3D Image Fusion and Guidance for Computer-Assisted Bronchoscopy

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SPIE Optic East: Three-Dimensional TV, Video, and Display IV, Boston, MA, 25 Oct. 2005.

Lung Cancer

- Lung Cancer: #1 cancer killer, 30% of all cancer deaths,
  1.5 million deaths world-wide,
  < 15% 5-year survival rate (nearly the worst of cancer types)

- To diagnose and treat lung cancer,

  1) 3D CT-image preplanning – noninvasive
  2) Bronchoscopy – invasive

- 500,000 bronchoscopies done each year in U.S. alone

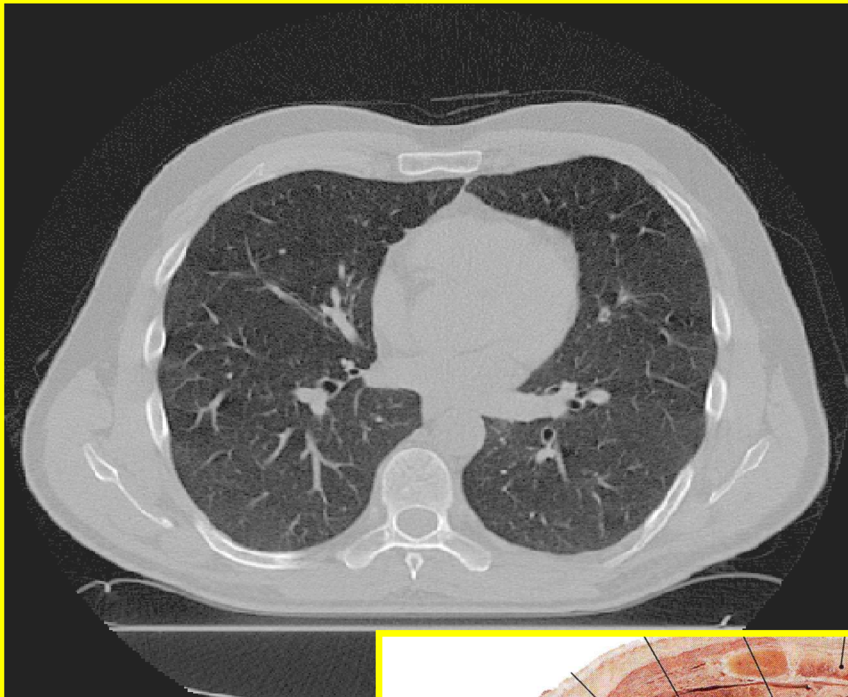
  → Procedure is LITTLE HELP if diagnosis/treatment are poor

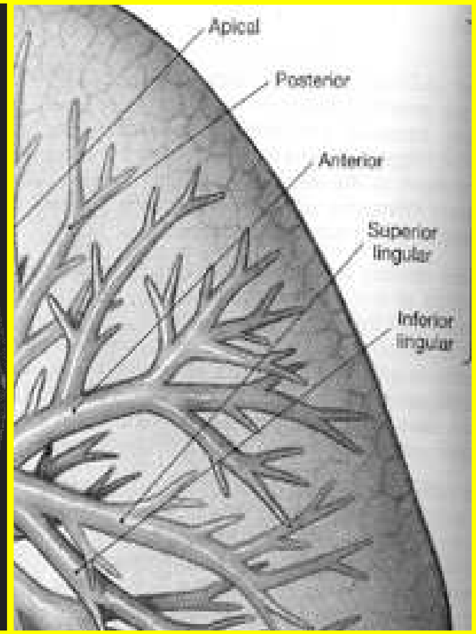
- A test for CT Image-based Lung-Cancer Screening in progress!

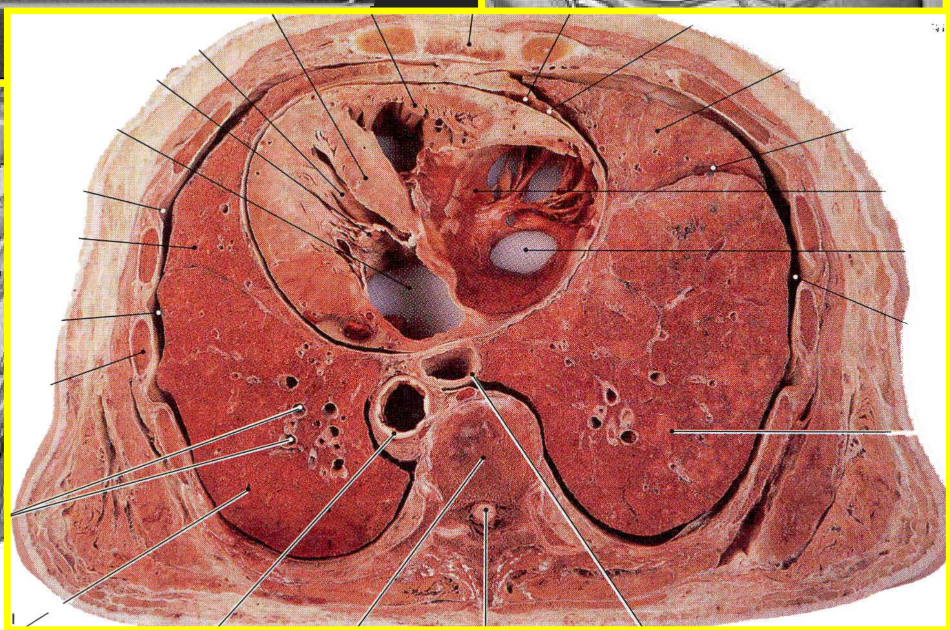
  10-30 million patient population in U.S. alone!

  → Screening is WORTHLESS if diagnosis/treatment are poor

3D CT Chest Images

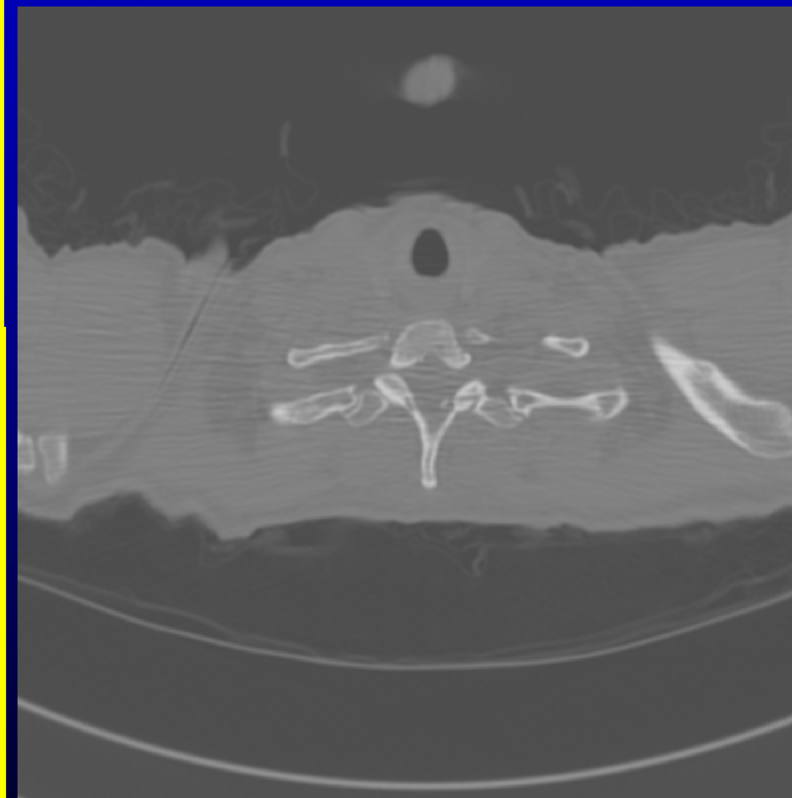


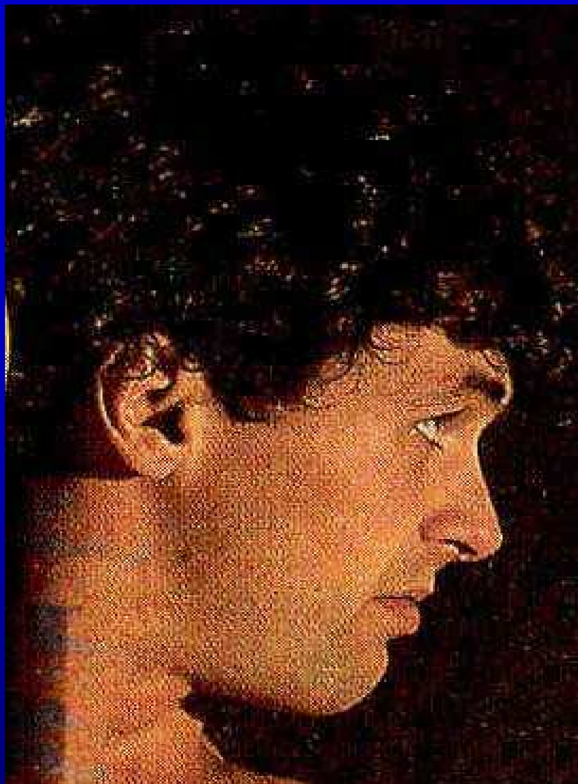


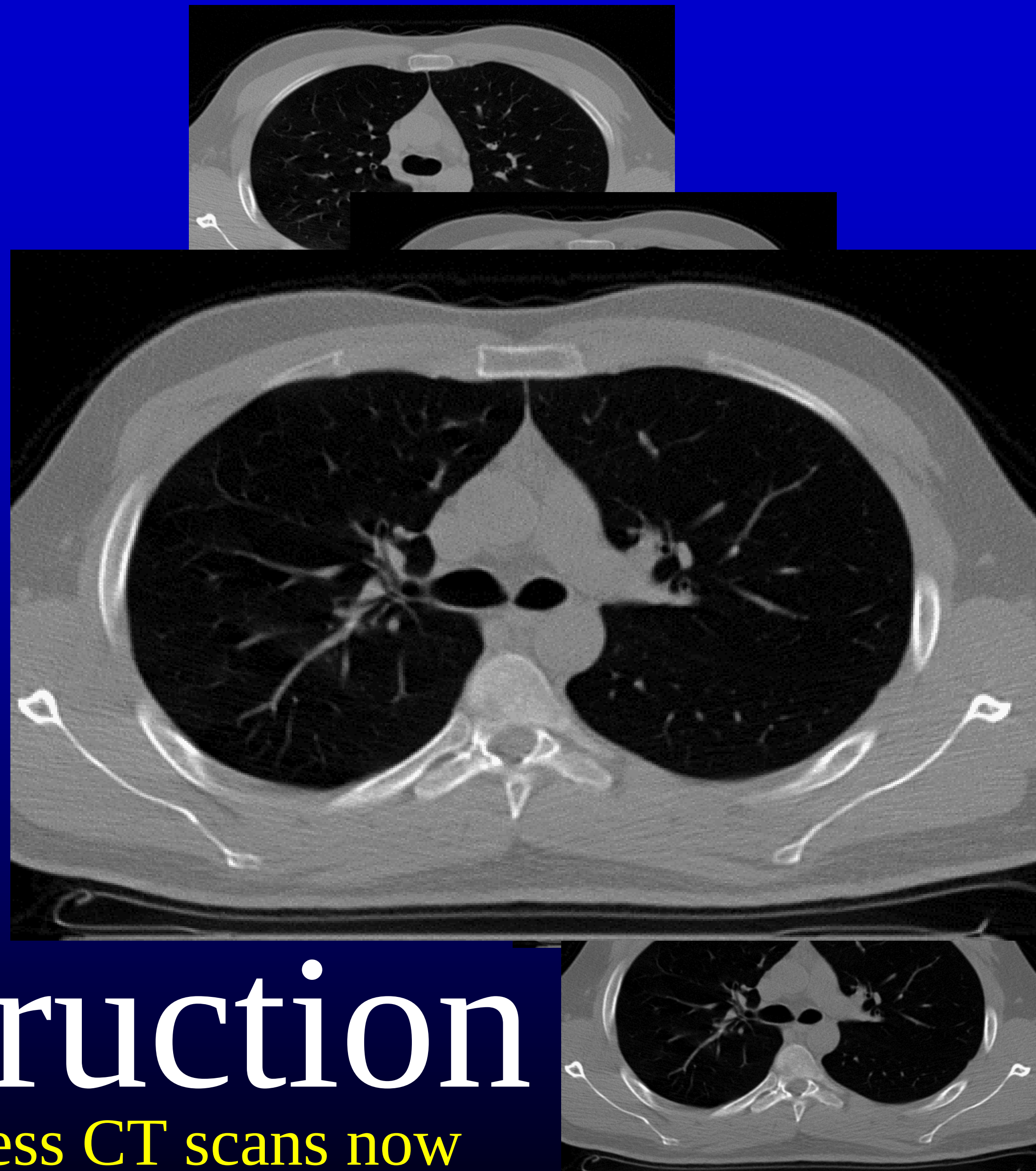


Typical chest scan V(x,y,z):

1. 500 512X512 slices V(x,y,.)
2. 0.5mm sampling interval







3D Mental Reconstruction

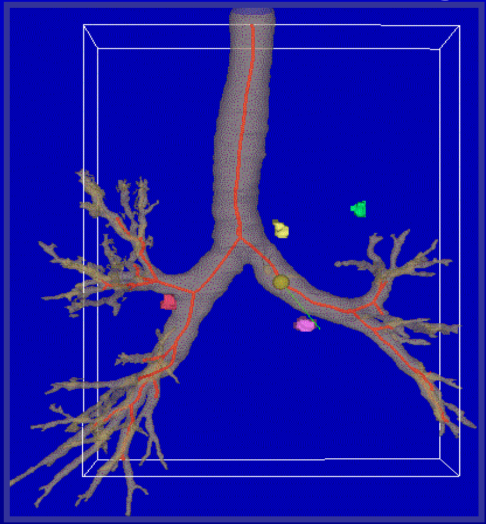
→ How physicians assess CT scans now

Visualization Techniques – see “inside” 3D Images

multi-planar reconstruction[2]

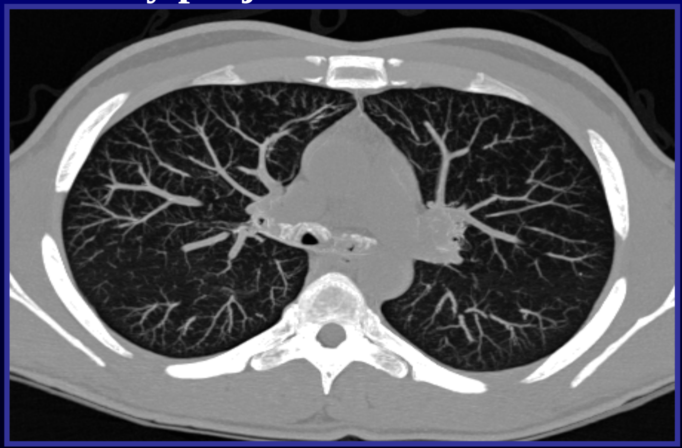
projection imaging[1]

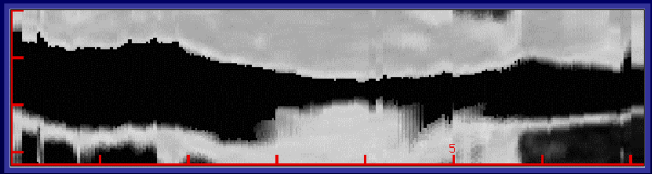
volume/surface rendering[4]



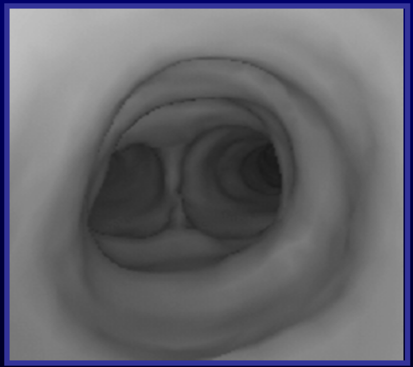
virtual endoscopic rendering[5]

STS-MIP
sliding-thin-slab maximum intensity projection[6]



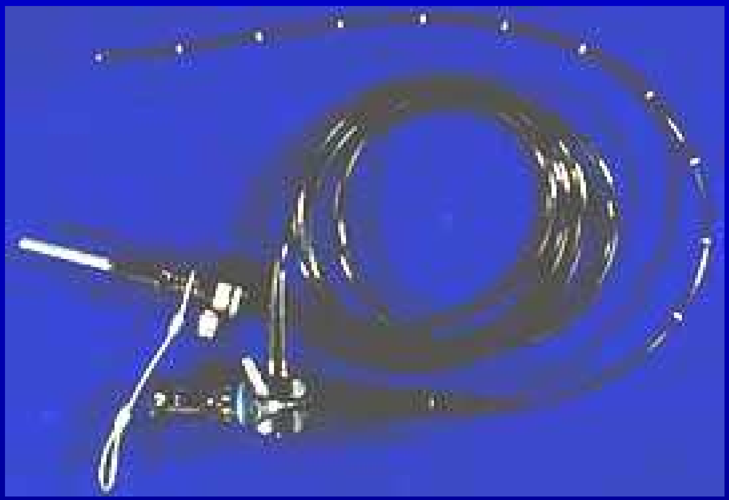


curved-section reformatting[3]



[1]{Hohne87,Napel92} [2]{Robb1988,Remy96,McGuinness97} [3]{Robb1988,Hara96,Ramaswamy99} [4]{Ney90,Drebin88,Tiede90} [5]{Vining94,Ramaswamy99, Helferty01} [6]{Napel, 92}

Bronchoscopy → For "live" procedures



video from bronchoscope

$I_V(x,y)$

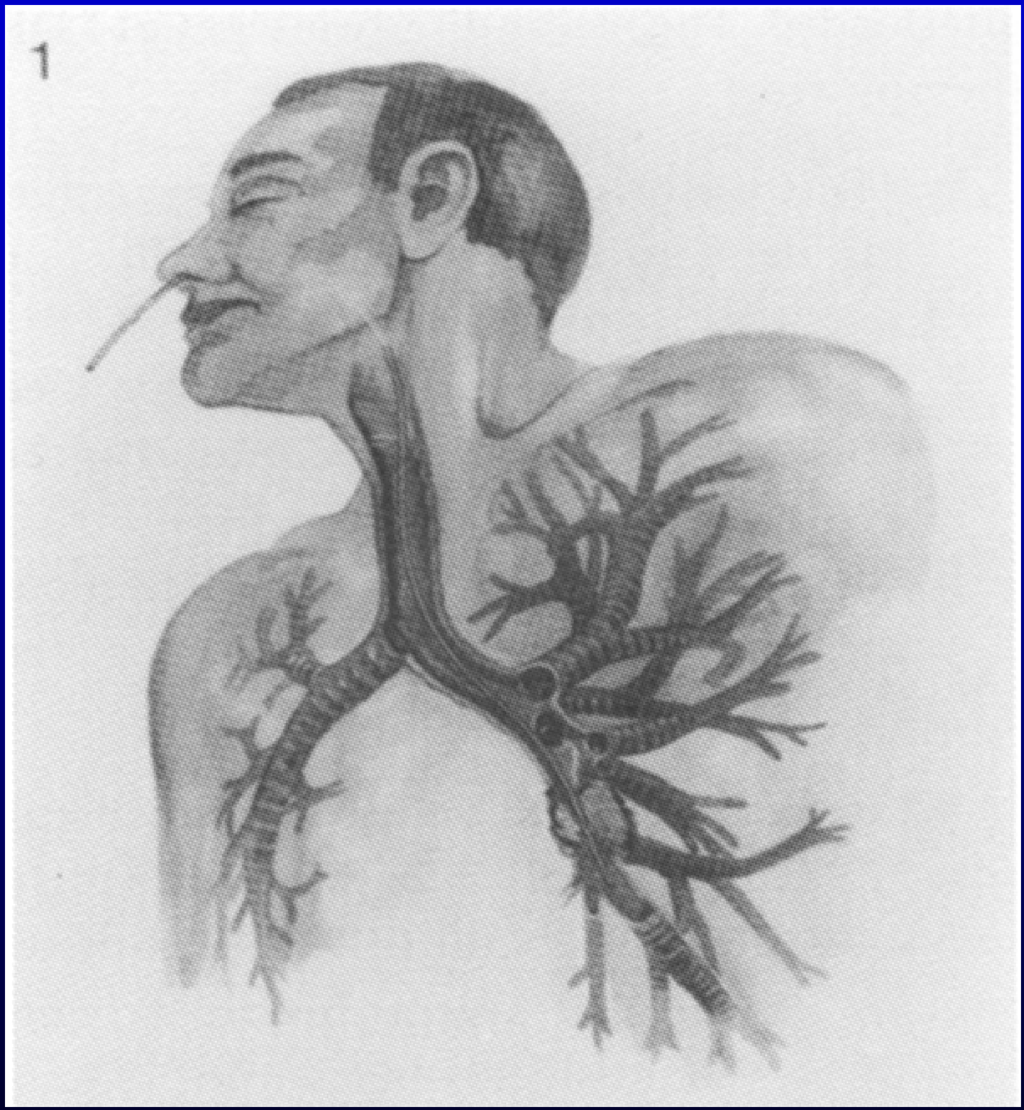
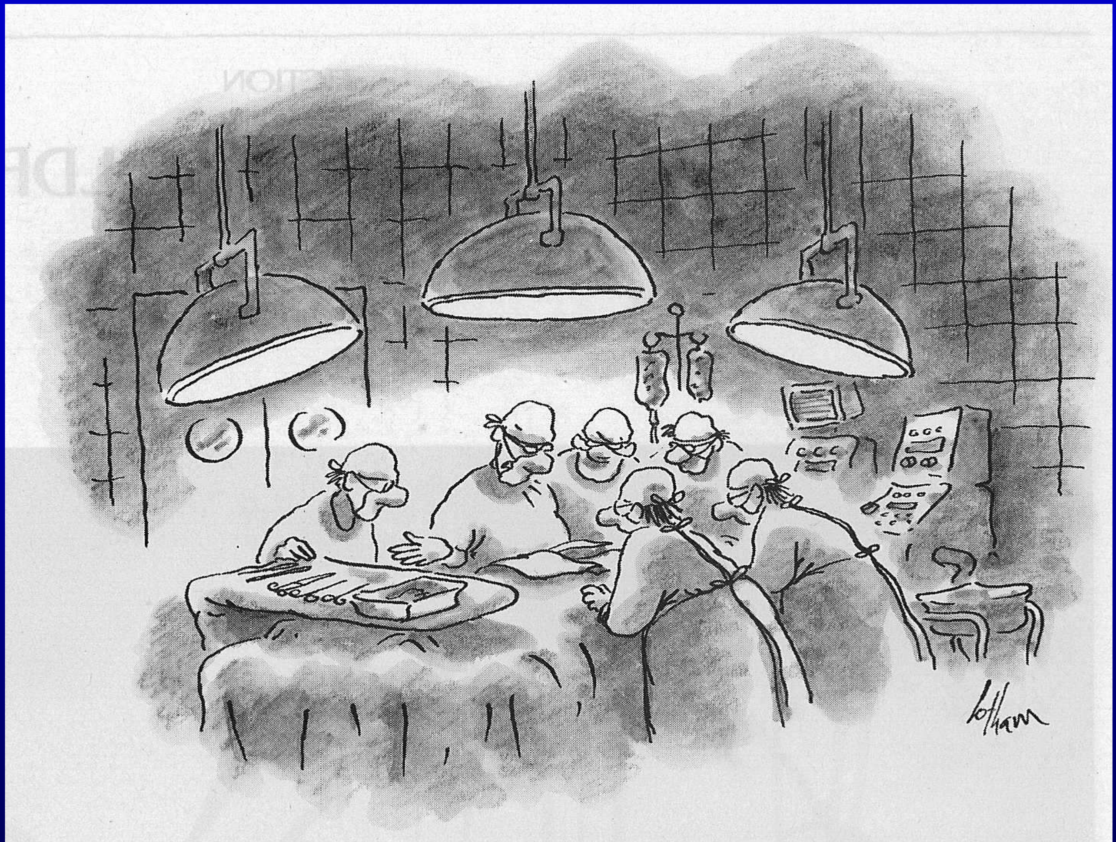


Figure 19.4, Wang/Mehta '95

Difficulties with Bronchoscopy

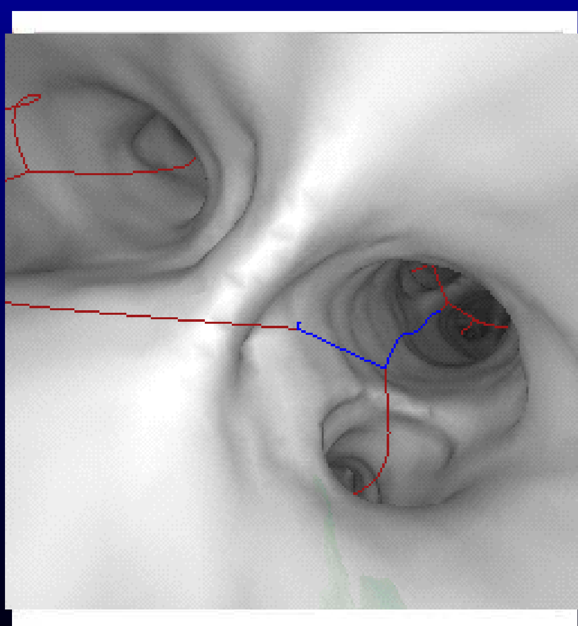
1. Physician skill varies greatly!
2. Low biopsy yield. Many “missed” cancers.
3. Biopsy sites are beyond airway walls – biopsies are done blindly!



“Let’s just start cutting and see what happens.”

Virtual Endoscopy (Bronchoscopy)

- Input a high-resolution 3D CT chest image
  - ➔ *virtual copy of chest anatomy*
- Use computer to explore virtual anatomy
  - ➔ permits unlimited “exploration”
  - ➔ no risk to patient



Endoluminal Rendering

$I_{CT}(x,y)$

(inside airways)

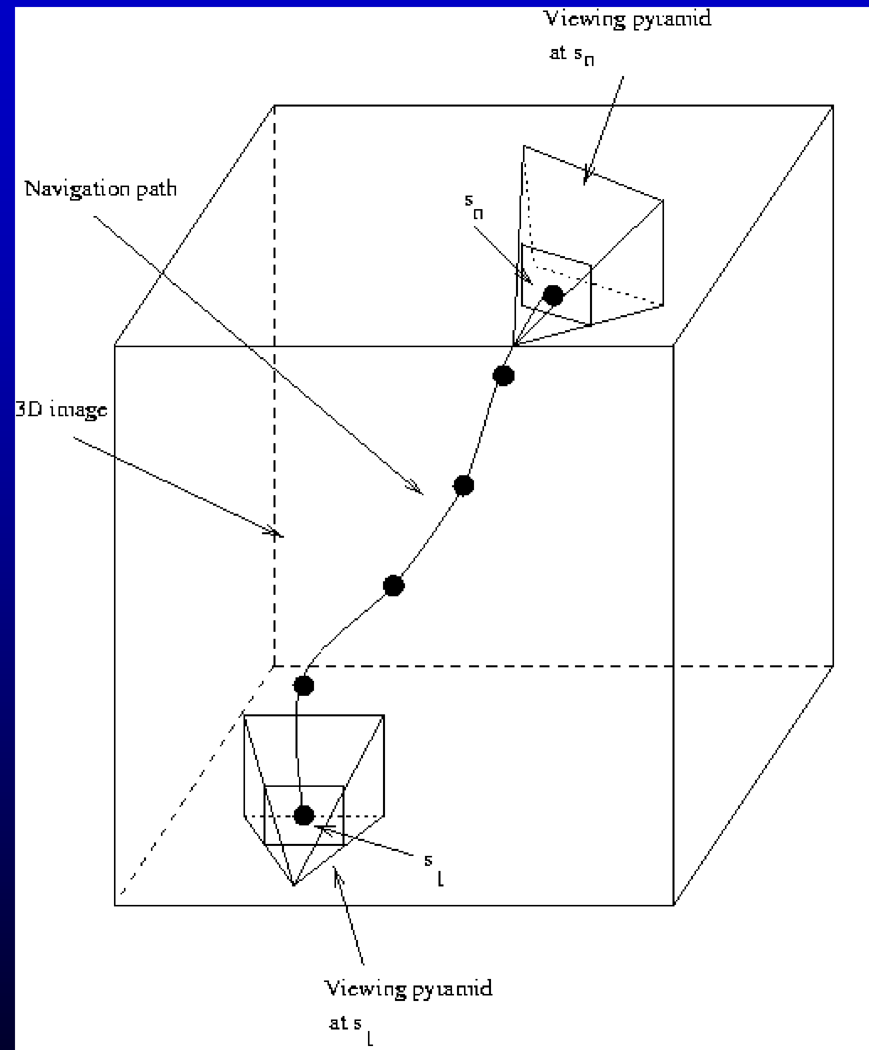


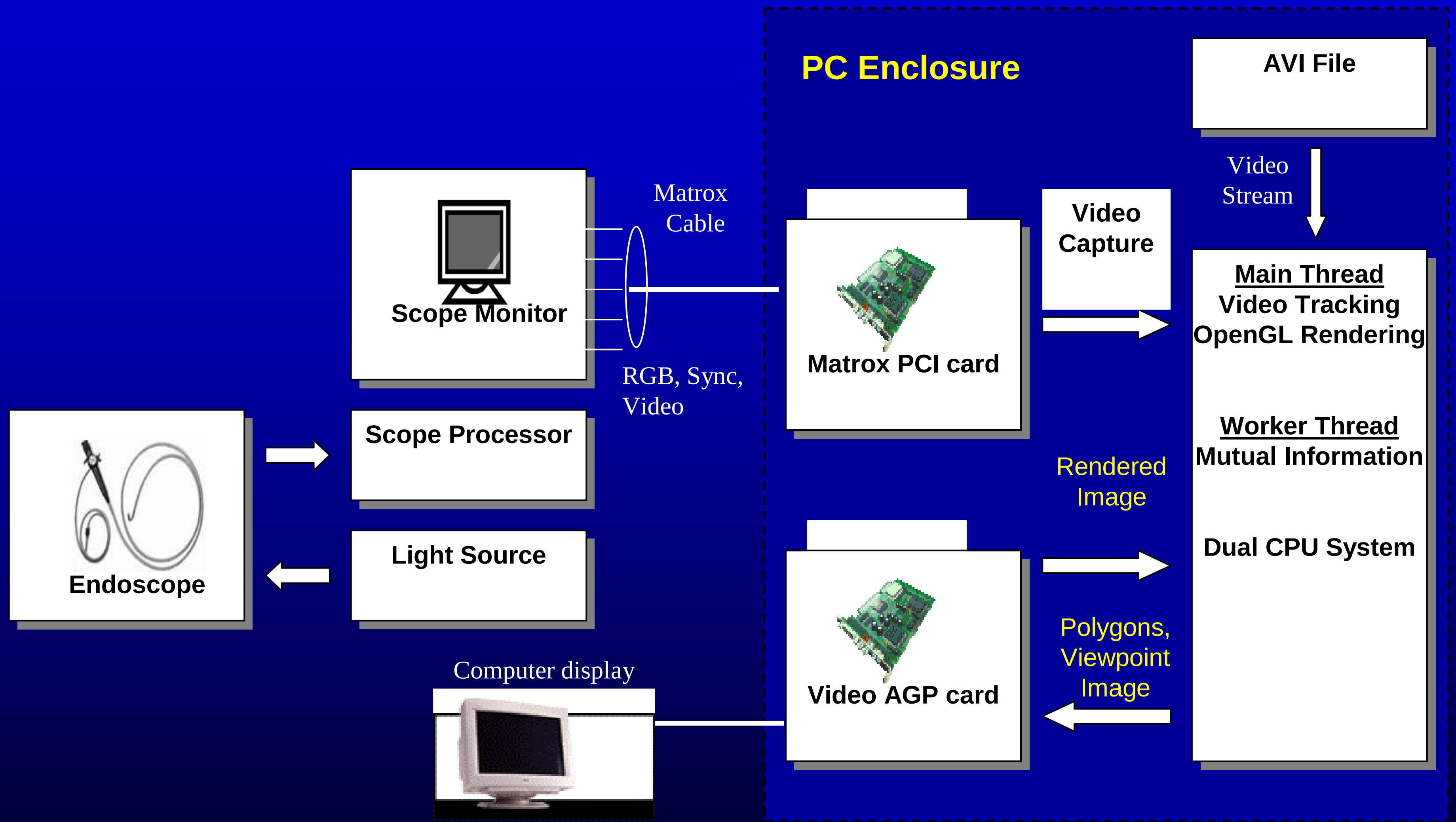
Image-Guided Bronchoscopy Systems

Show potential, but recently proposed systems have limitations:

- CT-Image-based
  - McAdams *et al. (AJR 1998)* and Hopper *et al. (Radiology 2001)*
  - Bricault *et al. (IEEE-TMI 1998)*
  - Mori *et al. (SPIE Med. Imaging 2001, 2002)*
- Electromagnetic Device attached to scope
  - Schwarz *et al. (Respiration 2003)*

→ *Our system*: reduce skill variation, easy to use, reduce “blindness”

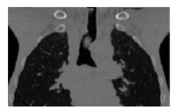
Our System: Hardware



Software written in Visual C++.

Our System: Work Flow

Data Sources



3D CT Scan

Bronchoscope

Data Processing

<u>Stage 1: 3D CT Assessment</u>

1) Segment 3D Airway Tree
2) Calculate Centerline Paths
3) Define Target ROI biopsy sites
4) Compute polygon data

→ Case Study

<u>Stage 2: Live Bronchoscopy</u>

For each ROI:

1) Present virtual ROI site to physician
2) Physician moves scope “close” to site
3) Do CT-Video registration and fusion
4) Repeat steps (1-3) until ROI reached

Stage 1:   3D CT Assessment (Briefly)

1. Segment Airway tree (Kiraly *et al.*, *Acad. Rad.* 10/02)
2. Extract centerlines (Kiraly *et al.*, *IEEE-TMI* 11/04)
3. Define ROIs (e.g., suspect cancer)

4. Compute tree-surface polygon data (Marching Cubes – vtk)

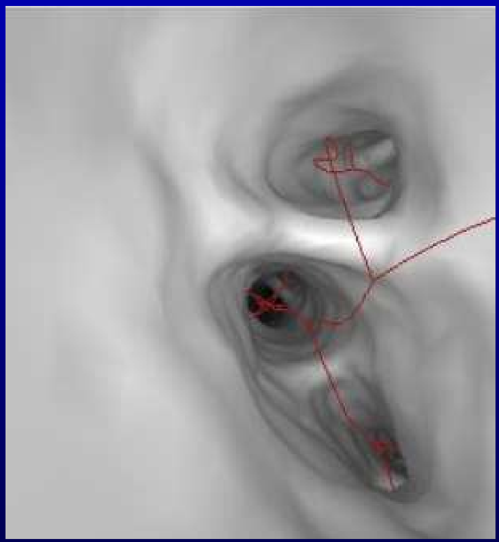
→ CASE STUDY to help guide bronchoscopy

Stage 2: Bronchoscopy - Key Step: CT-Video Registration

Register To the

Virtual 3D CT World Real Endoscopic Video World

$I_{CT}^{X_i}(x, y)$ (Image Source 1) $I_V^F(x, y)$ (Image Source 2)



→*Maximize normalized mutual information to get* $I_{CT}^{X_o}(x, y)$

CT-Video Registration: 1) Match viewpoints of two cameras

Both image sources, I_V and I_{CT}, are cameras.

6-parameter vector representing camera viewpoint $\chi = (X, Y, Z, \alpha, \beta, \gamma)$

3D point $\mathbf{p} = (X_p, Y_p, Z_p)$ mapped to camera point (X_c, Y_c)

through the standard transformation

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = \mathbf{R}(\alpha, \beta, \gamma) \begin{bmatrix} X_p - X \\ Y_p - Y \\ Z_p - Z \end{bmatrix}$$

The final camera screen point is given by (x, y) where

$$x = \frac{f X_c}{Z_c}, \quad y = \frac{f Y_c}{Z_c}$$

Bronchoscope Video Camera Model

Following Okatani and Deguchi (*CVIU* 5/97), assume video frame *I(p)*

abides by a Lambertian surface model; i.e.,

$$I(\mathbf{p}) = \sigma \frac{L \cos \theta_s}{\pi R^2}$$

where

$\mathbf{p} = (X_p, Y_p, Z_p)$

θ_s = light source-to-surface angle

R = distance from camera to surface point **p**

Make FOVs of both Cameras equal

To facilitate registration, make both cameras I_V and I_{CT} have the *same* FOV.

To do this, use an endoscope calibration technique (Helferty et al., *IEEE-TMI* 7/01).

Measure the bronchoscope's focal length (done off-line):

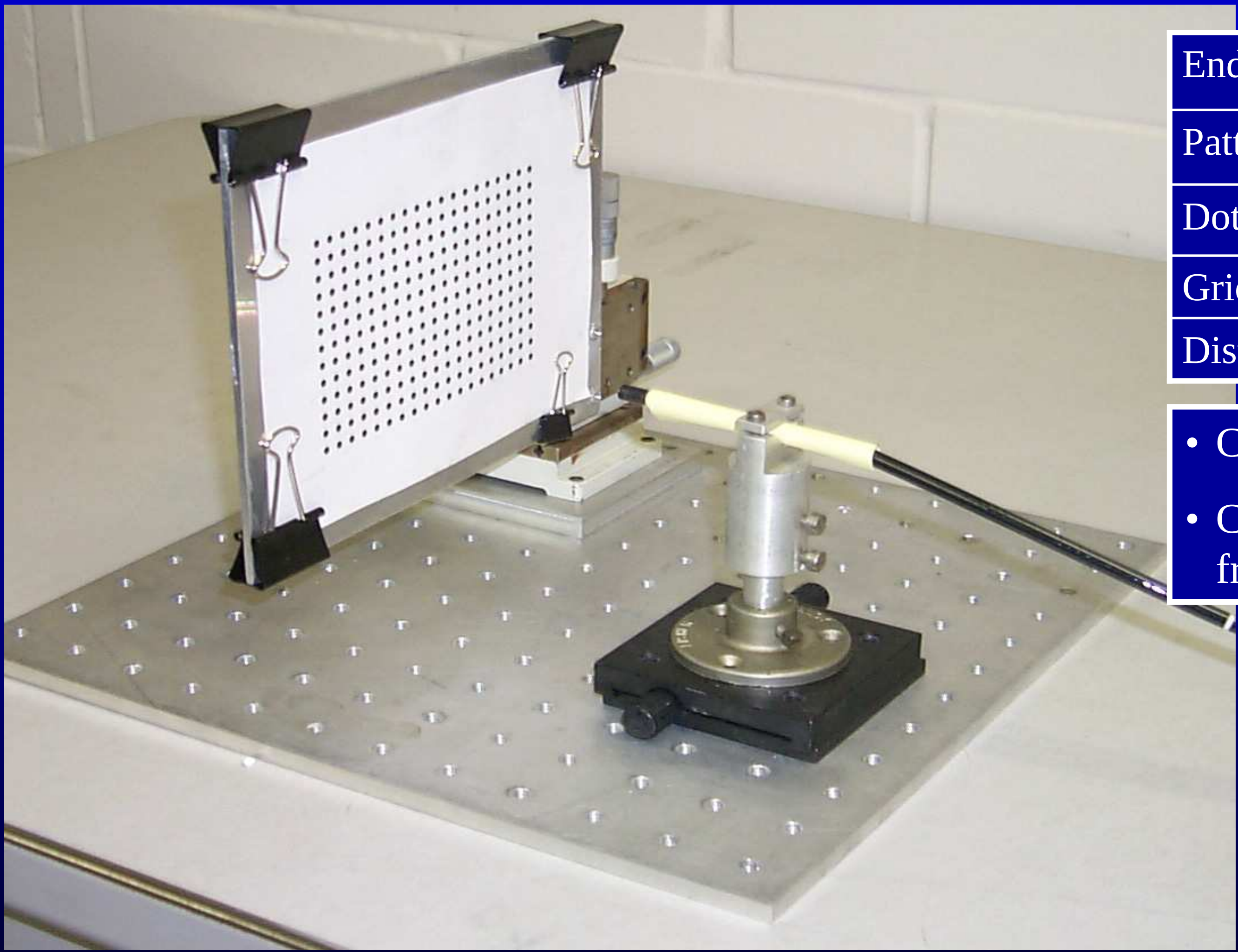
$$f = \frac{(x_r - x_l) Z_m}{(X_r - X_l)}$$

Then, the angle subtended by the scope's FOV is

$$\theta_{\mathrm{FOV}} = 2 \tan^{-1} \left(\frac{x_r - x_l}{2f} \right)$$

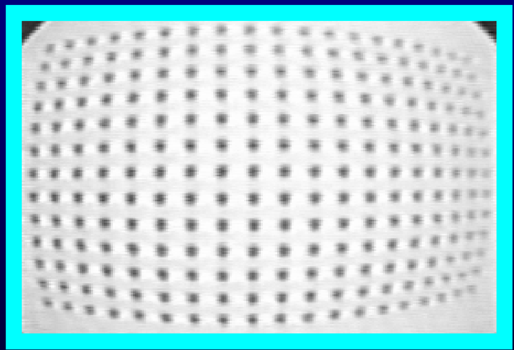
Use *same* value for endoluminal renderings, I_{CT}.

Bronchoscope Calibration Device



Endoscope	Olympus BF P200
Pattern size	4.5” x 3”
Dot Diameter	.1”
Grid size	19 x 13
Distance	3”

- Capture known dot pattern.
- Compute Calibration parameters from frame.



Captured Frame

See Helferty *et al.*, *IEEE Trans. Med. Imaging*, July 2001.

CT (Endoluminal Rendering) Camera Model

Related to video frame model *I(p)*:

$$I_{CT}(\mathrm{p}) = \frac{(\cos \phi_{\mathrm{p}})^{1/2} \cos \theta_s}{(1 + .0025R^2)} + L_a$$

where

$$\mathbf{p} = (X_p, Y_p, Z_p)$$

Use OpenGL

θ_s = light source-to-surface angle

θ_p = angle between camera axis and vector pointing toward **p**

R = distance from camera to surface point **p** (from range map)

L_a = ambient light (indirect lighting)

Normalized Mutual Information

Mutual Information (MI) – used for registering two different image sources:

a) Grimson *et al*. (*IEEE-TMI* 4/96)

b) Studholme *et al*. (*Patt. Recog*. 1/99) → <u>normalized MI (NMI)</u>

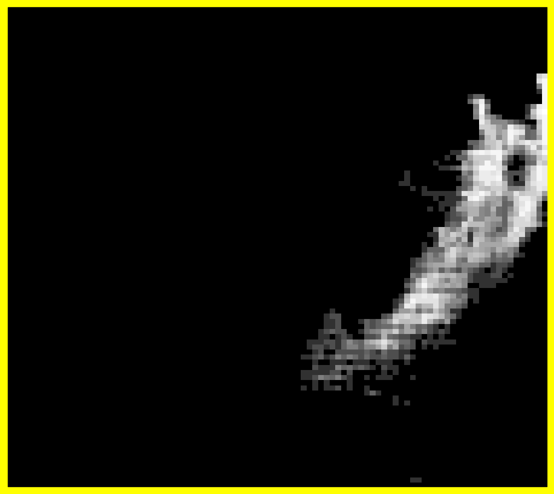
Normalized Mutual Information

Normalized mutual information (NMI):

$$S_{NMI}(I_V, I_{CT}) = \frac{h(V) + h(CT)}{h(V, CT)}$$

where

$$\begin{aligned} h(V) &= -\sum_{k=0}^{M-1}\sum_{l=0}^{M-1} p_{V,CT}(k,l)\log p_V(k) \\ h(CT) &= -\sum_{k=0}^{M-1}\sum_{l=0}^{M-1} p_{V,CT}(k,l)\log p_{CT}(l) \\ h(V,CT) &= -\sum_{k=0}^{M-1}\sum_{l=0}^{M-1} p_{V,CT}(k,l)\log p_{V,CT}(k,l) \end{aligned}$$



"optimal" $p_{V,CT}$

and $p_V(k) = \sum_{l=0}^{M-1} p_{V,CT}(k,l)$ is a histogram (marginal density)

CT-Video Registration – Optimization Problem

Given a fixed video frame $I_V^F(x,y)$ and starting CT view $I_{CT}^{\chi_i}(x,y)$

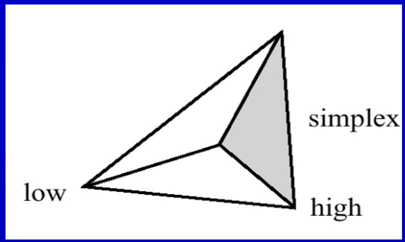
Search for the optimal CT rendering $I_{CT}^{\chi_o}(x,y)$ subject to

$$\chi_o = \arg\left\{ \max_{\chi \in N_{\chi_i}} \left[\, S_{NMI}\left(I_{CT}^{\chi}(x,y), I_V^F(x,y)\right) \, \right] \right\}$$

where viewpoint $\chi = (X, Y, Z, \alpha, \beta, \gamma)$ is varied over neighborhood N_{χ_i} about χ_i

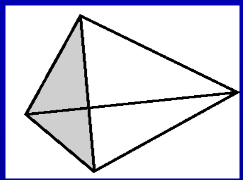
Optimization algorithms used: step-wise, simplex, and simulated annealing

Simplex Optimization



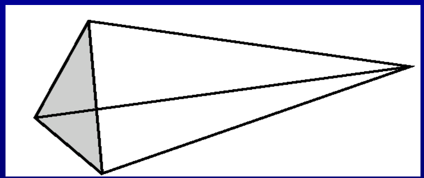
A simplex is an N dimensional figure with N+1 vertices

$$V^0 = ((X, Y, Z, \alpha, \beta, \gamma)$$
$$V^1 = ((X + \Delta X, Y, Z, \alpha, \beta, \gamma)$$
$$V^2 = ((X, Y + \Delta Y, Z, \alpha, \beta, \gamma)$$
$$\vdots$$
$$V^6 = ((X, Y, Z, \alpha, \beta, \gamma + \Delta\gamma)$$



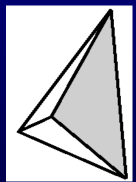
Reflection

$$V^* = \frac{2}{N} \sum_{i=0; i \neq i_{HI}}^{N} V^i - V^{i_{HI}}$$



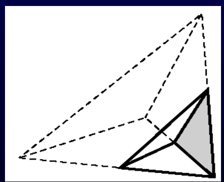
Expansion

$$V^{**} = \frac{3}{N} \sum_{i=0; i \neq i_{HI}}^{N} V^i - 2V^{i_{HI}}$$



Collapse

$$V^{***} = \frac{1}{2N} \sum_{i=0; i \neq i_{HI}}^{N} V^i - \frac{1}{2} V^{i_{HI}}$$



Collapse Simplex

$$V^i = \frac{1}{2} V^i + \frac{1}{2} V^{i_{LOW}}$$

CT-Video Registration: Simplex Optimization

Calculate vertices of initial simplex (N=6):

$\chi_0 = \{X, Y, Z, \alpha, \beta, \gamma\}$ (initial viewpoint), $\chi_1 = \{X + \Delta X, Y, Z, \alpha, \beta, \gamma\}, \ldots, \chi_N = \{X, Y, Z, \alpha, \beta, \gamma + \Delta\gamma\}$

iteration = 0

Do

Compute $S_{NMI}(\chi_i), \quad i = 0, 1, \ldots, N$

Note the best and worst vertices and associated NMI measures: χ_{min}, χ_{max}, S_{min}, S_{max}

Get reflection of χ_{min} across face of simplex: $\chi^* = (\frac{2}{N} \sum_{\chi_i \neq \chi_{min}} \chi_i) - \chi_{min}$

If $(S_{NMI}(\chi^*) > S_{max})$

Get $2\times$ reflection of χ_{min} across face of simplex: $\chi^{**} = (\frac{3}{N} \sum_{\chi_i \neq \chi_{min}} \chi_i) - 2\chi_{min}$

If $(S_{NMI}(\chi^{**}) > S_{max}) \quad \chi_{max} = \chi^{**}$

Else $\quad \chi_{max} = \chi^*$

Else

Contract χ_{min} $\frac{1}{2}$ distance toward face of simplex: $\chi^{***} = (\frac{1}{2N} \sum_{\chi_i \neq \chi_{min}} \chi_i) + \frac{1}{2}\chi_{min}$

If $(S_{NMI}(\chi^{***}) > S_{min}) \quad \chi_{min} = \chi^{***}$

Else contract all vertices $\chi_i \neq \chi_{max}$ $\frac{1}{2}$ distance toward χ_{max}: $\chi_i = \frac{1}{2}(\chi_i + \chi_{max})$

iteration = iteration + 1

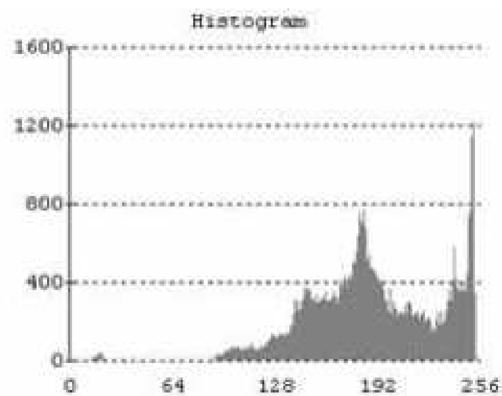
While $\{(S_{max} - S_{min}) >$ TOLERANCE and iteration $<$ MAX_ITER $\}$

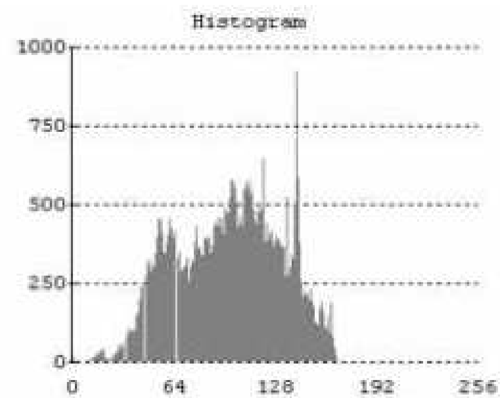
CT-Video Optimization Example

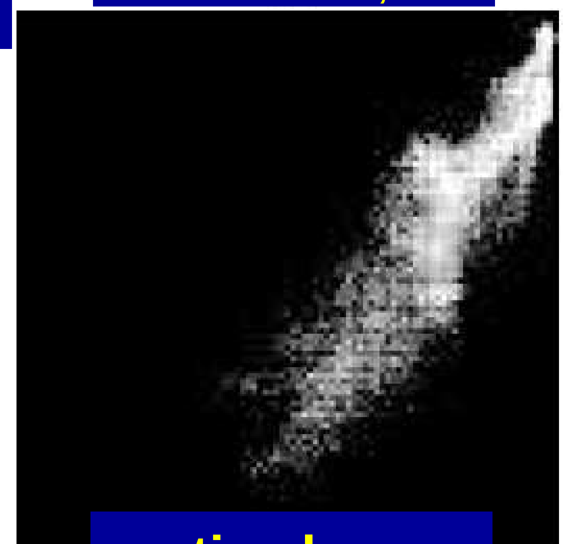
Fixed Video Frame

Optimal CT Rendering

initial $p_{V,CT}$







optimal $p_{V,CT}$

System Results

Three sets of results are presented:

A. Phantom Test
   controlled test, free of subject motion

B. Animal Studies
   controlled in vivo (live) tests

C. Human Lung-Cancer Patients
   real clinical circumstances

A. Phantom Test

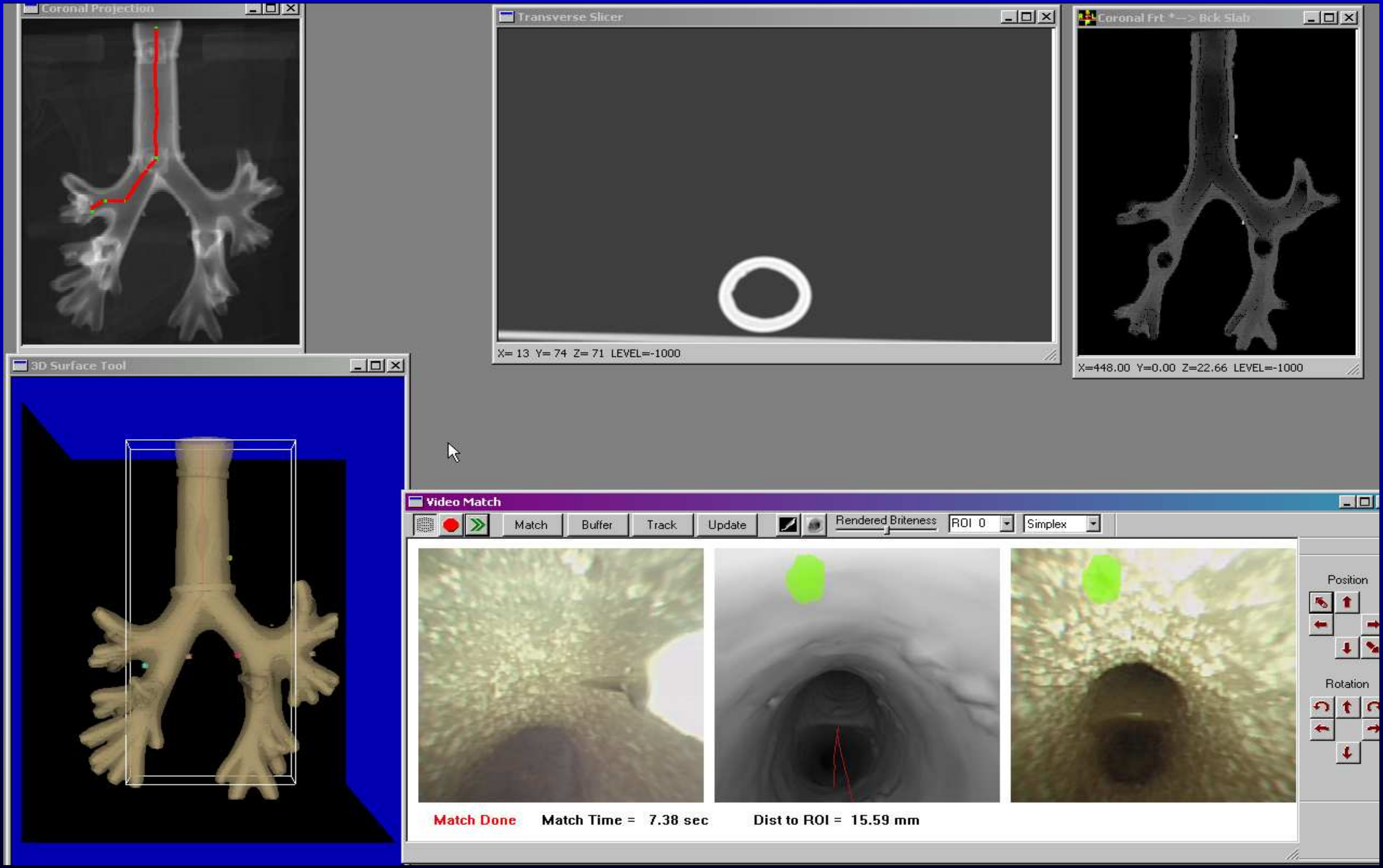
Goal: Compare biopsy accuracy under controlled stationary circumstances using (1) the standard CT-film approach versus (2) image-guided bronchoscopy.

Experimental Set-up:

Rubber phantom - human airway tree model used for training new physicians.

CT Film - standard form of CT data.

Computer Set-up during Image-Guided Phantom “Biopsy”



Phantom Accuracy Results (6 physicians tested)

Film biopsy accuracy: **5.53mm** Std Dev: **4.36mm**

Guided biopsy accuracy: **1.58mm** Std Dev: **1.57mm**

Physician	film accuracy (mm)	guided accuracy (mm)
1	5.80	1.38
2	2.73	1.33
3	4.00	1.49
4	8.87	1.60
5	8.62	2.45
6	3.19	1.24

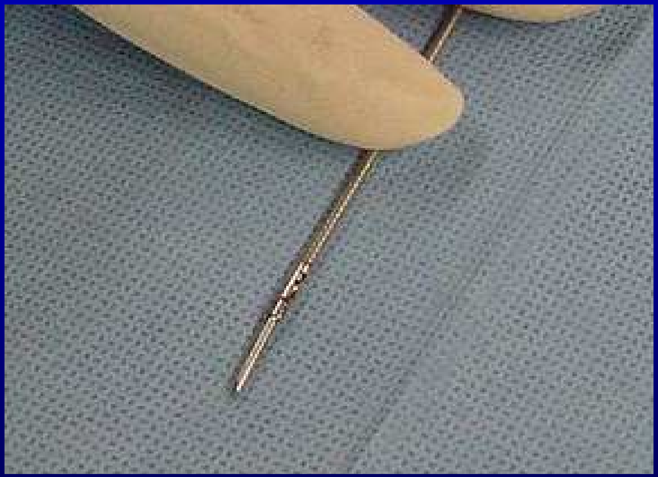
→ALL physicians improved greatly with guidance

→ALL performed nearly the **SAME** with guidance!

B. Animal Studies

Goals: Test the performance of the image-guided system under controlled in vivo circumstances (breathing and heart motion present).

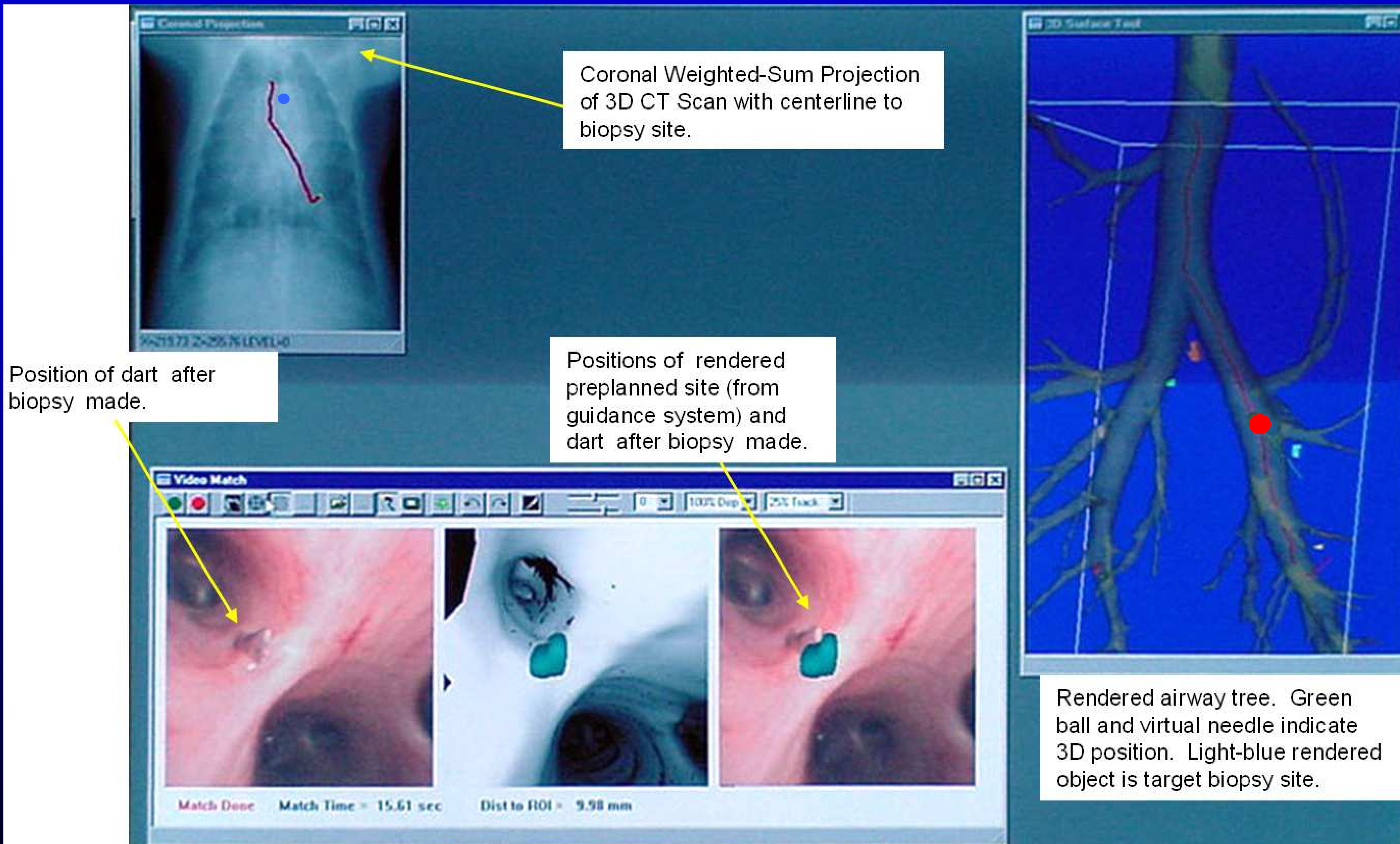
Experimental Set-up:



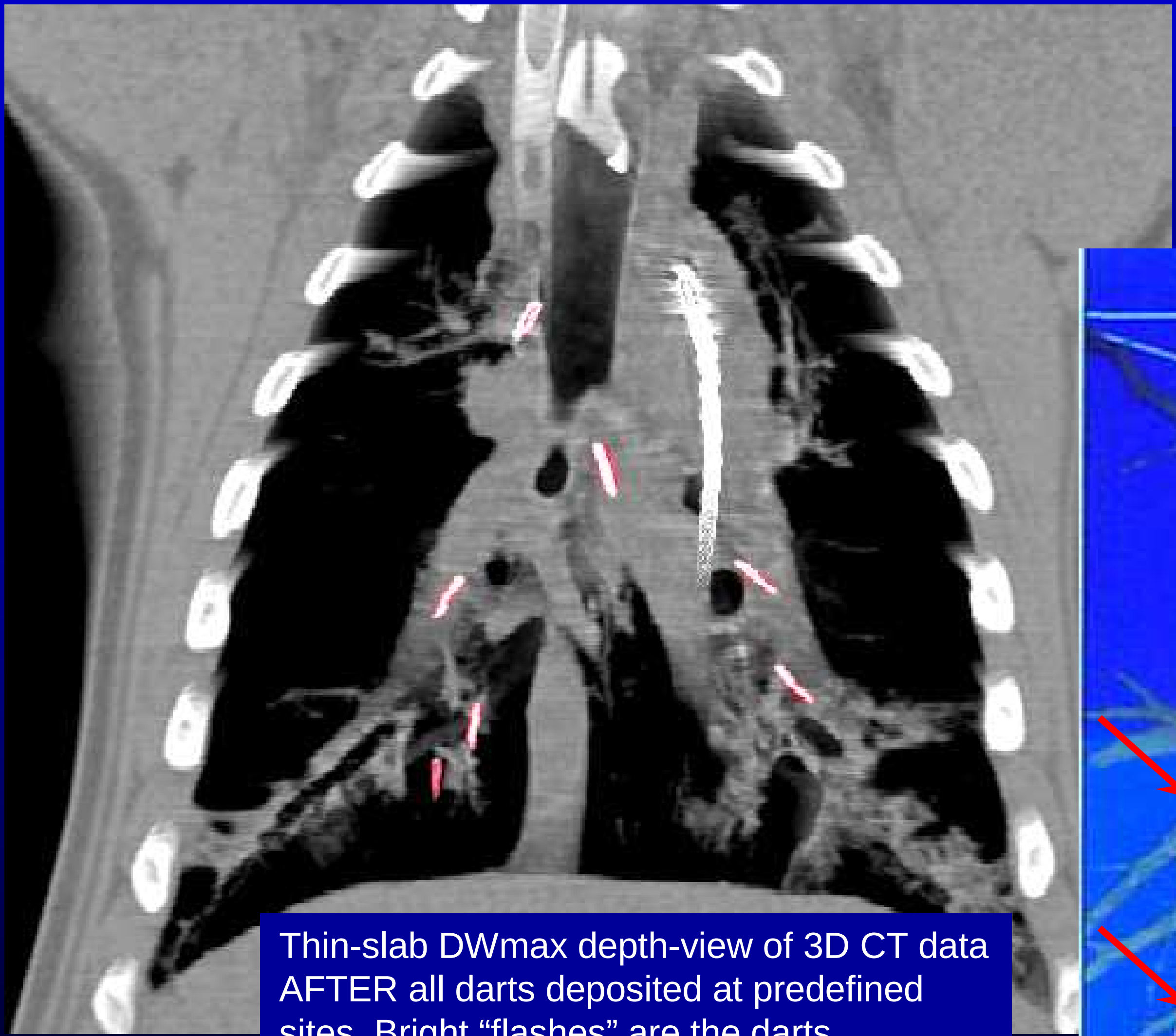
biopsy dart

Computer system during animal test
(done in EBCT scanner suite).

Animal Study - Stage 2: Image-Guided Bronchoscopy



Composite View after All Real Biopsies Performed

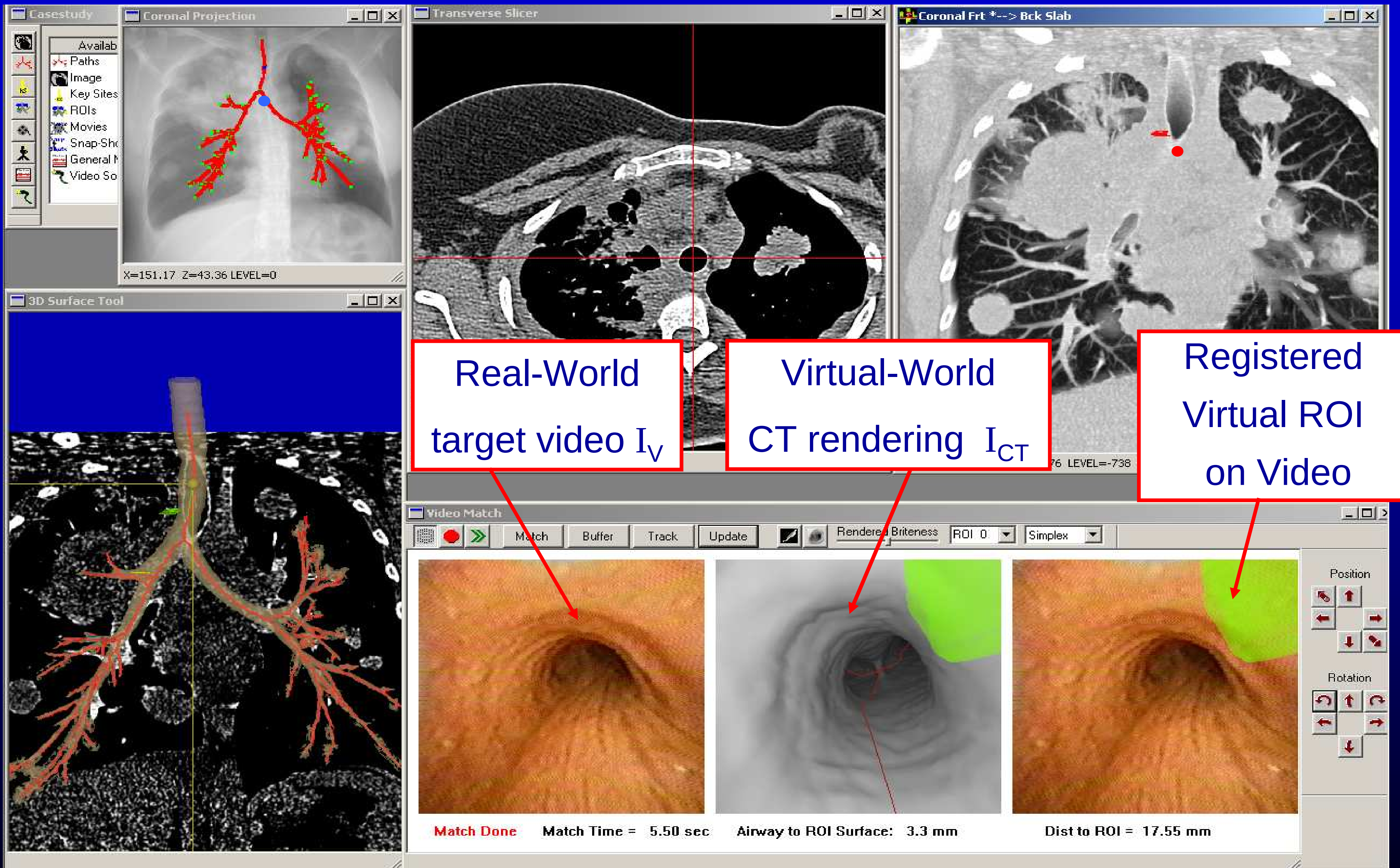


Thin-slab DWmax depth-view of 3D CT data AFTER all darts deposited at predefined sites. Bright “flashes” are the darts.

Rendered view of preplanned biopsy Sites

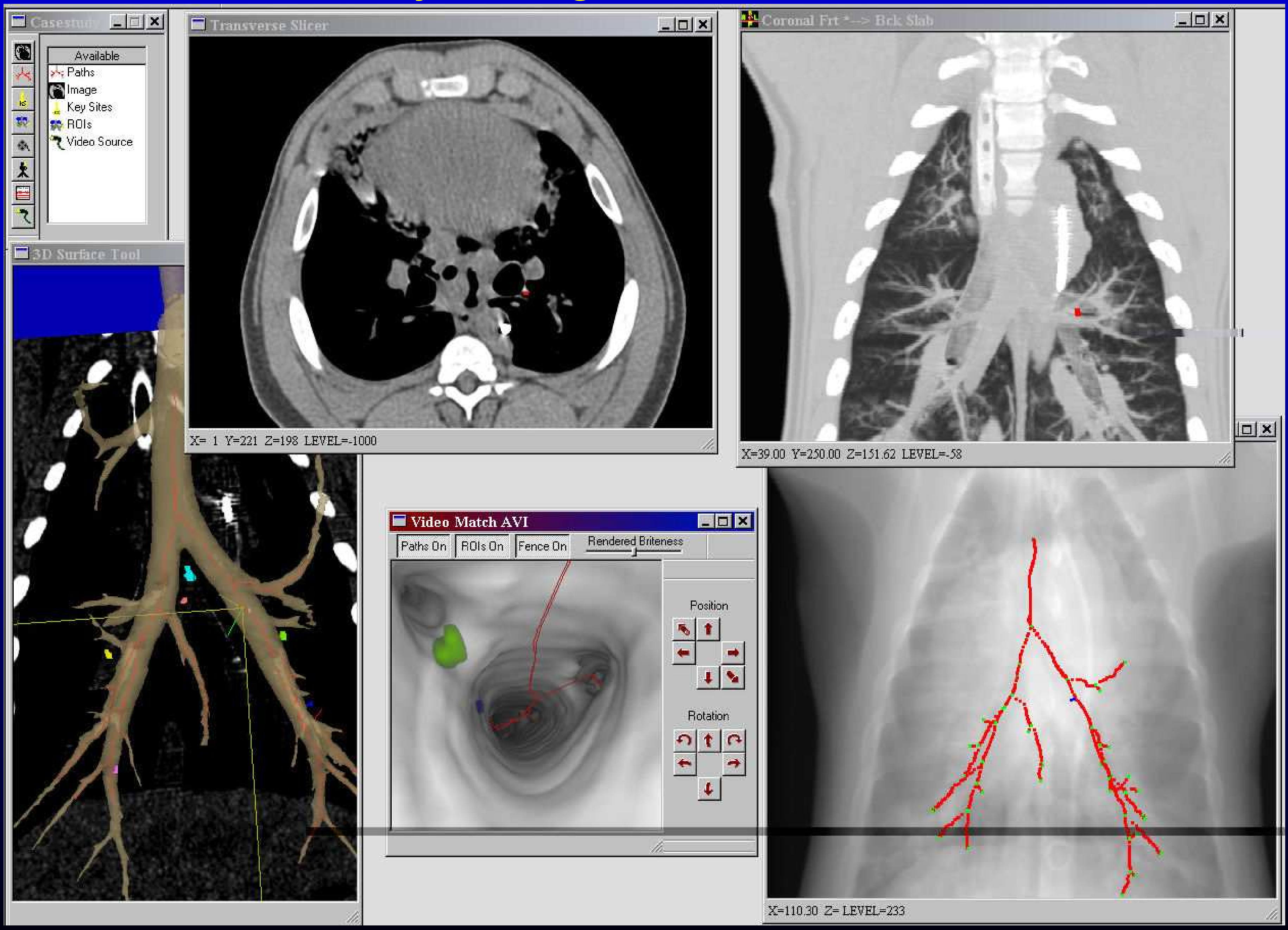
C. Human Studies

Stage 2: Image-Guided Bronchoscopy

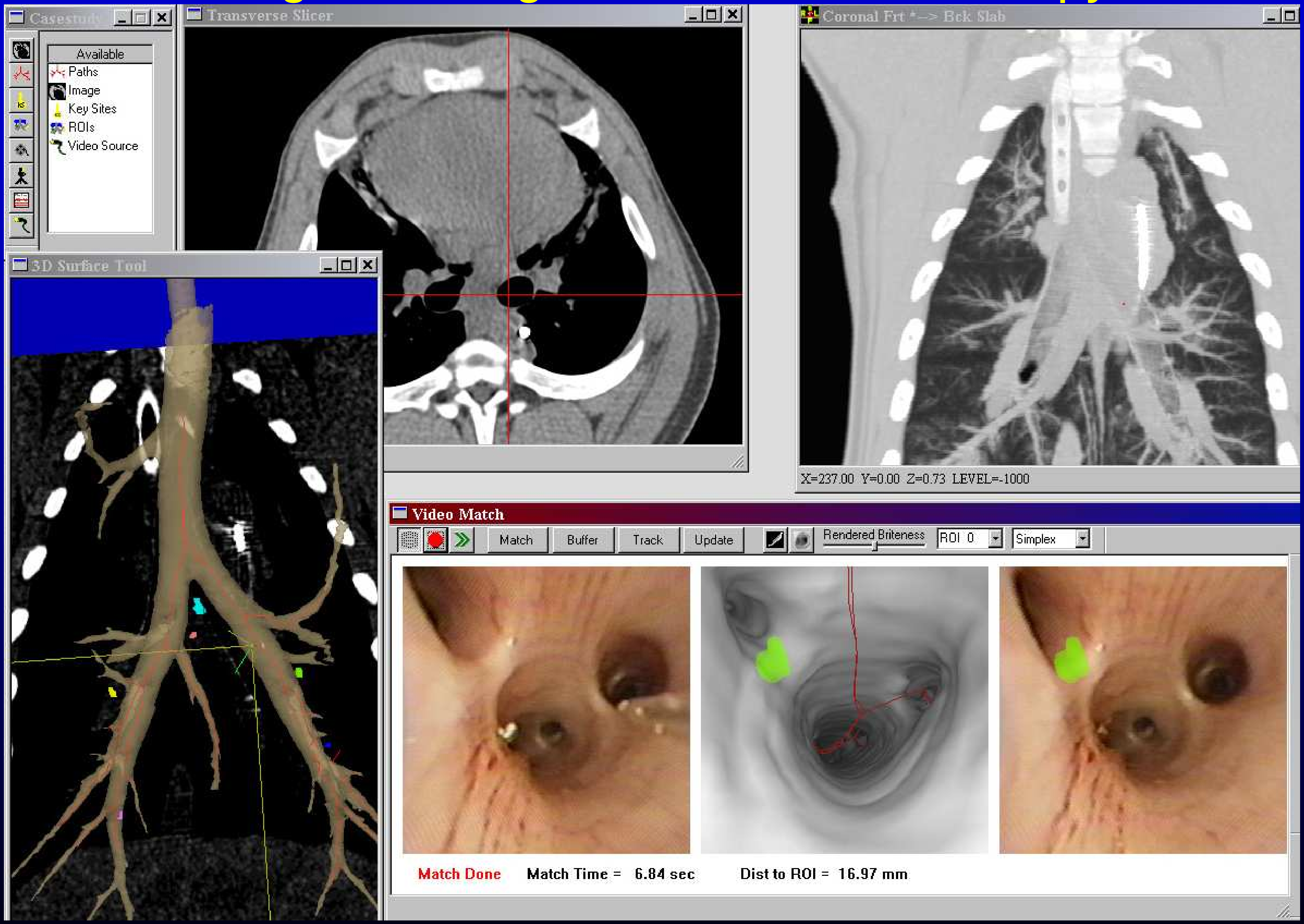


(case h005 [UF], mediastinal lymph-node biopsy, in-plane res. = 0.59mm, slice spacing = 0.60mm)

Animal Study - Stage 1: 3D CT Assessment



Stage 2: Image-Guided Bronchoscopy



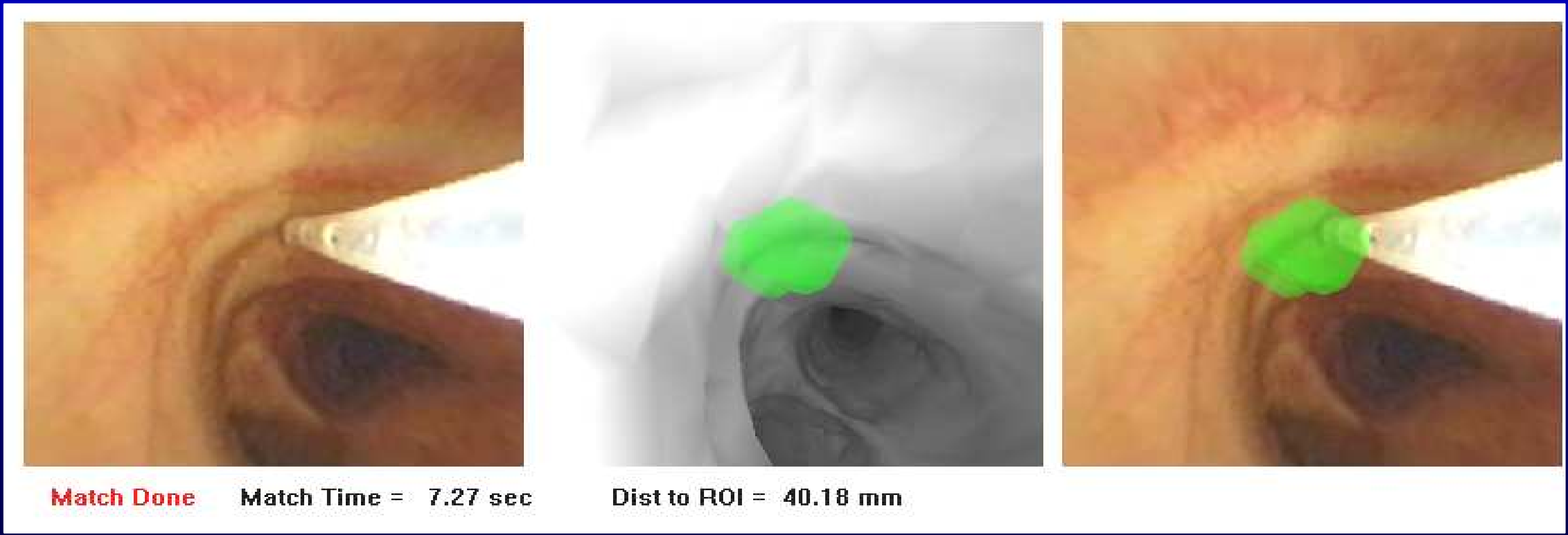
Case DC: performing a biopsy

Left view: Real-time bronchoscopic video view; biopsy needle in view

Center: Matching virtual-bronchoscopic view showing preplanned region (green)

Right: Preplanned region mapped onto bronchoscopic view, with biopsy needle in view.

Distance to ROI = scope's current distance from preplanned biopsy site (ROI).



- All nodal-region samples showed normal appearing lymphocytes.
- Subsequent open-lung biopsy showed a suspect mass to be inflammatory tissue.

→ 40 lung-cancer patients done to date

Case UF: approaching a biopsy site

Left view: Real-time bronchoscopic video view

Center: Matching virtual-bronchoscopic view showing preplanned region (blue); red line is preplanned guidance path

Right: Preplanned region mapped onto real bronchoscopic view.

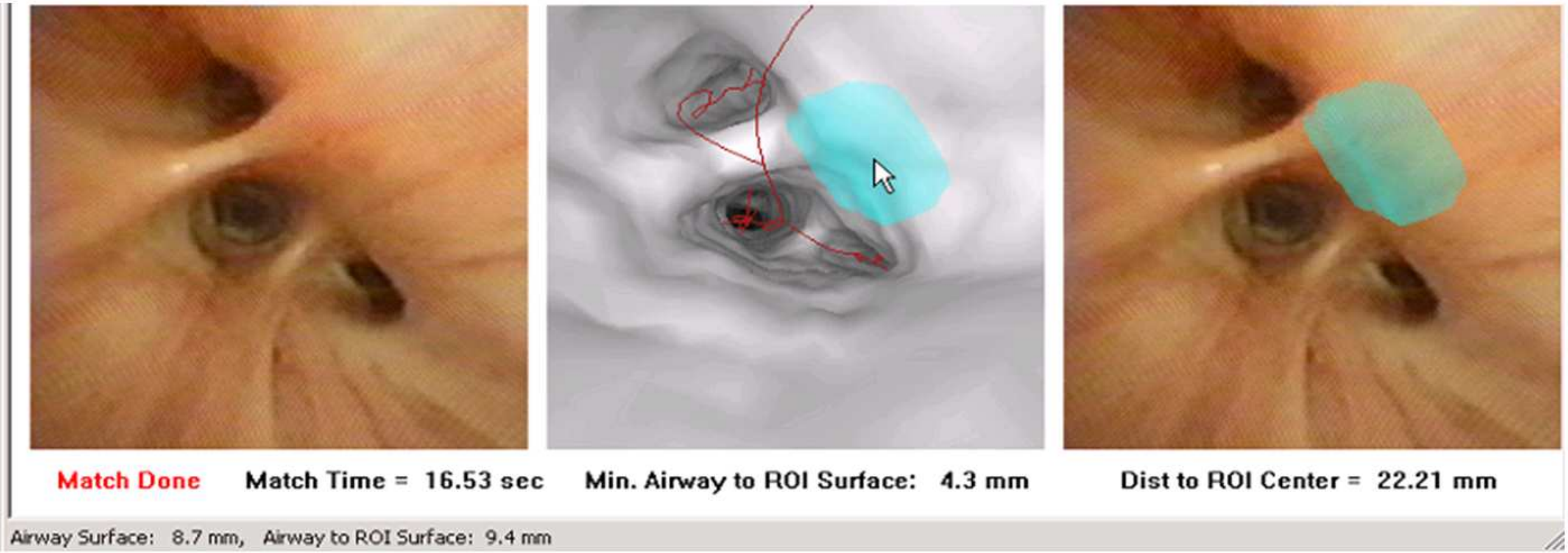
Distance Measures:

Min Airway to ROI Surface = distance of closest airway surface point to ROI (target lymph node)

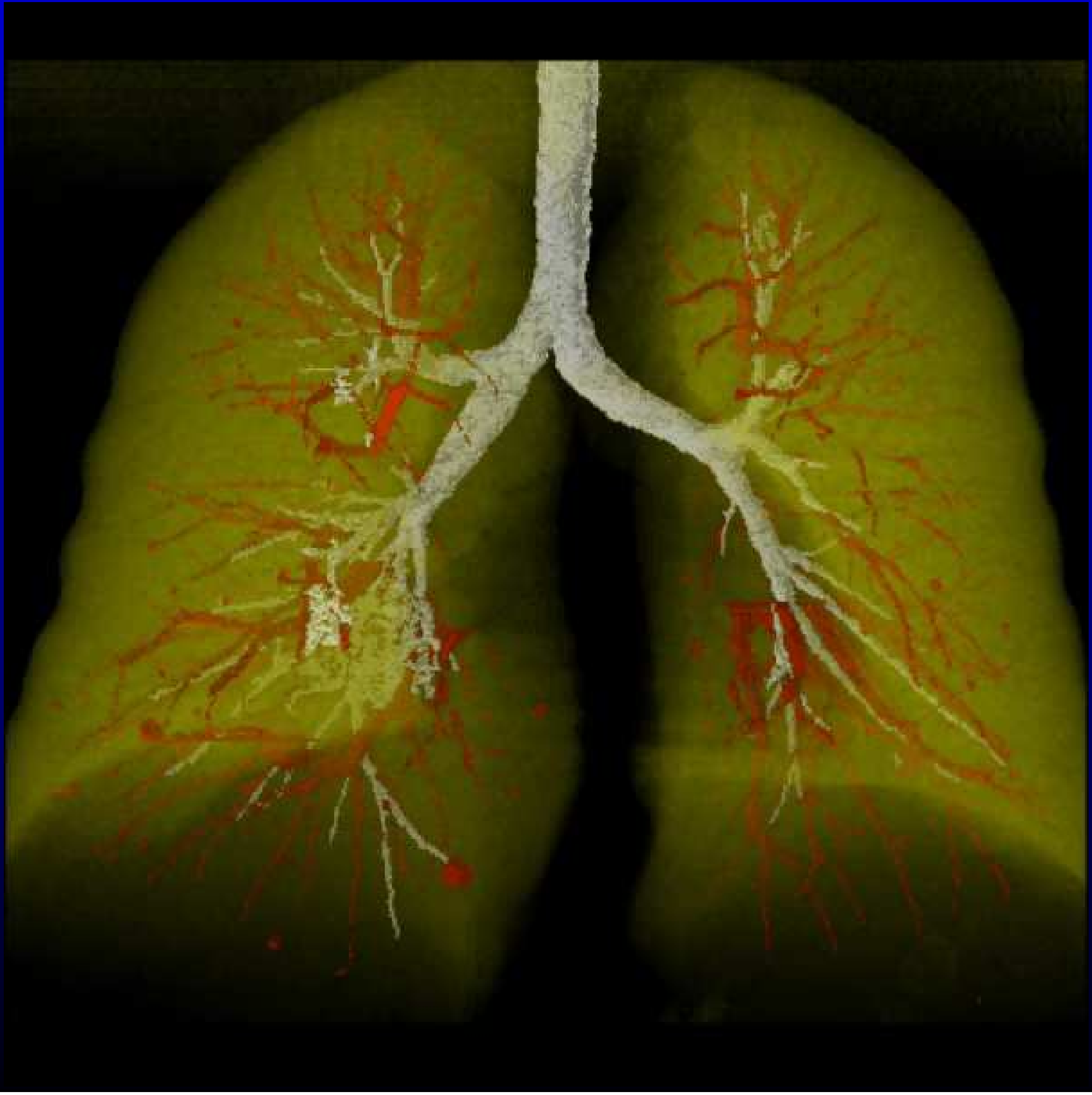
Distance to ROI Center = cursor's current distance from center of preplanned biopsy site (ROI).

Airway Surface = distance of cursor to airway surface

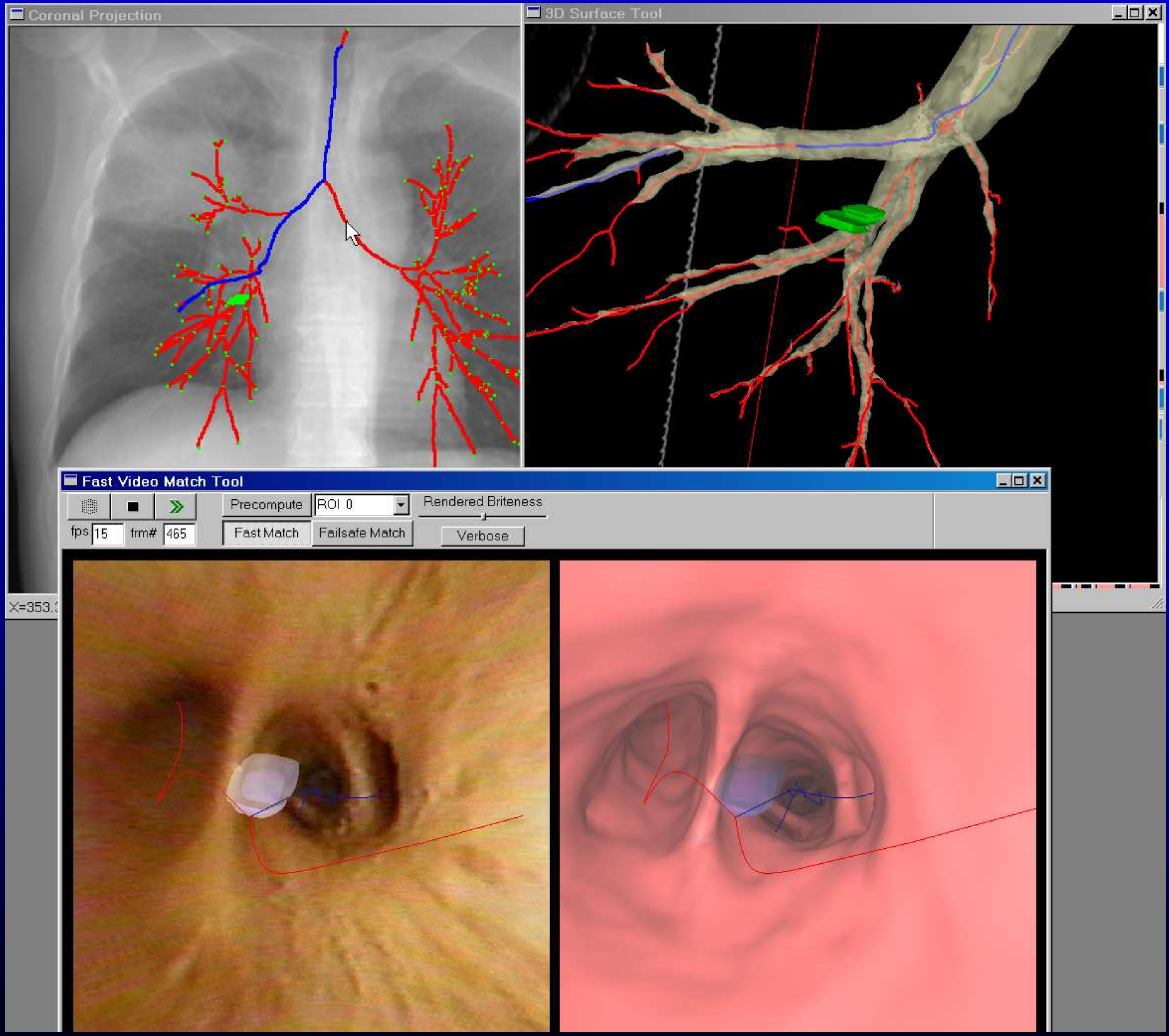
Airway to ROI Surface = distance of airway surface point that cursor is on to ROI



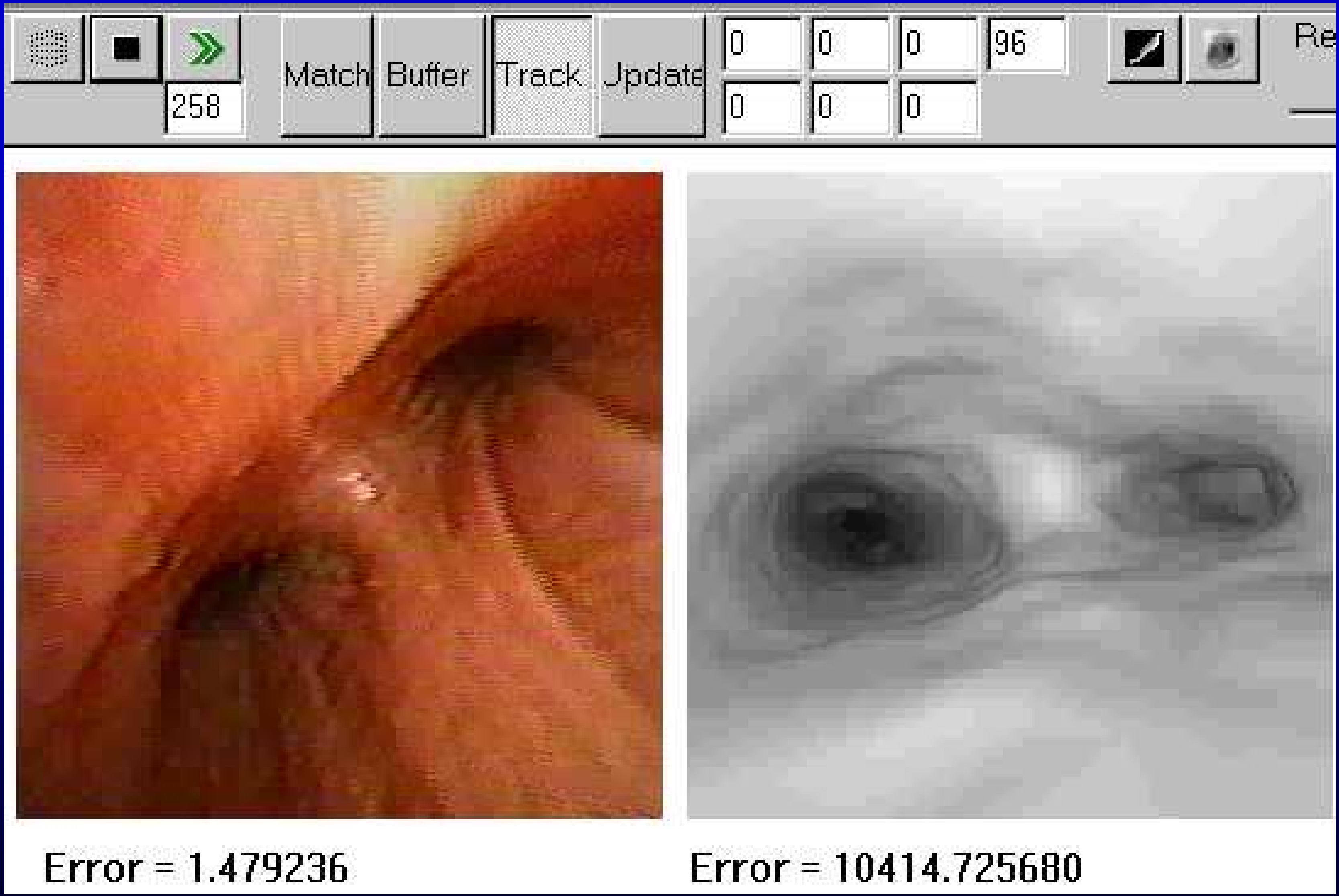
Guidance to Peripheral Lung-Cancer Nodules – In Progress



Real-Time Image-Guided Bronchoscopy – In Progress



Real-Time Image-Guided Bronchoscopy – In Progress



Comments on System

- Effective, easy to use

  → A technician – instead of $$ physician – performs nearly all operations

- Gives a considerable “augmented reality” view of patient anatomy

  → less physician stress

- Fits seamlessly into the clinical lung-cancer management process.

- Appears to greatly reduce the variation in physician skill level.

This work was partially supported by:

NIH Grants #CA74325, CA91534, HL64368, and RR11800

Whitaker Foundation, Olympus Corporation

Thank You!

Lung Cancer

- Lung Cancer: #1 cancer killer, 30% of all cancer deaths,
  1.5 million deaths world-wide,
  < 15% 5-year survival rate (nearly the worst of cancer types)

- To diagnose and treat lung cancer,

1) 3D CT-image assessment – preplanning, noninvasive
2) Bronchoscopy – invasive

→ Procedure is LITTLE HELP if diagnosis/treatment are poor

Normalized Mutual Information

Mutual Information (MI) – used for registering two different image sources:

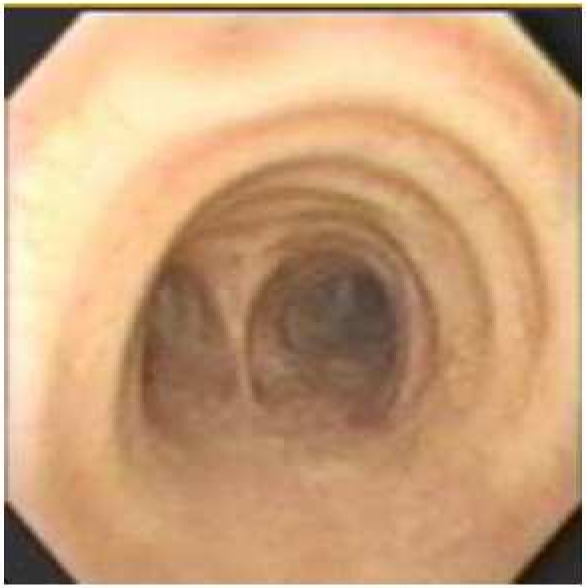
a) Grimson *et al*. (*IEEE-TMI* 4/96)

b) Studholme *et al*. (*Patt. Recog*. 1/99) → normalized MI (NMI)

We use normalized mutual information (NMI) for registration:

$$S_{NMI}(I_V, I_{CT}) = \frac{h(V) + h(CT)}{h(V, CT)}$$

(a)



(b)