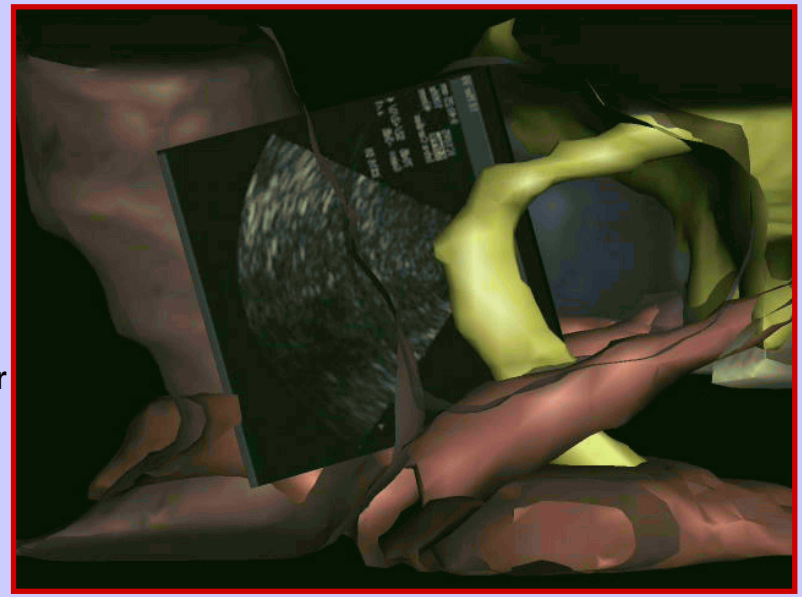
Procedure

MRI Scan Volume



Patient-Specific Model

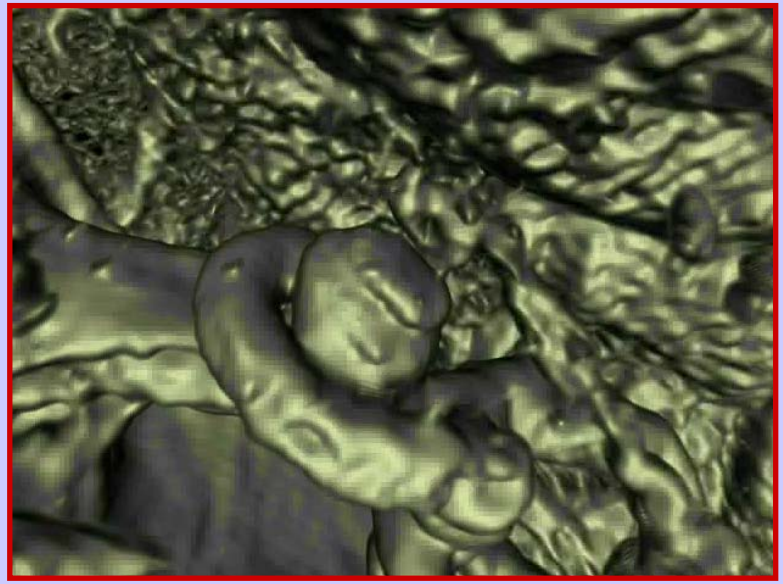
Transurethral ultrasound for optimal seed placement

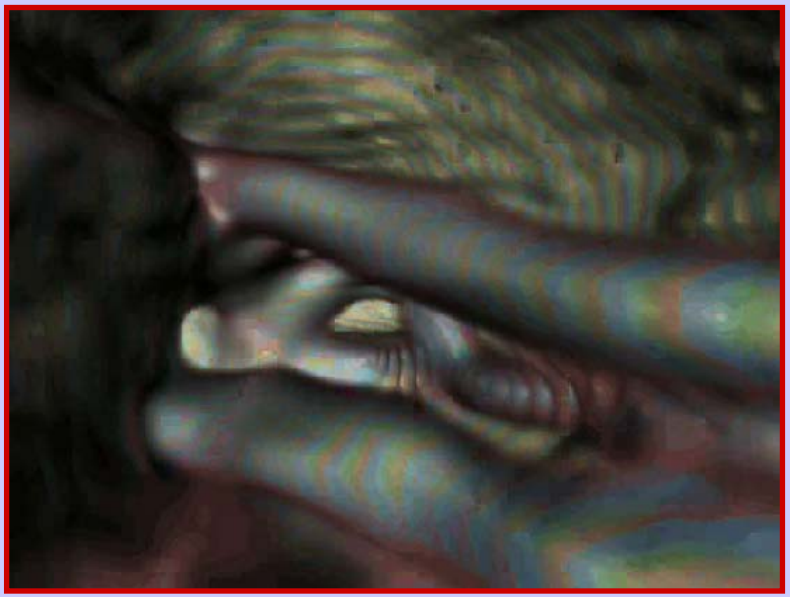


MAYO CLINIC College of Medicine

With Dr. Brian Davis

Image-Guided Planning of Cochlear Implants

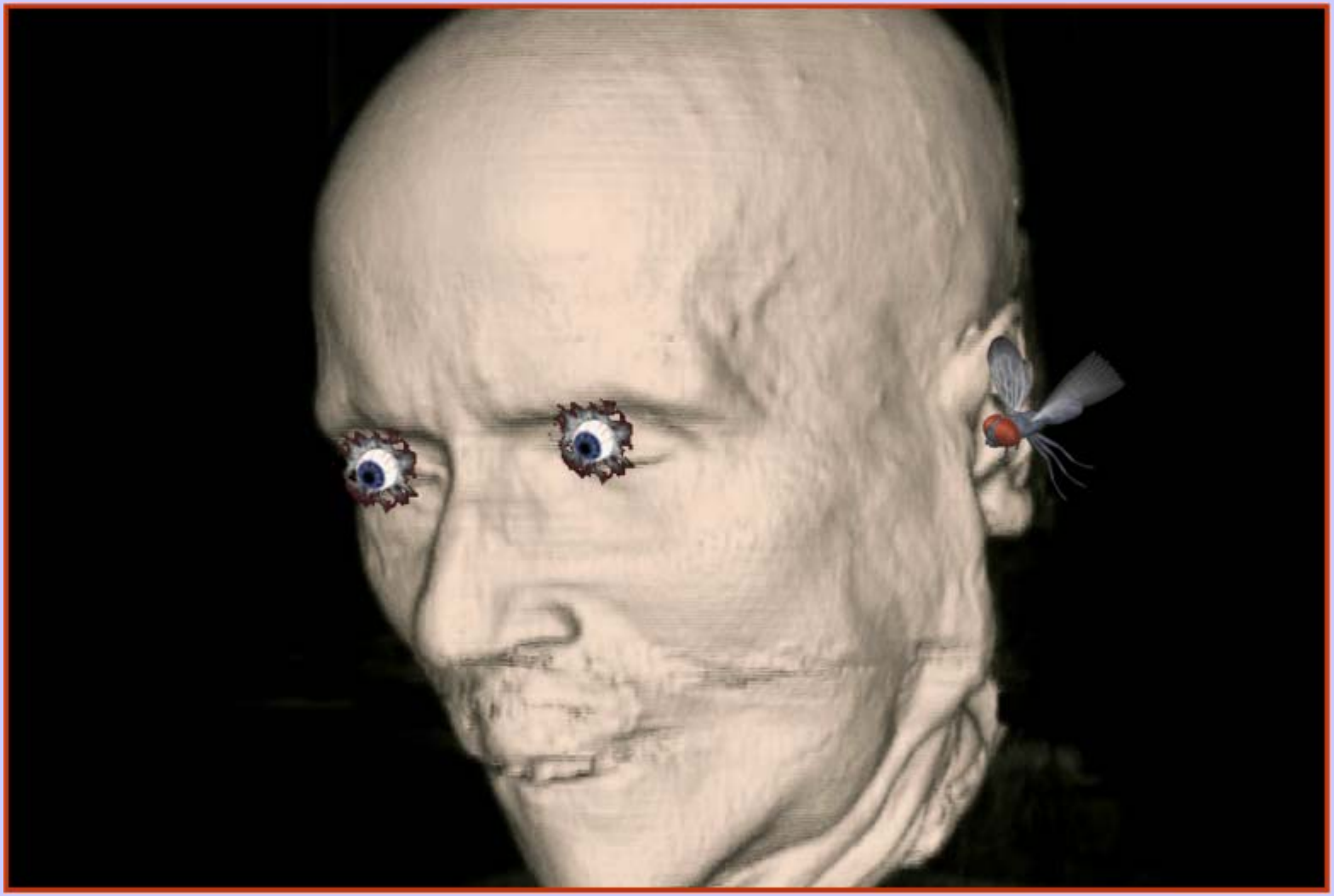




With Dr. Colin Driscoll

“Let me put a bug in your ear.”

“Fly Through”



With Drs. Jack Lane, Bob Brey & Colin Driscoll

Conclusion

If You Don't Have A Village…
IGI Can Wait Until The Cows Come Home!