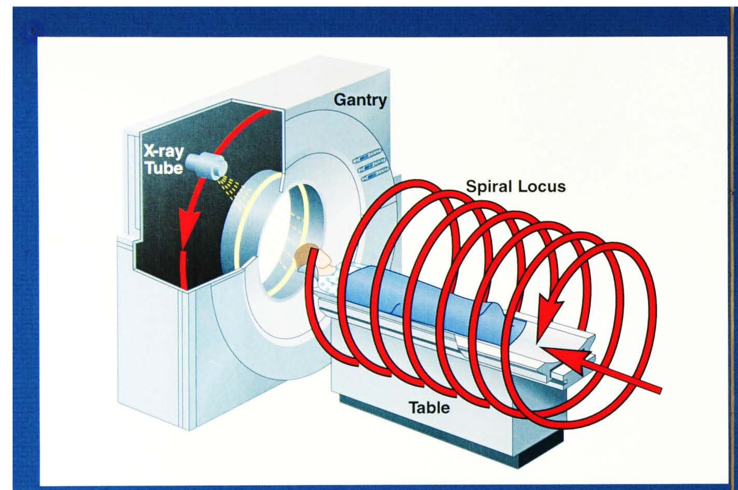
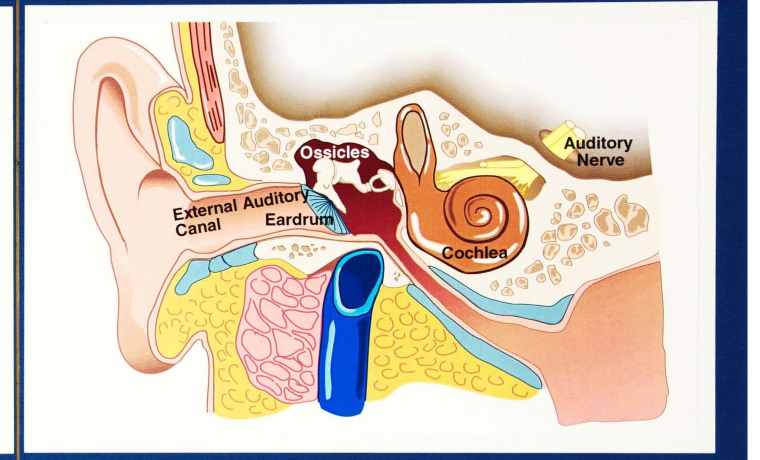
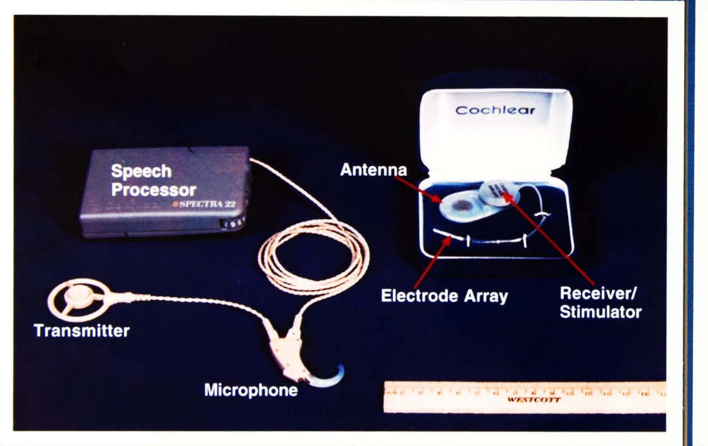


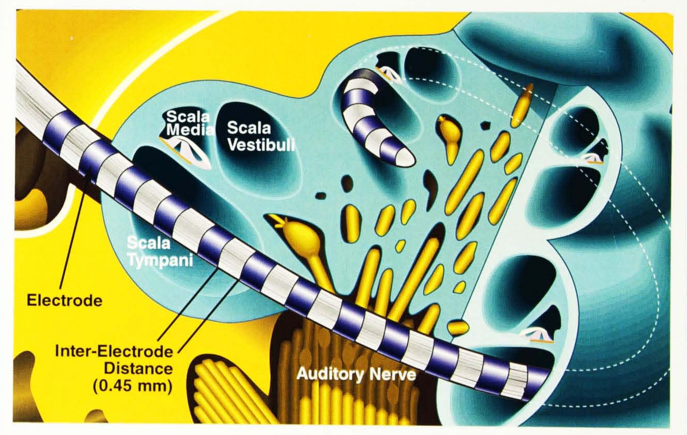


Spiral CT is a prime diagnostic imaging modality, in which X-ray source rotation and patient translation are performed *simultaneously*. Compared to other imaging means, spiral CT is advantageous when bony and metallic structures are involved.

The temporal bone, located on each side of the skull, contains many sub-mm sized features of the middle and inner ear. The shape and orientation of these features varies substantially among individuals. Hearing occurs when sound waves, conducted through the external auditory canal, cause the eardrum, middle ear ossicles, and cochlear fluids to vibrate. In the cochlea, these vibrations are converted to neural signals to be interpreted by the brain. In profound hearing loss, there is little or no neural signal generated in the cochlea.

Cochlear implantation is the standard treatment for profound hearing loss. More than 14,000 patients have received various types of cochlear implants, with different degrees of speech recognition.





The Nucleus Cochlear Implant System (Cochlear Corporation, Englewood, Colorado) consists of external parts - a microphone, a speech processor, and a transmitter, as well as internal parts - an antenna, a receiver/stimulator, and an electrode array. The system converts sound waves detected by the microphone into auditory nerve fiber stimulation via the electrodes.

Temporal bone imaging is essential to:

Pre-operatively
- Assess feasibility of cochlear implantation
- Select an ear for implantation
- Plan surgery
- Improve insertion procedures
- Modify design of the electrode array

Post-operatively
- Determine electrode positions in relation to the cochlear anatomy
- Program the processor to optimize each patient's speech recognition
- Compare electrode positions with hearing percepts
- Model electrical fields generated by electrodes
- Understand sources of variability in patients' speech recognition

The problem is that maximum image resolution with commercial spiral CT scanners is inadequate to define clearly the anatomical features and electrode positions within this intricate, 3D space.

The goal of this project is to develop theory, algorithms and equipment to increase spiral CT image resolution for temporal bone imaging, especially in cochlear implantation.

Spiral CT of the Temporal Bone

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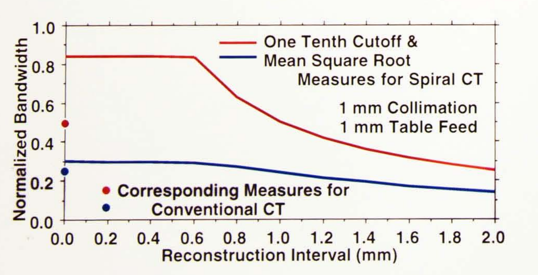
Theory

Overlapping Reconstruction for Inherent Resolution

Spiral CT was introduced for much faster scanning than conventional CT that involves incremental stepping and shooting. However, spiral CT does not produce consistent projection data for any transaxial plane, and broadens the slice sensitivity profile (SSP) as compared to that in conventional CT. It appeared to many that improved temporal resolution of spiral CT was at the cost of degraded spatial resolution.

An important feature of spiral CT is retrospective reconstruction: raw data are collected first, any transaxial slice can be reconstructed afterwards. Based on CT system bandwidth analysis, we theoretically established that **with overlapping transaxial reconstruction spiral CT allows substantially better longitudinal resolution than conventional CT for a given X-ray dose, and 3 to 5 slices should be reconstructed per table feed**. Experiments also demonstrated the merits of overlapping reconstruction and the un-compromised transaxial resolution in spiral CT. This finding was highlighted by Kalender in his editorial as "**the state of the art in spiral CT**" (*Radiology* 197:578, 1995).



Algorithms

EM Image Deblurring for Super-Resolution

Why EM? It has been recently recognized that the well-known expectation maximization (EM) approach is applicable to deterministic linear inverse problems with the following advantages:
- Monotonic convergence
- Nonnegative solution
- Minimum *I*-divergence between measurement and prediction

Therefore, we developed deterministic EM algorithms for various CT problems, including image deblurring.

The spiral CT model:

$$g(\vec{x})=p_{\sigma_{CT}}(\vec{x})\otimes f(\vec{x})$$

where $g(\vec{x})$, $p_{\sigma_{CT}}(\vec{x})$ and $f(\vec{x})$ are a spiral CT image, a Gaussian point spread function (PSF) with a standard deviation σ_{CT} and the actual image, respectively.

The image deblurring algorithm:

$$\sigma_D{}^2=\sigma_{CT}{}^2+\sigma_S{}^2-\sigma_R{}^2$$

$$g_{k+1}(\vec{x})=g_k(\vec{x})\left[p_{\sigma_D}(\vec{x})\otimes\frac{g(\vec{x})}{p_{\sigma_D}(\vec{x})\otimes g_k(\vec{x})}\right],\quad k=1,2,\ldots,n$$

$$\hat{g}_{k+1}(\vec{x})=p_{\sigma_S}(\vec{x})\otimes g_{k+1}(\vec{x})$$

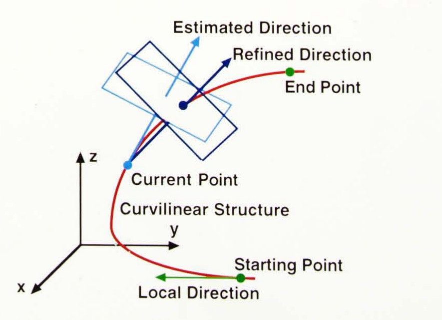
where σ_D, σ_S and σ_R are respectively deblurring, sieve and resolution kernels, $g_k(\vec{x})$ and $g_{k+1}(\vec{x})$ current and updated guesses, and $\hat{g}_{k+1}(\vec{x})$ is the deblurred result after n iterations.

Implant Unwrapping for Electrode Localization

Why unwrapping? By computationally unwrapping an implanted electrode array in a spiral CT image into an elongated volume along the array axis, longitudinal and cross-sectional positions of individual electrodes can be inferred based on *a priori* knowledge on the array.

The implant unwrapping algorithm: Specify a starting point, the local direction at the starting point, an end point and a tracking step length, take the starting point as the current point. The following steps are repeated until the end point is sufficiently close:
1. Estimate the next point along the local direction;
2. Adjust the estimated point to the mass center of the cross-section orthogonal to the local direction;
3. Scale the arc increment vector to the tracking step length;
4. Update the current point and the local direction.

The optimal tracking step length corresponds to the minimum average turning angle of the arc increment vector.



Equipment

Sub-mm Scanning for Higher Resolution

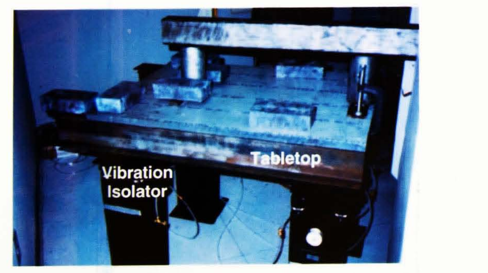
Why sub-mm scanning? We derived a spiral CT slice thickness formula:

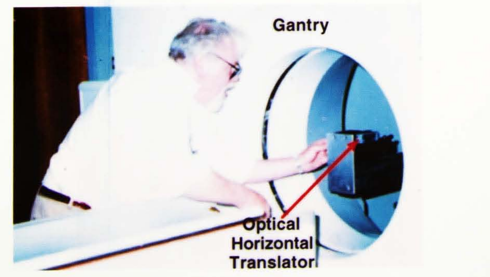
$$\sigma^2=\frac{D^2}{12}+\frac{T^2}{24}$$

where σ is the standard deviation of the SSP, D and T are detector collimation and table feed, respectively. This formula shows that thinner transaxial sections can be obtained with smaller D and T.

A sub-mm feed table was constructed to reduce T. The table consists of a supporting stage, which includes four vibration isolators and a heavy tabletop, and an optical horizontal translator, which advances a phantom through the gantry at a user-specified sub-mm table feed.

Sub-mm table feed and collimation was commercially implemented in an Elscint spiral CT scanner last year.





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We appreciate the contributions of
- **Collaborators** - B. A. Bohne, B. Brunsden, G. H. Esselman, G. W. Harding, W. A. Kalender, D. R. Ketten, E. Klotz, K. Kopecky, Y. Liang, A. Polacin, R. Robb, D. L. Snyder, and B. Wilson
- **Consultants** - G. E. Christensen, C. R. Crawford, Z. Li, and S. Y. Zhao
- **Technical staff** - K. Fritts, N. Hente, S. Howe, R. Knapp, T. H. Murry, R. Walkup, and M. E. Wynn
- **The Analyze™ system of the Mayo Clinic, the Somaton Plus S scanner and the experimental sub-mm spiral CT software of the Siemens, and the CT Twin Flash scanner of the Elscint**

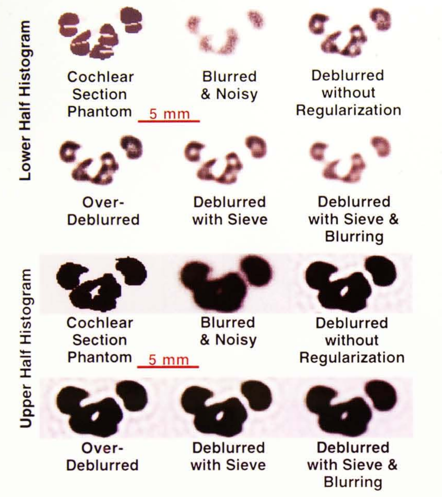
Image Deblurring

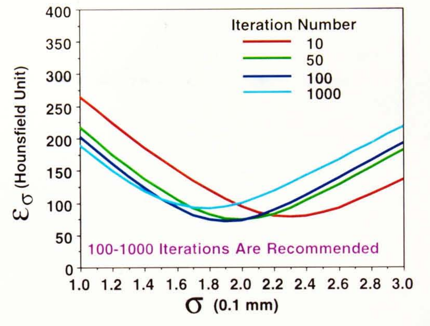
A cochlear cross-section phantom synthesized based on histologic and CT images consists of three types of structures: fluid, tissue and bone. A blurred noisy phantom was deblurred.

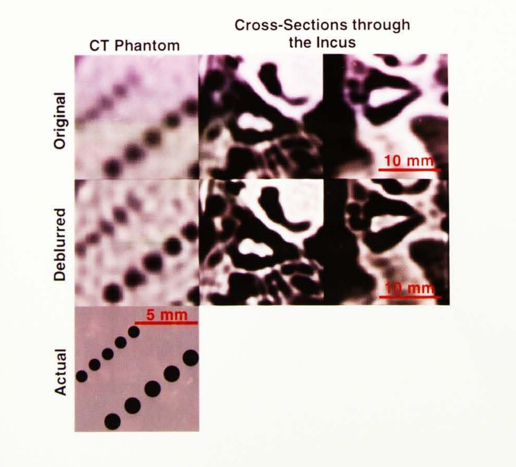
The deblurred PSF $p_{\sigma'_{CT}}(\vec{x})$ and the fitting error ε_σ are

$$\sigma'_{CT}=\arg\min\varepsilon_\sigma{}^2$$

$$\varepsilon_\sigma=\sqrt{\int\left[g(\vec{x})-p_\sigma(\vec{x})\otimes f(\vec{x})\right]^2 d\vec{x}}$$

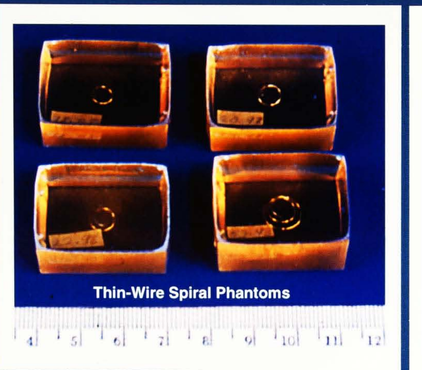


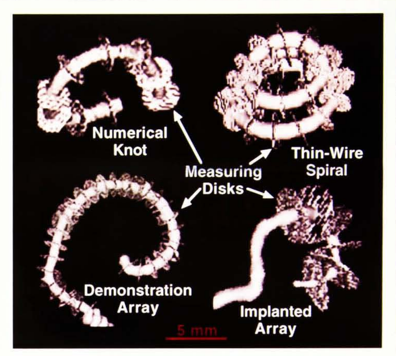




Implant Unwrapping

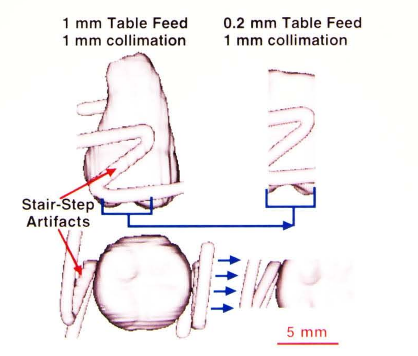
The evaluation was done with
- 4 synthetic curvilinear structures
- 4 thin-wire spiral phantoms
- 20 post-implantation spiral CT scans





Sub-mm Scanning

Our phantoms were scanned using a Siemens spiral CT scanner with our sub-mm table at 0.2 mm feed and 1 mm collimation, and an Elscint spiral CT scanner at 0.6 mm feed and 0.5 mm collimation.



Summary

- Spiral CT with overlapping reconstruction allows better 3D resolution than conventional CT, and is important for temporal bone imaging
- Spiral CT image deblurring achieves a 40% resolution gain without significant noise and ringing artifacts
- Implant unwrapping measures the array insertion length with a 0.3 mm mean accuracy, and facilitates electrode localization
- Sub-mm scanning improves high-contrast resolution and suppresses stair-step artifacts. However, 0.5 mm collimation introduced more than doubled image noise

Future Work

- Improve spiral CT using *a priori* knowledge, especially deformable electronic atlases of the cochlea and cochlear implants
- Combine predictive auditory models with post-implantation measurement from spiral CT
- Develop cone-beam spiral CT with high resolution and low dose for temporal bone imaging

Publications Supported by the Whitaker Foundation

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Related Grants Recently Funded

- Spiral CT deblurring for *in-situ* cochlear implant study, NIH, 8/1995-7/1997, $77,000
- Unraveling the GI tract by spiral CT, NIH, 4/1996-3/2001, $543,628