PENTAX Contract
Scanning Fiber Endoscope (SFE)
Quarterly Report

15 June 2007

University of Washington
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Project Overview

Technology Summary

- 2 long (4.35 meter) probes shipped to PENTAX
- 30 Hz probe produced and tested
  - 10 KHz scan frequency
- 30 Hz software in coding phase
- Have better understanding of and modified braking control software for improved performance
- Temperature control improved for increased image stability and reduced central image distortion
- Lens test system operational
- Developed better understanding of resolution and delivered Powerpoint to PENTAX
- Several imaging tests performed
- Software and user interface improved
- New bending method developed

Modified PENTAX Project Milestones

Agreed to on September 15, 2006

Date due	March 15, 2007	September 15, 2007
Proto type	SFE	SFE
Outer Diameter [mm]	1.0	1.2
Rigid Tip Length [mm]	<15	<10
Shaft Length [m]	5 (3/2)	5 (3/2)
Viewing Direction	Forward	Forward
Field of View [deg]	100 to 120	100 to 120
Resolution [um]	40	40
Depth of Field [mm]	2-50	2-50
Frame Rate [Hz]	15 plus scanner tests	30
Image quality	+++	++++ with no distortion
System	1 probe (1.6 mm diameter)	-
Animal Test	In Vivo	In Vivo

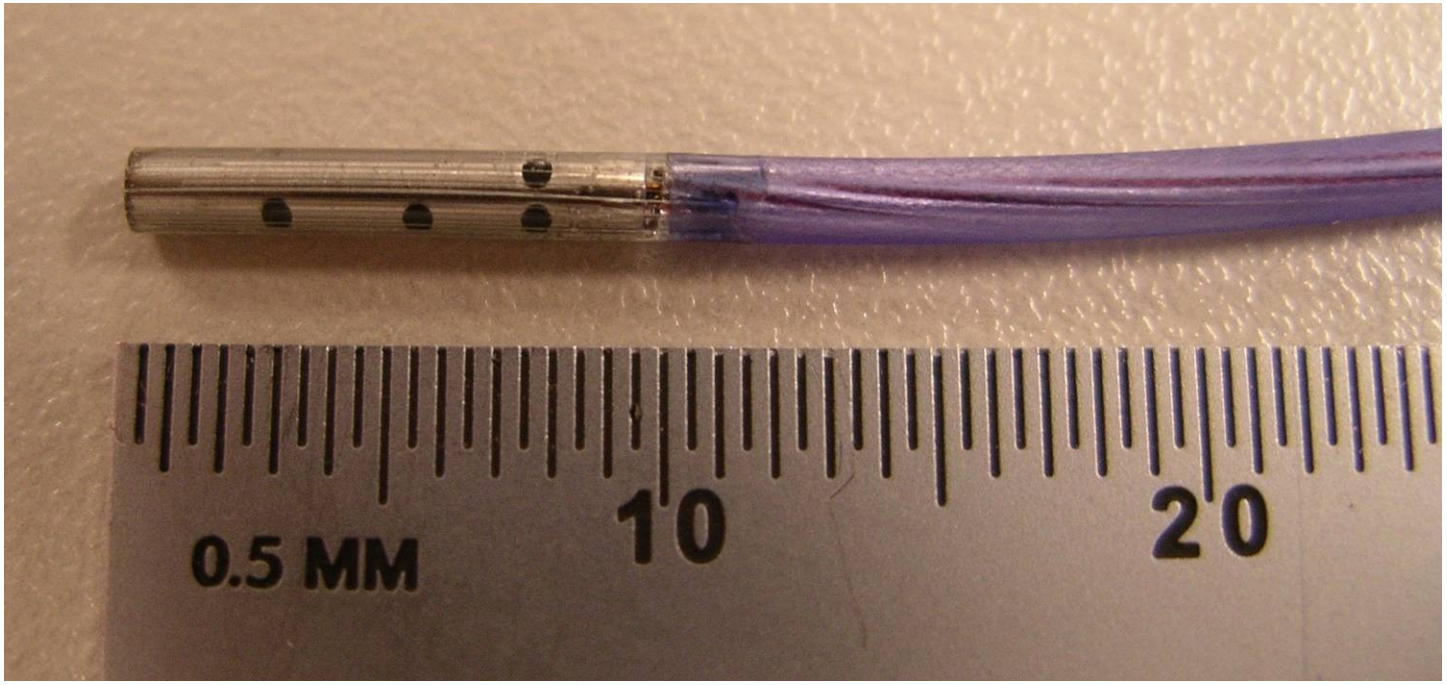
December 31, 2006 – Deliver new base station and two 1.5 m probes
Continue work on mosaic software
Test our ideas on tip bending when time permits

Progress and Status Details

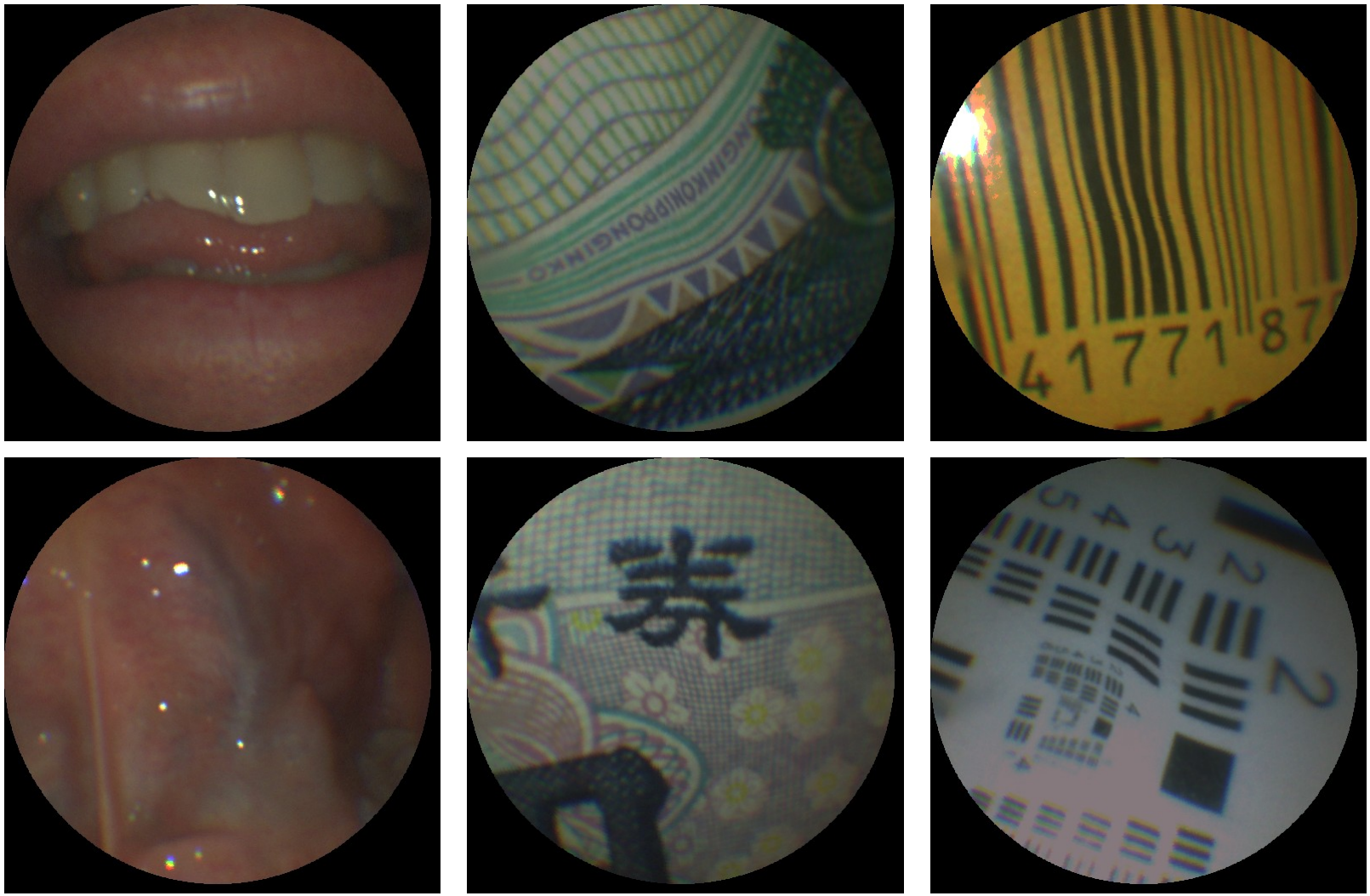
30 Hz Scanner Development

- Allows 500 line image resolution at 30 Hz frame rate
- Requires 10 KHz scanner resonant frequency
- Uses custom 80 micron cladding diameter fiber
  - Ordered from StockerYale
  - Single mode to 420 nm (RGB fiber)
- First probe built and tested
  - Fiber resonance of 10.13 KHz
  - Distal tip tube length of 10 mm
  - Used PENTAX 2 lens system and standard 250 micron return fibers for total diameter of 1.6 mm
- Images gathered
  - Used old software so image is undersampled
  - AGC did not operate properly (will be corrected in new SW)
  - Drive and braking not optimized so some image distortion is present
- Probe tested till destruction
  - Worked at 90 degree field-of-view
  - At higher drive fiber to piezo tube connection broke

30 Hz Probe



30 Hz Images



30 Hz Software Development

- FPGA code being rewritten for 10 KHz scanner
  - Pixel sampling rate increased from 10 MHz to 25 MHz
  - Chromatic aberration correction being implemented
  - Image contrast controls being added
  - Several smaller changes being made to improve overall system performance
- Architecture complete and coding has begun
  - Initial changes only to Image generator board
- Will require changes to LabVIEW software
  - Some new features (contrast control, etc.)
  - Most changes transparent to user

New Braking Software

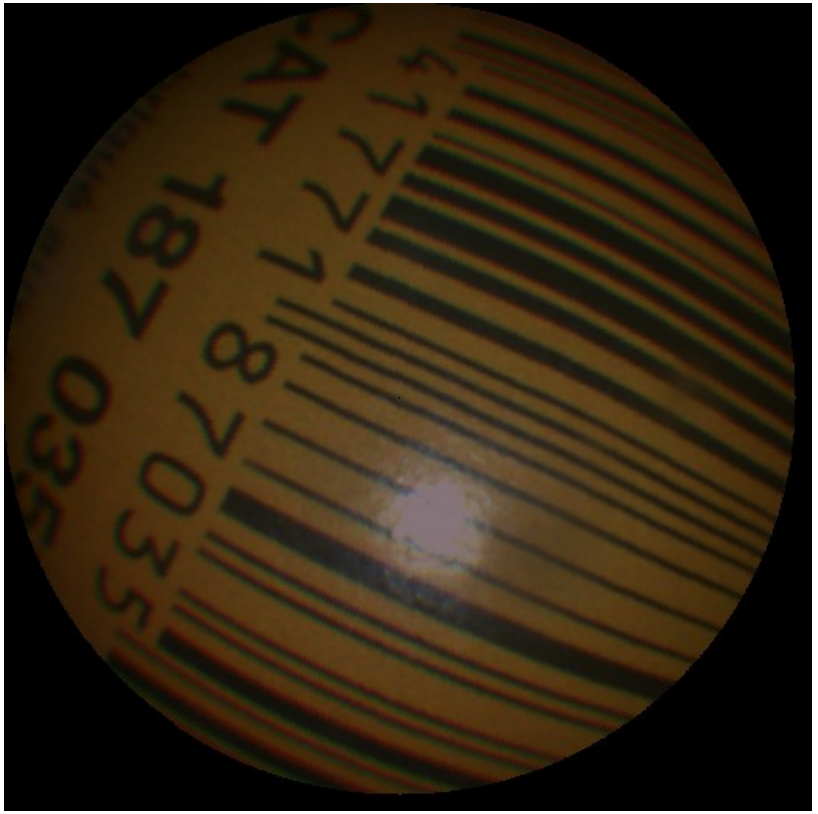
- Simplified parameter entry with greater control
- Two braking periods that have identical controls
- Parameters per braking period
  - Fiber frequency
  - Number of braking cycles (fractional cycles allowed)
  - X and Y braking voltage
  - X and Y phase change
  - Braking profile, sine or square wave
- Biggest improvement comes from ability to set separate X and Y phase changes
- New software requires new stored file structure

Laser Power and Image Distortion

- It was noticed that an image would rotate slightly when laser power was changed
- Cause was a slight change in temperature within the probe distal tip
  - Believed that light reflected from fiber tip entered cladding and exited near fiber piezo attachment point
  - This light heated the attachment point slightly
  - In operation the heating coil has slightly less measured current passing through it as the attachment point is a secondary heater
- The heating of the attachment point softens the adhesive, increasing damping, and slightly changing the resonant frequency
- The changes in fiber characteristics cause image rotation and central area distortion
  - Distortion is due to the fact that system was calibrated at one laser power level and operated at another
- Temporary fix allows user to adjust temperature set point to compensate for temperature change at the attachment point
- Note that scanner built with high temperature epoxy do not exhibit this behavior (but are more difficult to break due to the high Q)

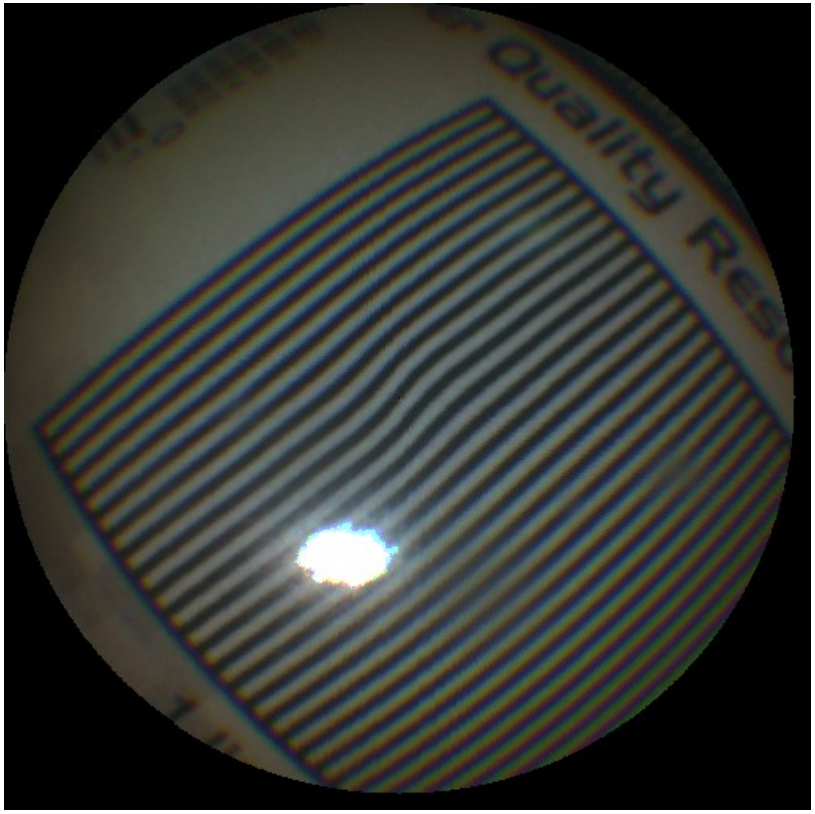
Temperature Compensation Example

Before temperature compensation

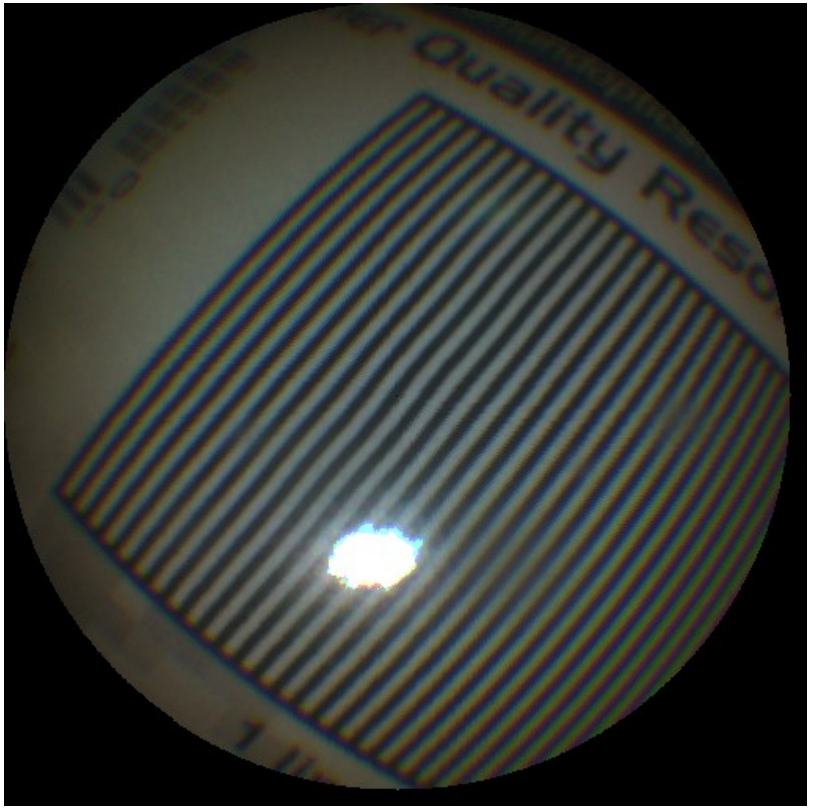


After temperature compensation

Temperature Compensation Example 2

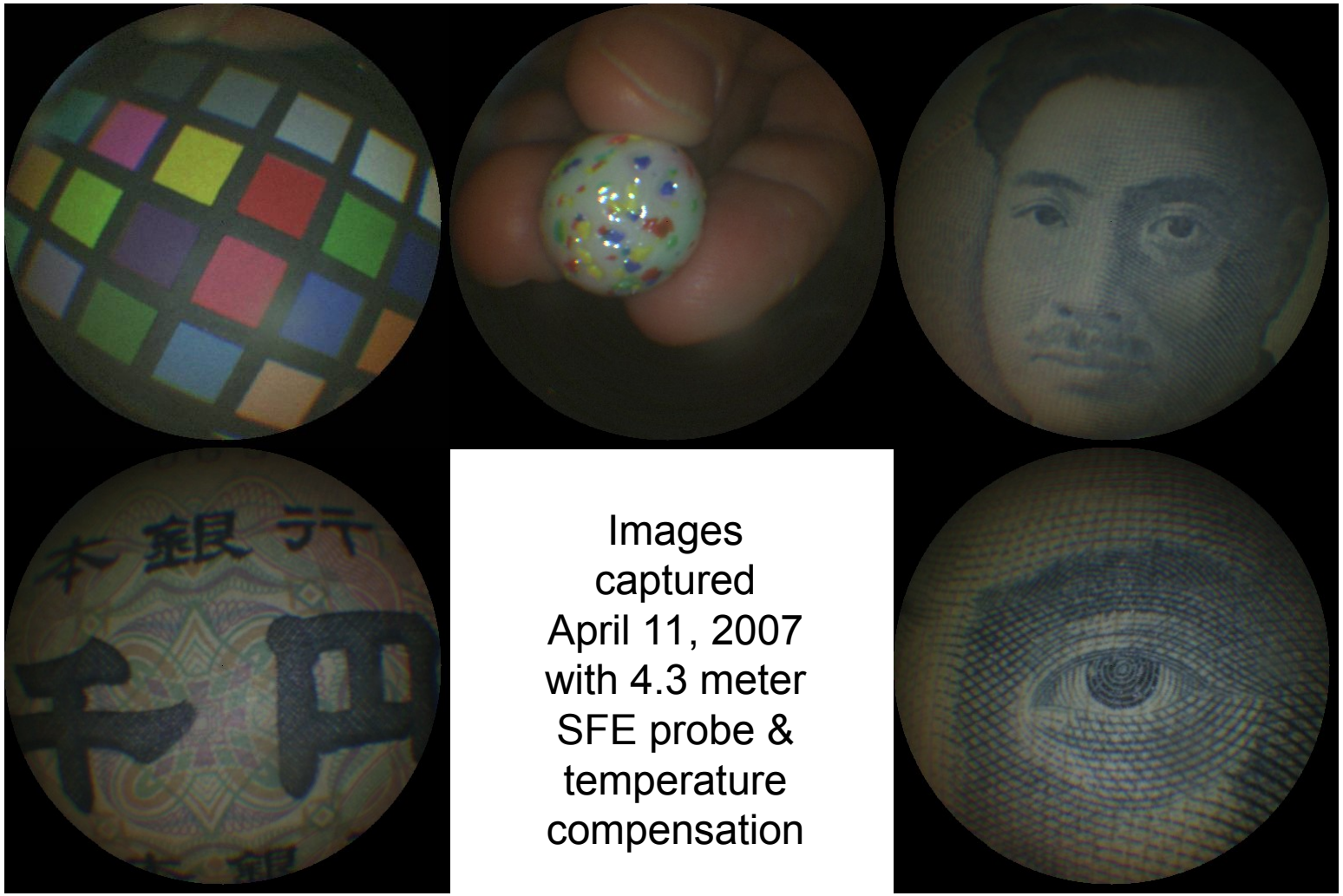


Before temperature compensation



After temperature compensation

SFE Images

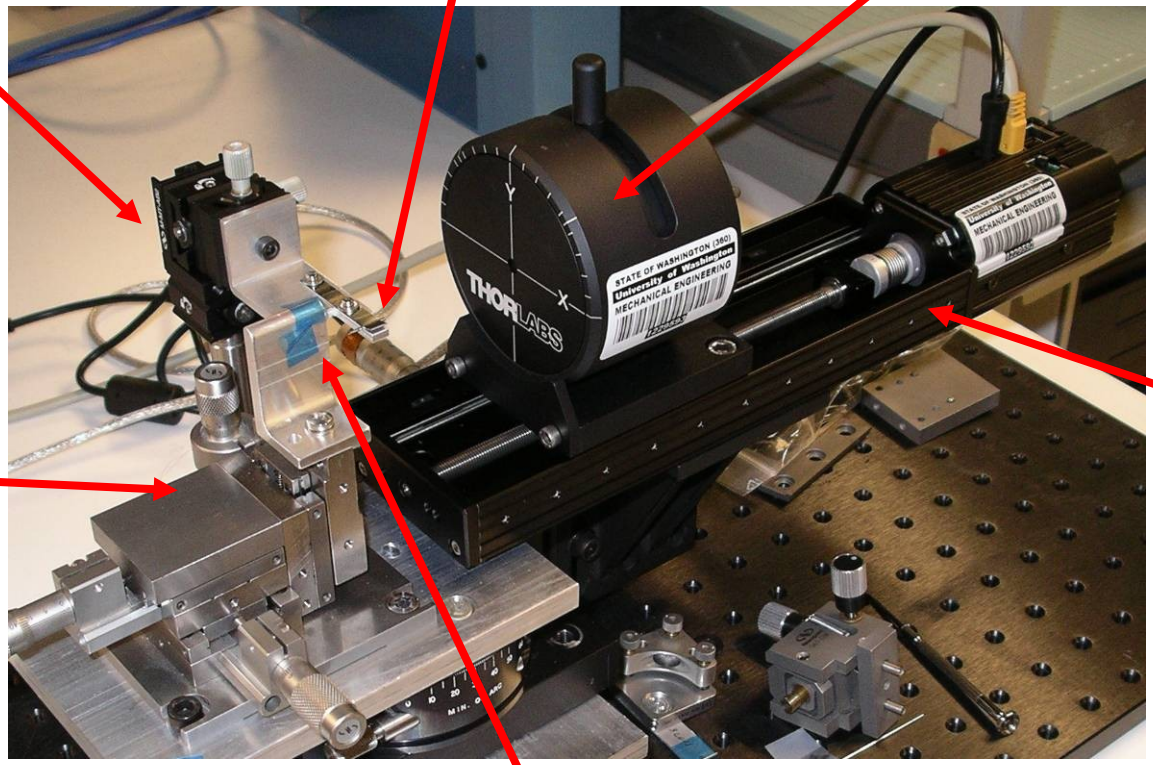


Images captured April 11, 2007 with 4.3 meter SFE probe & temperature compensation

Lens Test System

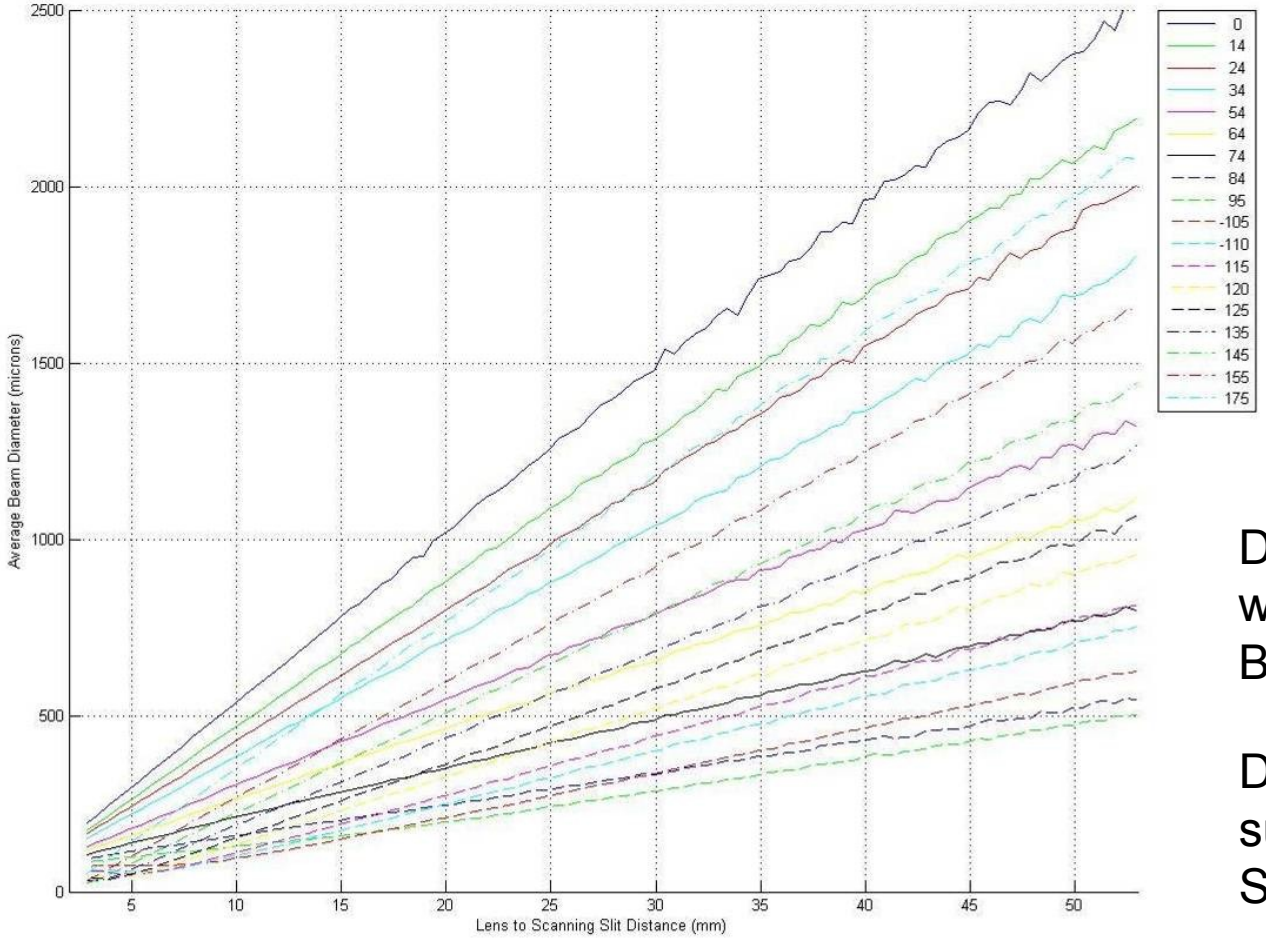
- Tests spot size of lens systems
  - At different distances from lens
  - At different fiber to lens distances
  - At different fiber to lens offsets (angles out)
  - At each color (red, green, and blue)
- Uses slit scanning beam profiler
  - Purchased from ThorLabs
  - Automated Z motion stage
- Will not operate while fiber is scanning
  - Fiber scans to rapidly
- Currently operational
  - Tested PENTAX standard 3 lens system and custom SFE 2 lens system
- Used to position fiber in scan tube for desired spot focus profile
  - Adjusts fiber to lens distance
  - Previously this was adjusted by hand
  - Allows much better system focus

Lens Test System



Example: Spot Size vs. Image Distance

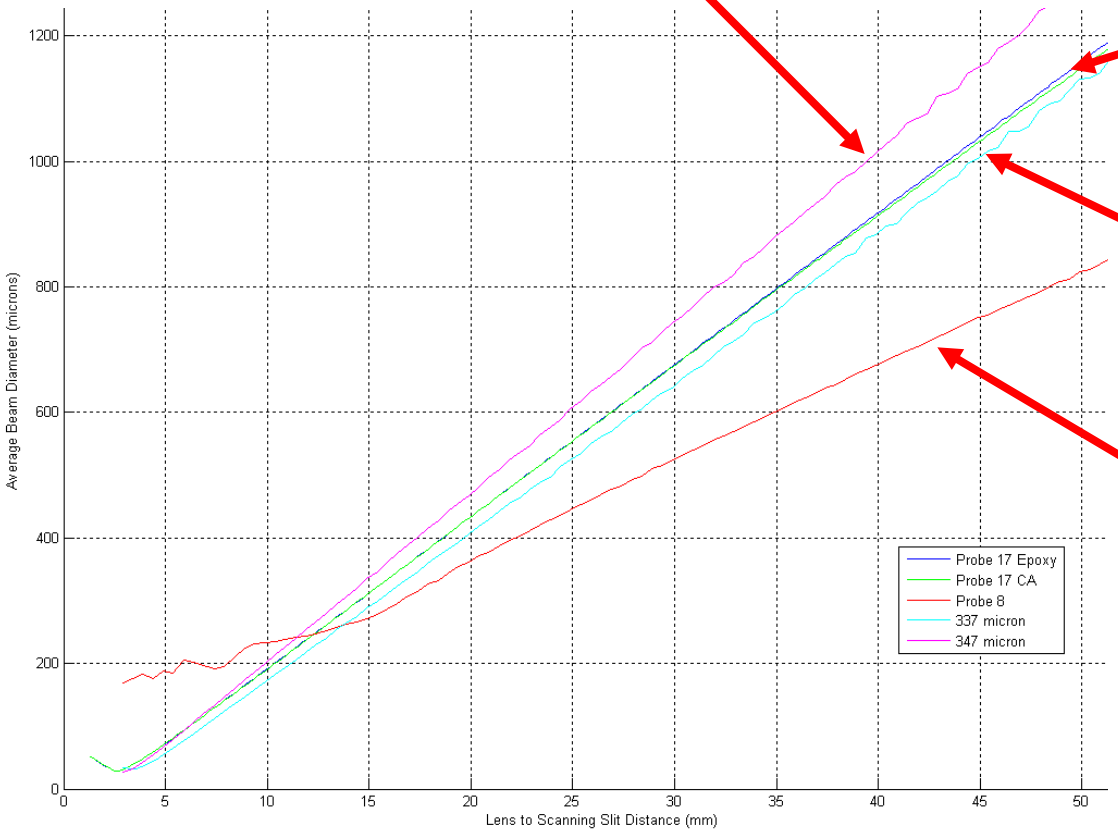
for different fiber to lens spacing



Data measured with Thorlabs Beam Profiler

Data for PENTAX supplied 2 element SFE lens system

Probe 17 Assembly Example



Upper desired focus curve

Probe 17 focus results using beam profiler to set lens to fiber distance

Lower desired focus curve

Probe 8 hand focus results

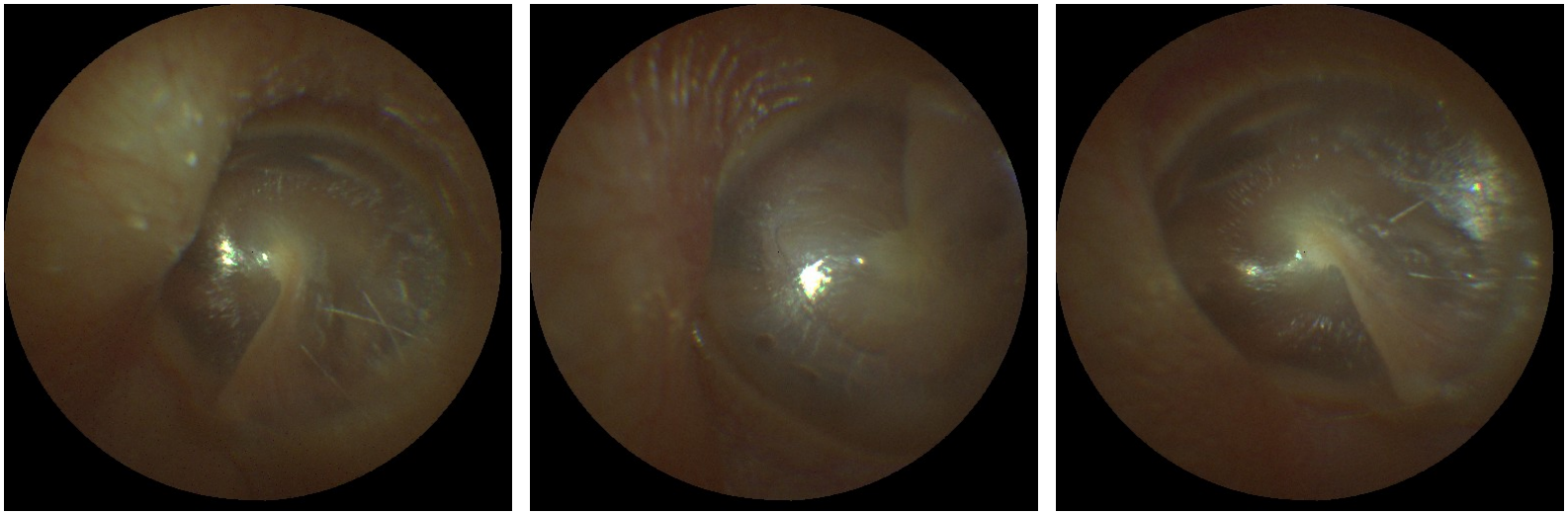
Rat Bladder Imaging

- Imaging performed on a recently dead rat
- 1.6 mm SFE probe inserted through urethra (opened abdomen to expose bladder for saline insertion)
- Initially no usable images were formed
  - Believe bladder was against probe tip
- Saline solution injected into bladder
  - To expand the bladder
  - Useful images then generated and captured

Imaging a Rat Bladder

Rat Bladder Images

Ear Images



- Images of the ear drum taken by placing the 1.1 mm diameter SFE probe into the ear canal
- Probe used by Dr. Thomas Lendvay on himself
- Recorded March 22, 2007

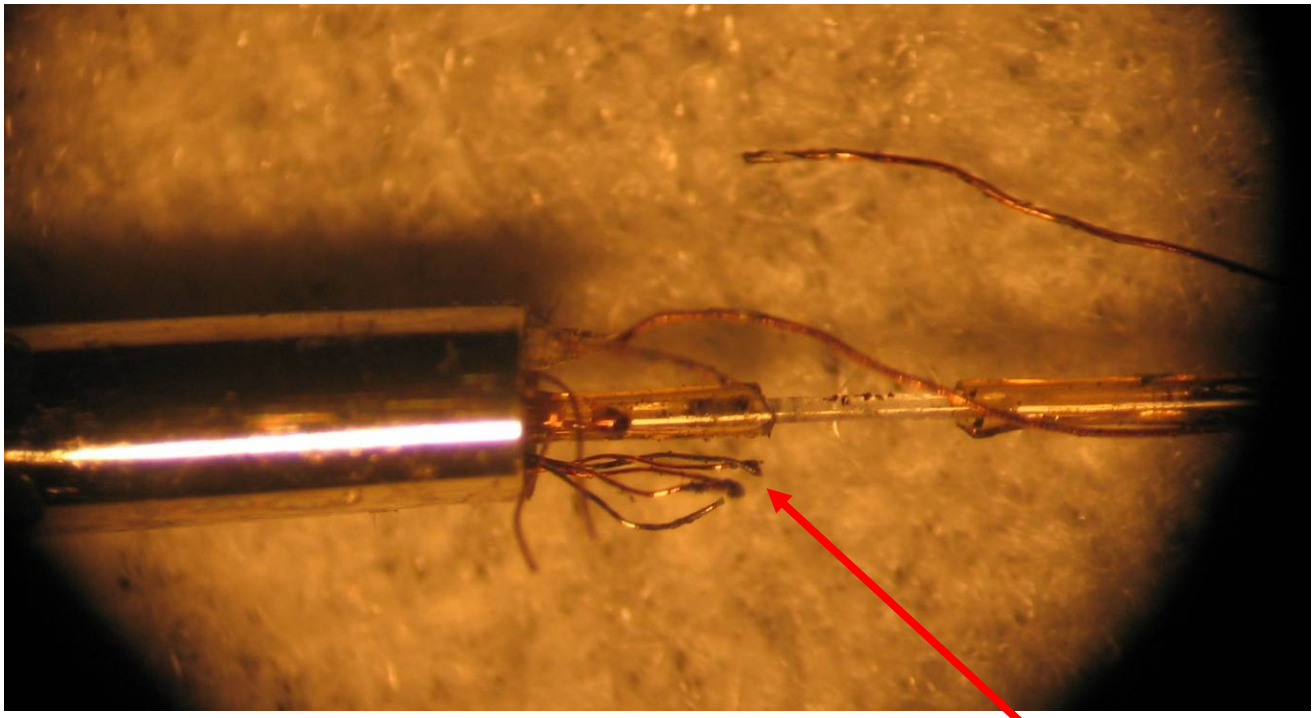
Pig Bile Duct Test

- Goal was to image inside the pigs bile duct
- Procedure
  - PENTAX duodenum scope used as mother scope
  - Fluoroscope used to position guide wire into bile duct
  - 4.3 meter SFE probe had guide wire loop attached to distal tip
  - SFE probe slid down guide wire
  - Mother scope elevator used to place SFE probe into bile duct
- Result
  - Single guide wire loop made it hard to control SFE probe
  - Blind use of elevator caused SFE probe to bend 90 degrees right after end of rigid tip
  - Wires in probe broke such that SFE stopped scanning
  - No images were captured
- Pig was then used for lung imaging experiments with another SFE probe (1.5 meter long)
- SFE probe will be redesigned to reduce this breakage method

Dr. Kimmey & Pig Bile Duct Test

Probe Broken During Pig Test

Probe Autopsy Results



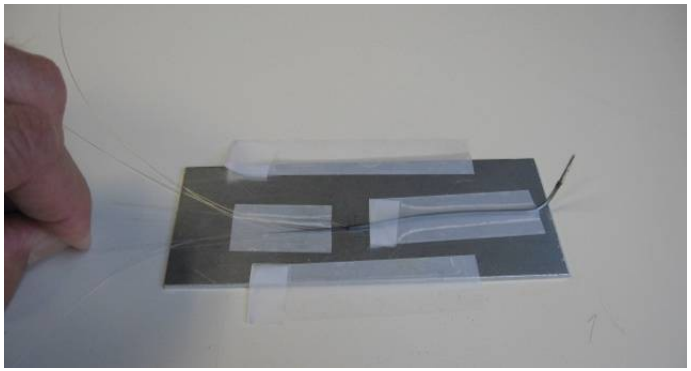
Other Work

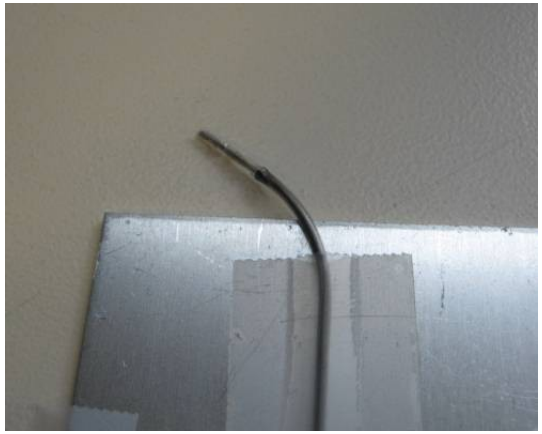
- Auto Calibration software
  - Works with new braking control
  - Better scan linearity
  - Added documentation
- SFE control software
  - Ability to store raw image files
  - Brightness control and improved AGC
    - Required change to FPGA code
  - Additional parameters added to stored file structure
  - Recording of probe usage time added
- Preliminary image calibration routines tested
  - Image parameter determination only
- Temperature control board modified for greater stability

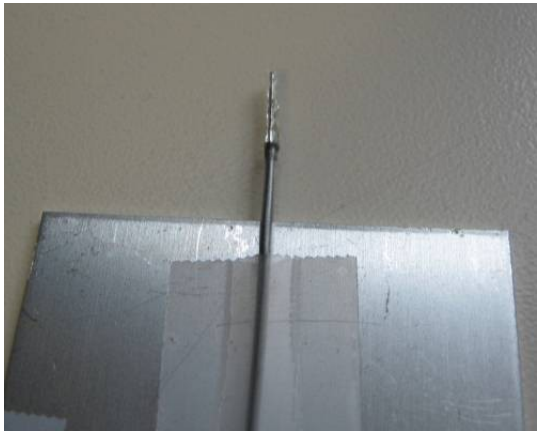
New Bending Method

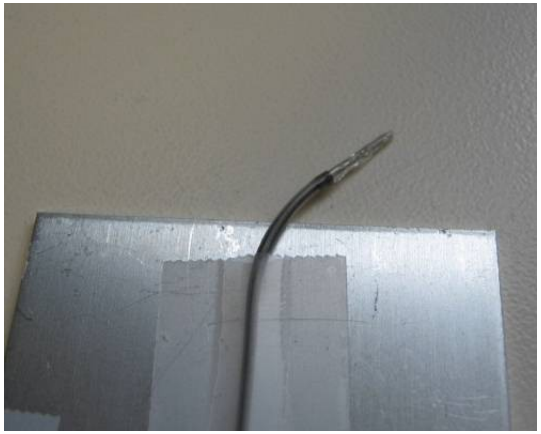
- Probe central single mode fiber used as the compression member
- Use probe return fibers as bend actuators
  - Plastic fiber have sufficient strength
- Method does not add volume to probe
- Simple proof of concept prototype built
- Allowed multi direction (2 axis) bending

Bender









Future Work Focus

- Build and test additional probes with various parameters
- Perfect 10 KHz scanners for use in 30 Hz RGB system
- Complete VHDL code to allow 30 Hz (25M sample rate) SFE operation
- Add chromatic aberration correction to VHDL code
- Reduce rigid tip length to less than 10 mm
- Reduce total 30 Hz probe diameter to less than 1.2 mm
- Continue to improve image quality and reduce distortion
- Continue to test and improve automated calibration software
- Continue development of SFE calibration with a passive target
- Continue development of improved probe assembly procedures and fixtures to speed the process of making SFE probes
- Transfer technology as requested by PENTAX
- Human testing of BE Scope with Eric Seibel's UW Human Subjects Committee approval including building 30+ BE Scope probes
- Develop 2nd Follow-on contract work with PentaxMicroline

Publications and IP

DDW'07 SFE Presentations

(Abstracts published in April 2007 issue of Gastrointestinal Endoscopy)

- Seibel, Johnston, Brown, Dominitz, and Kimmey. (oral on May 22, 2007) Novel ultrathin scanning fiber endoscope for cholangioscopy and pancreatoscopy. DDW 2007, WA DC.
- Dominitz, Johnston, Melville, Kimmey, Seibel. (poster on May 23, 2007) Low-cost tethered capsule endoscope (TCE) for unsedated esophagoscopy. DDW 2007 in WA DC.
- Seibel, E.J. (May 18, 2007 – invited talk) The Scanning Fiber Endoscope, Division of Gastroenterology, The Johns Hopkins University, host Dr. Mimi Canto.

Recent SFE Publications

- Atmosukarto, I., Soper, T.D., Glenny, R.W., Seibel, E.J., and Shapiro, L.G. (2007) An interactive 3D user interface for guided bronchoscopy. SPIE Medical Imaging 2007, Visualization and Image-Guided Procedures session. Selected as a finalist for Best Conference Paper Award.
- Soper, T.D., Haynor, D.R., Glenny, R.W., and Seibel, E.J. (2007) A model of respiratory airway motion for real-time tracking of an ultrathin bronchoscope. SPIE Medical Imaging 2007, Feb 17-22, 2007, San Diego, CA.
- Brown, C.M., Maggio-Price, L., and Seibel, E.J. (2007) Laser Induced Fluorescence as a Diagnostic Tool Integrated into a Scanning Fiber Endoscope for Mouse Imaging. In *Optical Fibers and Sensors for Medical Diagnostics and Treatment Applications VII*, Ed., I. Gannot, Proc. SPIE, vol 6433: 64330M-1 to -12.
- Kelloff, …Seibel,…et al. 2007 Cancer Biomarkers special issue devoted to the NIH/NCI Workshop on imaging science development for cancer prevention and preemption, Cancer Biomarkers vol 3, no 1 (see full reference later).
- Yoon, W.J., Reinhall, P.G., and Seibel, E.J. (in press) Steerable guidewire with eyes for image guided intervention in the upper urinary tract. Proc. BioMed 2007-38059, presented at 2nd Frontiers in Biomedical Devices Conference, Irvine CA, June 7-8, 2007.

Invited Publications & Presentations

- Seibel, E.J. (Sep 17-19, 2007) Novel approaches in optical imaging and visualization of early cancer screening, diagnosis, and treatment, Frontiers in Optics, The Optical Society of America, San Jose, CA.
- Seibel, Brown, Dominitz, and Kimmey (invited article) Scanning fiber endoscopy: a new platform technology for integrated imaging, diagnosis, and future therapies, Gastrointenstinal Endoscopy Clinics of North America.
- Seibel, E.J. (Jan 25-29, 2008) 1-mm Catheterscope, In *Optical Fibers and Sensors for Medical Diagnostics and Treatment Applications VIII*, Ed., I. Gannot, Proc. SPIE.
- Seibel, E.J. (Mar 8, 2008) ASGE Future of Endoscopy Conference, The Scanning Fiber Endoscope technology, invited by ASGE president Dr. Grace Elta, Ann Arbor, MI.

Full reference to Kelloff et al.,'07

- **Kelloff, Gary J.**, and co-authors: Daniel M. Sullivan, Houston Baker, Lawrence P. Clarke, Robert Nordstrom, James L. Tatum, Gary S. Dorfman, Paula Jacobs, Christine D. Berg, Martin G. Pomper, Michael J. Birrer, Margaret Tempero, Howard R. Higley, Brenda Gumbs Petty, Caroline C. Sigman, Miriam C. Provost, Carlo Maley, Prateek Sharma, Adam Wax, Gregory G. Ginsberg, Andrew J. Dannenberg, Ernest T. Hawk, Edward M. Messing, H. Barton Grossman, Mukesh Harisinghani, Irving J. Bigio, Donna Griebel, Donald E. Henson, Carol J. Fabian, Katherine Ferrara, Sergio Fantini, Mitchell D. Schnall, Jo Anne Zujewski, Wendy Hayes, Eric A. Klein, Angelo DeMarzo, Iclal Ocak, Jeffrey A. Ketterling, Clare Tempany, Faina Shtern, Howard L. Parnes, Jorge Gomez, Sudhir Srivastava, Eva Szabo, Stephen Lam, **Eric J. Seibel**, Pierre Massion, Geoffrey McLennan, Kevin Cleary, Robert Suh, Randall W. Burt, Ruth M. Pfeiffer, John M. Hoffman, Hemant K. Roy, Thomas Wang, Paul J. Limburg, Wafik S. El-Deiry, Vali Papadimitrakopoulou, Walter N. Hittelman, Calum MacAulay, Robert Veltri, Diane Solomon, Jose Jeronimo, Rebecca Richards-Kortum, Karen A. Johnson, Jaye L. Viner, Steven P. Stratton, Milind Rajadhyaksha, Atam Dhawan (2007) "Imaging science development for cancer prevention and preemption" Special Issue of **Disease Markers – Cancer Biomarkers**, IOS Press, Amsterdam, vol 3, no 1, (70-page review article).

Intellectual Property (IP)

Patent Summary - Numbers

- UW-SFE technology
  - ~9 issued patents (counting USA only)
  - ~25 filed patent applications
  - ~14 inventions (no patent filed yet)
- Joint UW-PENTAX technology dev.
  - ~4 filed patent applications
- PENTAX-SFE technology from PC
  - ~6 filed patent applications

Patent Summary - Technologies

- SFE Designs
  - 1st issued patent of non-confocal design
  - 2nd issued patent of dual modes of use
  - SFE designs
    - Fiber scanner
      - Compact, scanned microlens, custom lensing, needle probe, piezo tube manufacture, controllers, microsensor
    - Endoscope
      - Tip bending, compressed collection fibers, custom detectors, side-viewing, babyscope, config. memory
  - Unique procedures (remapping, phase breaking, sequential color, image processing, calibration)
  - Unique SFE features
    - 3D, stereo, and range finding
    - Laser diagnostics & therapies (3 separate techniques)
    - OCT and confocal fluorescence (multi-photon)
    - Active tip bending and tip displacer
    - Image stitching or mosaicing software
    - Eyes on tip of endoscopic tools
- SFE Applications
  - Tracked bronchoscope for accurate & efficient image-guided biopsy
  - Magnetic tracking system for insertion
  - BE-Scope (TCE) and capsule scope
  - Cannula tools with SFE
- Non-endoscope SFE technologies and applications
  - Scanner for laser ophthalmoscope
  - Scanner for microdisplay
- Separate UW SFE technology – MEMS embodiment of resonant waveguide scanner