Medical Imaging in IMRT Planning

Charles A. Pelizzari
Radiation Oncology
The University of Chicago

Overview

- RT as image guided therapy
- Imaging in the RT process
- Modalities
  - anatomical
  - functional / molecular
- Image registration and fusion
- Segmentation
- Image communication: DICOM, DICOM-RT, RTOG

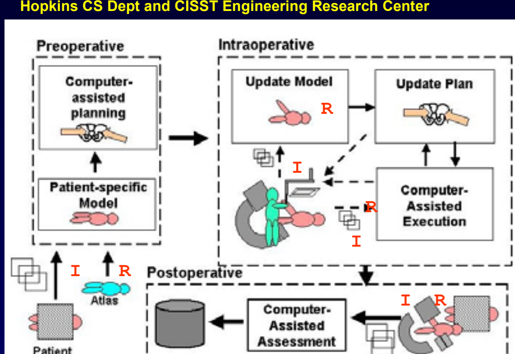
IMRT is image guided therapy

- maybe even the original image guided therapy!
- Reinstein, McShan mid-late 1970's showed 3D image guidance (e.g., BEV) could allow critical organ sparing
- JCRT group same time period used computer controlled linac to conform dose to target, avoid normal structures from image based patient model

Imaging for therapy guidance

- Stages of guidance
  - planning
  - setup
  - real time guidance
  - real time feedback (typically not, in RT)
  - adaptation of multiple treatments
  - assessment of effect
  - followup
- Not every application uses all of these, but RT uses nearly every one.

Information flow in computer integrated surgery: R.H. Taylor, Johns Hopkins CS Dept and CISST Engineering Research Center



I: Imaging R: Registration

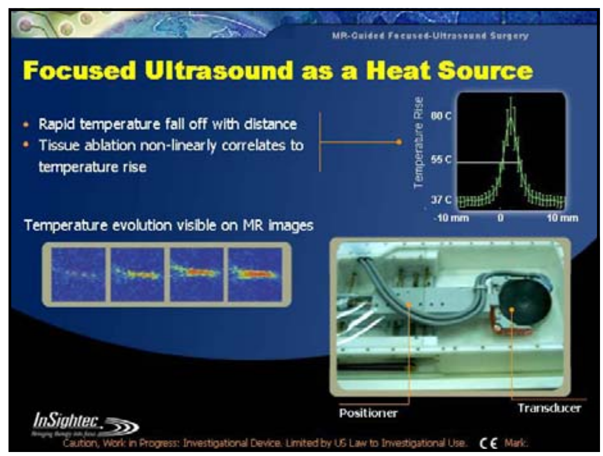
- Planning stage: what do we need? Target and organs at risk
  - anatomy: usual scan gives a snapshot (with a slow shutter speed!)
    - dynamic scanning to get a movie
    - gated acquisition to get a freeze frame
  - functional information, e.g. important brain areas, functional lung, bioimaging for tumor
    - registration methods; data communication; new image modalities
  - sensitivity is paramount – must identify all the tumor [1]
    - multimodality imaging; registration
  - specificity is desirable – want to avoid complications

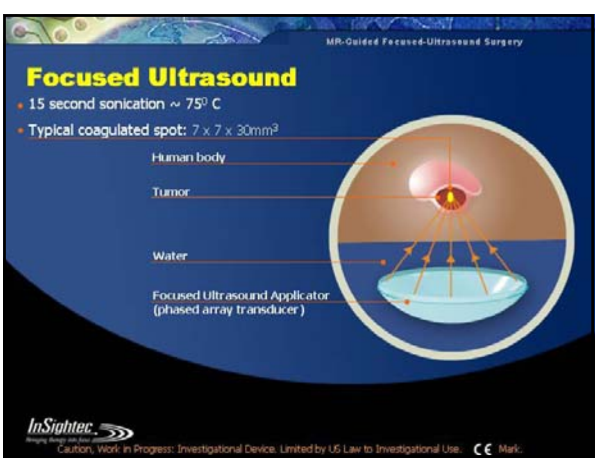
[1]F. Jolesz, in Oncologic Imaging, Bragg et al., Chap. 4

- Setup stage: what do we need? rapid registration of plan ("virtual patient") with the actual patient in treatment room
    - registration methods; data communication; position measurement / tracking; display technologies; imaging technologies (radiographs? video?); validation/QA (accuracy!)
  - registration of treatment device with both virtual patient and interactive imaging system(s)
    - multiview radiography to register with 3D patient model? 2D/3D registration; registration of radiography and US;
  - note external beam RT has similar issues as robotic procedures

- Real time guidance: hit a moving target
  - gating
    - based on direct physiologic signal (e.g., spirometer)
    - based on images (e.g., video or IR fiducials)
  - "4D" treatment – attempt to follow motion of anatomy
    - actual anatomy
    - inferred position from dynamic model synchronized with gating signal
  - (re) registration methods; data communication; position measurement / tracking; display technologies; image fusion; correction of planning images / plan as procedure changes anatomy?

- Real time feedback example: MR guided focused US tissue ablation
  - rapid image acquisition and display during treatment
  - comparison of actually treated region with plan
- Analog in RT: intratreatment dose determination with portal imager – accumulating dose to patient model as Tx is delivered. Not as direct as thermal MR imaging in FUS



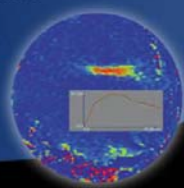


MR-Guided Focused-Ultrasound Surgery

Step 2: Treatment

During energy delivery of <u>every sonication</u>

- System acquires thermal **MR images**; Shows sonication location and anatomy
- System computes temperature map
- User adjusts parameters to achieve desired outcome



InSightec

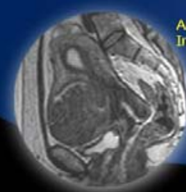
Caution, Work in Progress: Investigational Device. Limited by US Law to Investigational Use. CE Mark.

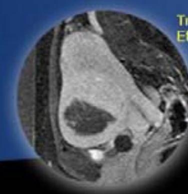
MR-Guided Focused-Ultrasound Surgery

Step 3: Outcome Assessment

After Treatment

- **MR contrast enhanced images** identify change in contrast uptake to provide feedback on treatment effect





InSightec

Caution, Work in Progress: Investigational Device. Limited by US Law to Investigational Use. CE Mark.

- <u>Adaptation of fractionated treatments</u>: Adaptive radiotherapy
  - problem: fractionated treatment over weeks
  - intra and inter fraction targeting errors
    - patient pose (setup) variation
    - variation in anatomy – organ motion
  - approach: image at each fraction, infer range of uncertainties. Adapt subsequent fractions. At some point stop imaging – diminishing return
    - imaging methods; anatomical modeling from images; biomechanics of organ motion; optimization of corrections; decision theory

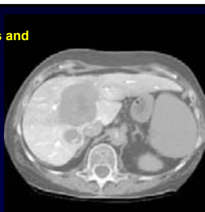
- <u>Assessment</u>
  - what is the signature of successful vs unsuccessful treatment?
    - anatomical changes
    - functional changes from familiar modalities
      - registration; image processing; data communication; display / analysis; validation / QA (get the right answer!)
    - evidence from new functional modalities
      - macro/meso/micro scale registration / fusion; handling large datasets; validation/QA (what does it mean?); detailed investigation of biological content of imaging evidence

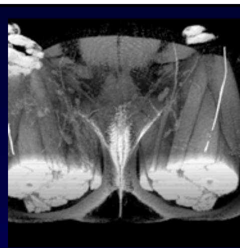
- <u>Followup</u>
  - serial imaging over time contributes to monitoring of patient status, robustness of response
    - anatomical imaging
    - old and new functional modalities
    - need to register retrospectively

Anatomical Modalities

- Advantages of CT
  - widely available; (relatively) inexpensive
  - good geometric accuracy
  - visualization of bony anatomy for comparison with radiographs (DRR)
  - potential for rapid scanning
  - siting issues not difficult
  - with contrast, many tumors and nodes visualized reasonably well

Liver lesions and vessels with contrast

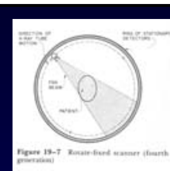




NLM Visible Female CT

Neck nodes from RTP CT

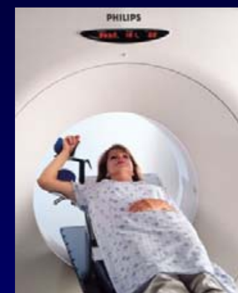
J. Lee MD
U of Chicago

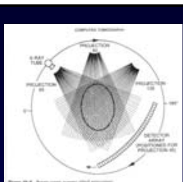


Picker/Philips PQ series and AcQSim CT: fourth generation scanners

ring of 4096 detectors at 850 mm radius

source at 630 mm



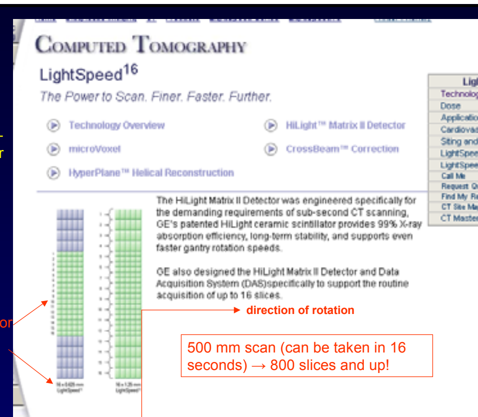


GE HiSpeed, LightSpeed: third generation scanners

mechanically more complex – easier to change SAD with 4th generation (same detector ring)

far less detector solid angle – 3rd generation more favorable for multislice on basis of detector cost

Multislice CT – matrix detector



5/8 mm detector slice spacing

direction of couch translation

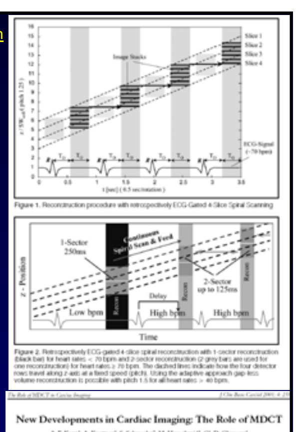
Acquiring data to characterize organ motion

Retrospective gating: acquire physiologic signal and projection data synchronized; sort slices or projections into time bins at each position in postprocessing. Thus get series of images at chosen time point at each location.

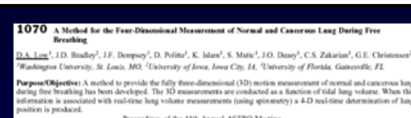
Can do this with a single slice scanner, but requires very slow axial motion. Faster rotation always better

Suitable gating signals?

4 x 1 mm slices, pitch 1.5



New Developments in Cardiac Imaging: The Role of MDCT

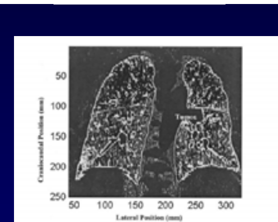


1070 A Method for the Four-Dimensional Measurement of Normal and Cancerous Lung During Free Breathing

Proceedings of the 44th Annual ASTRO Meeting

Retrospective respiratory gating using spirometer signal

ASTRO 2002



Anatomical modalities

- Advantages of MRI
  - no patient radiation dose
  - unparalleled soft tissue delineation
  - vast flexibility in imaging protocols – optimize for tissue of interest
  - multiparameter imaging in single coordinate system
  - adjustable resolution with specialized head, body, endorectal, etc. coils
  - vascular imaging with contrast agents
  - functional imaging capability (e.g. BOLD fMRI)
  - molecular imaging capability (spectroscopy and more)
  - ability to infer temperature, diffusion coefficient, diffusion tensor, etc.

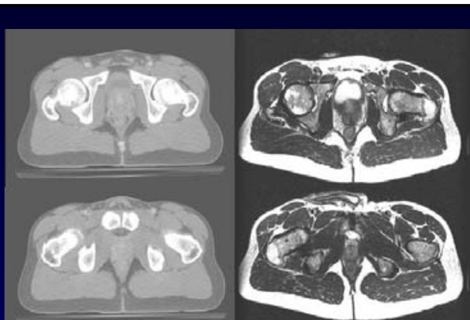
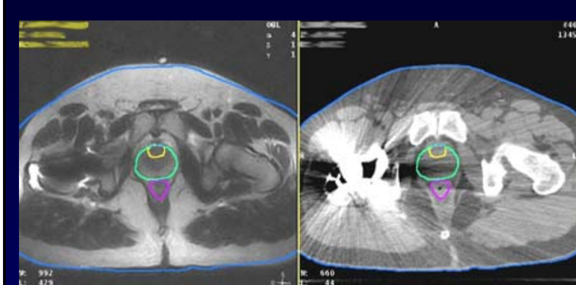


Figure 3. CT (left) and MR slices through approximately corresponding sections near the middle (above) and apex (below) of the prostate. Image parameters: CT, 5mm slice thickness, single-slice axial acquisition mode, 0.78 mm pixel size; MR, 4.5 mm slice thickness, 0.74 mm pixel size.

Open magnet

Plus: good access, easier to scan patient immobilized

Minus: low field – no spectroscopy, lower ultimate spatial resolution, more prone to field distortion artifacts



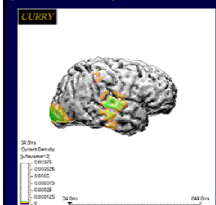
Philips 0.23T open MRI

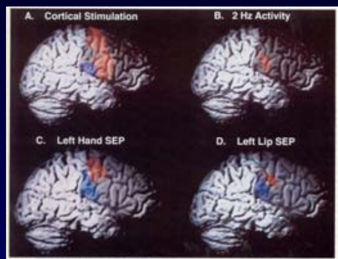
Functional and Molecular Imaging

- Refine target identification
  - tumor vs normal tissue
  - clarify ambiguities, e.g. vs edema in MRI
  - active vs necrotic tumor regions
  - estimate cell density – use IMRT to optimize dose distribution
  - hypoxic vs necrotic regions – increase dose?
- Refine organ at risk definition
  - spare important functional areas, e.g. lung, brain regions
- Assessment
  - early feedback on treatment success – “signature” of Tx effect
    - **molecular**
    - **genetic**
    - **vascular**
    - **others / combinations**
  - **adapt subsequent treatment based on this assessment?**

Nontraditional (for RTP at least) sources of functional information can be integrated into the planning process via image or patient-image registration.

High-res EEG maps regions involved in stimulus response (NeuroScan Inc)





EEG Evoked potentials delineate motor and sensory cortex (Leo Towle, U of C)

Molecular imaging with MRI – spectroscopic imaging

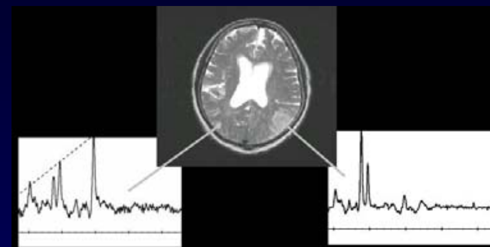


Figure 9. T2-weighted brain image with spectra from normal and tumor regions. The normal linearly increasing relationship between several spectral peaks on the left is absent on the right, indicative of tumor. (Image courtesy of P. MacEneaney, MD, University of Chicago)

UCSF / GEMS

Choline/Citrate as indicator of malignancy

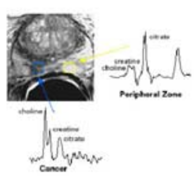
Use in tumor localization

MAGNETIC RESONANCE IMAGING
Signa Infinity 1.5T
Prostate Spectroscopy/Imaging Exam
John Kurhanewicz, Ph.D.
University of California, San Francisco

Prose

(PROstate Spectroscopy and imaging Exam)

The PROSE Prostate package is the first clinically available Prostate Spectroscopy exam. This Package brings 3D Spectroscopy to the prostate providing adding high resolution Spectroscopy to the imaging capabilities already available on Signa systems. An endorectal coil used in combination with an external phased array coil is recommended for this technique. The data can be reviewed as Spectra or as parametric color metabolite images. When interpreted by a trained Physician, the relative concentrations of the In Vivo metabolites can be very useful in identifying and staging pathology in Prostate diseases.



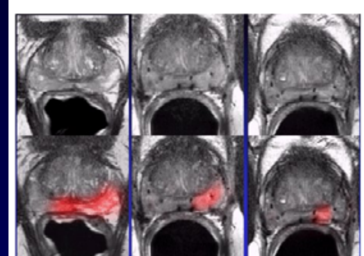
UCSF / GEMS

Choline/Citrate as indicator of malignancy

Use in treatment assessment

Case Study 2

For a patient for whom brachytherapy was recommended, MRSI was used pre- and post- bra



Prior to therapy — Three months after brachytherapy — Twelve months after brachytherapy

In vivo magnetic resonance imaging of transgene expression

RALPH WEISSLEDER[1], ANNA MOORE[1], UMAR MAHMOOD[1], RAJEEV BHORADE[1], HELENE BENVENISTE[2], E. ANTONIO CHIOCCA[3] & JAMES P. BASILION[1,3]

[1]Center for Molecular Imaging Research, Massachusetts General Hospital and Harvard Medical School, Building 149, 13th Street, 5403, Charlestown, Massachusetts 02129, USA
[2]The Center for In vivo Microscopy, Duke University, Durham, North Carolina, USA
[3]Molecular Neurooncology Laboratory, Neurosurgery Service, Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts, USA
Correspondence should be addressed to R.W.; email: weissleder@helix.mgh.harvard.edu

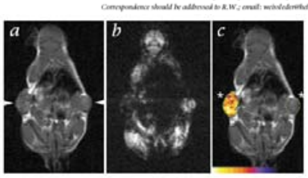


Fig. 3 *In vivo* MR imaging of a single mouse with ETR+ (left arrowheads) and ETR- (right arrowheads) flank tumors. ***a***, T1-weighted coronal SE image (imaging time, 3.5 min; voxel resolution, 300 × 300 × 3000 μm). ETR- and ETR+ tumors have similar signal intensities. ***b***, T2-weighted gradient-echo image corresponding to the image in *a*, showing substantial differences between ETR- and ETR+ tumors (imaging time, 8 min; voxel resolution, 300 × 300 × 3000 μm). As expected, ETR-mediated cellular accumulation of the superparamagnetic probe decreases signal intensity.

Monocrystalline iron oxide nanoparticles (MIONs) conjugated with transferrin; tumors engineered to express (or not) gene for transferrin receptor (ETR +/-). MIONs accumulate in ETR+ tumor on left, decrease T2* and signal intensity.

PET-GUIDED IMRT FOR CERVICAL CARCINOMA WITH POSITIVE PARA-AORTIC LYMPH NODES—A DOSE-ESCALATION TREATMENT PLANNING STUDY

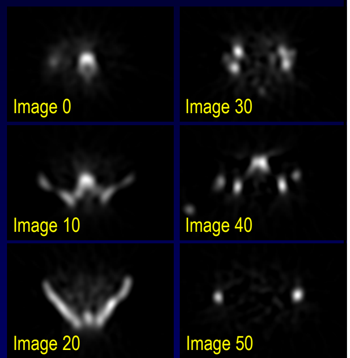
SASA MUTIC, M.S.,* ROBERT S. MALYAPA, M.D., PH.D.,* PERRY W. GRIGSBY, M.D.,* FARROKH DEHDASHTI, M.D.,† TOM R. MILLER, M.D., PH.D.,† IMRAN ZOBERI, M.D.,* WALTER R. BOSCH, D.SC.,* JACQUELINE ESTHAPPAN, PH.D.,* AND DANIEL A. LOW, PH.D.*

*Department of Radiation Oncology and †Division of Nuclear Medicine, Mallinckrodt Institute of Radiology, Washington University School of Medicine, St. Louis, MO

PET / CT fusion for improving sensitivity (more complete definition of target volume)

Tc-99m Bone Marrow Images

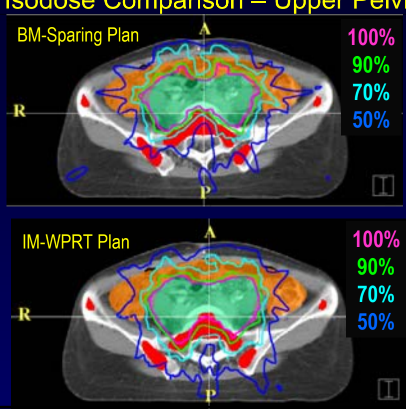
From J. Roeske, U of Chicago



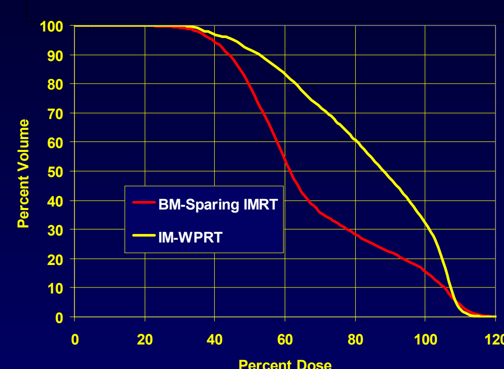
SPECT-CT Image Fusion

- Based on image fusion, highest intensity BM was contoured and used in planning process

Isodose Comparison – Upper Pelvis

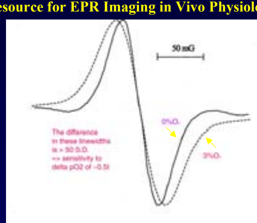


Bone Marrow DVHs



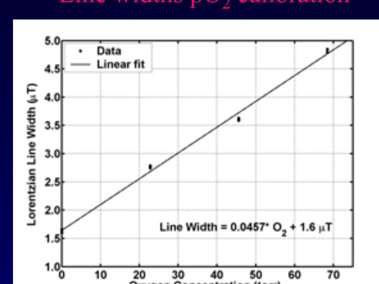
EPR Spectrum Response of Symmetric Trityl (deuterated) to Oxygen

NIH Research Resource for EPR Imaging in Vivo Physiology: H. Halpern



- No temp. dependence: < 0.05 mG/K
- Low viscosity dependence ~1mG/cP
- Minimal self quenching

Line widths pO_2 calibration

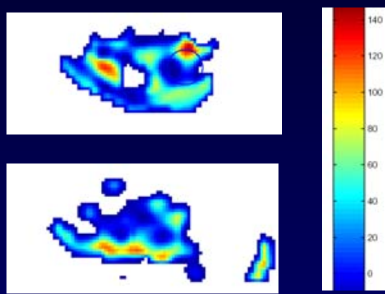


Oxygen dependence of spin packet width obtained in a series of homogenous solutions of OX31:
Since minimal viscosity dependence, aqueous=tissue

Oxygen Image of PC3 Xenograft Pre- and Post-Ad-EGR-TNFα + 20 Gy Radiation

3 hours Pre-

3 days Post

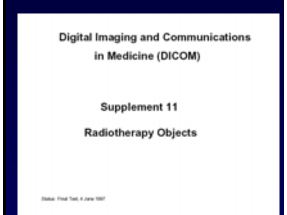


How do we get all these images?

DICOM – de-"Babelizing" image import.

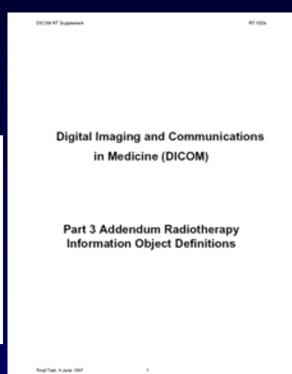
Every clinically used modality does or will support DICOM transfer of images. All we need to do is make sure we are capable of accepting them.

DICOM-RT: support for communication of RT-specific non-image information


Digital Imaging and Communications in Medicine (DICOM)

Supplement 11

Radiotherapy Objects


Digital Imaging and Communications in Medicine (DICOM)

Part 3 Addendum Radiotherapy Information Object Definitions

DICOM basic concepts: information objects

An *Information Object* is "an abstraction of a real information entity (e.g., CT Image, Study, etc.) Which is acted upon by one or more DICOM Commands." An *Information Object Instance* is "a representation of an occurrence of an real-world entity, which includes values for the attributes of the Information Object Class to which the entity belongs" (e.g., a specific CT image).

"An *Information Object Definition* (IOD) is an object-oriented abstract data model used to specify information about Real-World Objects. An IOD provides communicating Application Entities with a common view of the information to be exchanged."

IODs are thus a common language by which different computers and programs may "read" and "write" images. IODs must exist for each type of image (or non-image) dataset which is to be communicated using DICOM. IODs are defined in the 2001 standard for CT, Computed Radiography (CR), Nuclear Medicine, MR, PET, US, Secondary Capture (SC, e.g. digitized film, screen dump), Overlay, Curve, X-ray Angiography, X-ray Radiography/Fluoroscopy, RT Image, RT Dose, RT Structure Set, RT Plan, Digital Mammography, Digital Oral X-ray, RT Beams Treatment Record, RT Brachy Treatment Record, Visible Light Image, Waveform and others.

DICOM basic concepts – service and service object pair classes

A *Service Class* is "a structured description of a service which is supported by cooperating DICOM Application Entities using specific DICOM commands acting on a specific class of Information Object." Examples include storage, query, retrieval and print service classes.

A *Service-Object Pair (SOP) Class* is "the union of a specific set of ... Services and one related Information Object Definition (as specified by a Service Class Definition) which completely defines a precise context for communication." For example, CT Image (the object) Storage (the service) is a Service-Object Pair.

A Service Class User (SCU) is a client that utilizes a service

A Service Class Provider (SCP) is a server that offers a service

Your desktop PC when receiving images from your PACS system is a storage SCP, and the PACS is an SCU of your service.

B.5 STANDARD SOP CLASSES

The SOP Classes in the Storage Service Class identify the Composite IODs to be stored. Table B.5-1 identifies Standard SOP Classes.

Table B.5-1
STANDARD SOP CLASSES

SOP Class Name	SOP Class UID	IOD Specification (defined in PS 3.3)
Computed Radiography Image Storage	1.2.840.10008.5.1.4.1.1.1	
CT Image Storage	1.2.840.10008.5.1.4.1.1.2	
Hardcopy Color Image Storage	1.2.840.10008.5.1.1.30	
Hardcopy Grayscale Image Storage	1.2.840.10008.5.1.1.29	
MR Image Storage	1.2.840.10008.5.1.4.1.1.4	
Nuclear Medicine Image Storage	1.2.840.10008.5.1.4.1.1.20	
Positron Emission Tomography Image Storage	1.2.840.10008.5.1.4.1.1.128	
RT Dose Storage	1.2.840.10008.5.1.4.1.1.481.2	
RT Image Storage	1.2.840.10008.5.1.4.1.1.481.1	
RT Plan Storage	1.2.840.10008.5.1.4.1.1.481.5	
RT Structure Set Storage	1.2.840.10008.5.1.4.1.1.481.3	
RT Beams Treatment Record Storage	1.2.840.10008.5.1.4.1.1.481.4	
RT Brachy Treatment Record Storage	1.2.840.10008.5.1.4.1.1.481.6	
RT Treatment Summary Record Storage	1.2.840.10008.5.1.4.1.1.481.7	
Secondary Capture Image Storage	1.2.840.10008.5.1.4.1.1.7	

DICOM basic concepts - conformance

PS 3.2 defines principles that implementations claiming conformance to the Standard shall follow. PS 3.2 specifies:

- the minimum general conformance requirements that must be met by any implementation claiming conformance to the DICOM Standard. Additional conformance requirements for particular features, Service Classes, Information Objects, and communications protocols may be found in the conformance sections of other Parts of the DICOM Standard;
- the purpose and structure of a Conformance Statement. PS 3.2 provides a framework by which conformance information can be placed into a Conformance Statement as dictated by the conformance sections of other Parts of the DICOM Standard.

The DICOM Standard does not specify:

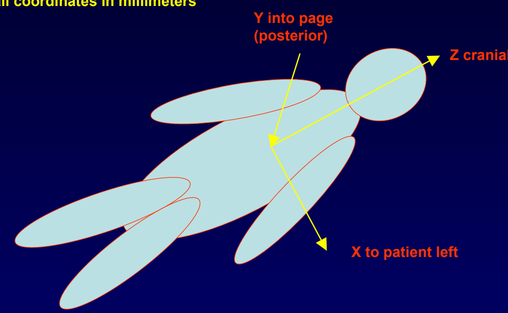
- testing or validation procedures to assess an implementation's conformance to the Standard;
- testing or validation procedures to assess whether an implementation matches to its Conformance Statement;
- what optional features, Service Classes, or Information Objects should be supported for a given type of device.

```
DICOM File: 25262.110

DCM Dump Elements
Object type: ELEMENT LIST
Object size: 526998
Group: 0008, Length:      486
0008 0000        4 //              ID Group Length//     1e6 486
0008 0005       10 //      ID Specific Character Set//ISO_IR 100
0008 0008       22 //                ID Image Type//ORIGINAL\PRIMARY\AXIAL
0008 0012        8 //      ID Instance Creation Date//20030527
0008 0013       14 //      ID Instance Creation Time//100000.000000
0008 0016       26 //             ID SOP Class UID//1.2.840.10008.5.1.4.1.1.2 CT IMAGE STORAGE SOP CLASS UID!
0008 0018       46 //          ID SOP Instance UID//2.16.840.1.113662.2.12.0.3034.1054033892.1335
0008 0020        8 //                ID Study Date//20030527
0008 0021        8 //               ID Series Date//20030527
0008 0022        8 //          ID Acquisition Date//20030527
0008 0030       14 //                ID Study Time//061629.000000
0008 0031       14 //               ID Series Time//095000.000000
0008 0032       14 //          ID Acquisition Time//100022.000000
0008 0050        0 //          ID Accession Number//
0008 0060        2 //                  ID Modality//CT
0008 0070        8 //              ID Manufacturer//Marconi
0008 0080       22 //          ID Institution Name//University of Chicago
0008 0081       20 //       ID Institution Address//Institution Address
0008 0090        4 //  ID Referring Physician's Name//ABJ
0008 1010        2 //              ID Station Name//#1
0008 1030       18 //         ID Study Description//POST IMPLANT SCAN
0008 1040       20 //ID Institutional Department Name//radiation  oncology
0008 1070        6 //            ID Operator's Name//AC/MM
0008 1090        8 //     ID Manufacturer Model Name//AcQSimCT
Group: 0010, Length:       58
0010 0000        4 //             PAT Group Length//      3a 58
0010 0010       16 //             PAT Patient Name//TEST
0010 0020        8 //               PAT Patient ID//0263404
0010 0030        0 //        PAT Patient Birthdate//
0010 0040        2 //              PAT Patient Sex//M
Group: 0011, Length:      540
0011 0000        4 //         Unknown group length//     21c 540
0011 0010       36 //                             //Unimplemented
```

Types of information transmitted and stored by DICOM
This is the info for a single CT slice

DICOM patient coordinate system
all coordinates in millimeters



Links to DICOM info and software for viewing, sending, receiving, ...

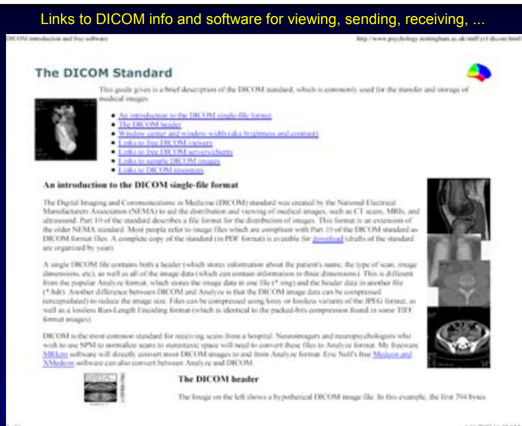


Image Fusion

and

Multimodality 3D Imaging

Terminology

- *Multimodality imaging*:
  - the use of two or more imaging techniques (modalities) to provide information in a given diagnostic or research situation.
- *Image fusion, sensor fusion*:
  - the synthesis of two or more signals into a single dataset; also often used to describe the process of displaying such synthesized data.
- *Image registration, matching*:
  - the process by which one dataset is mapped onto another. Involves establishment of a coordinate transformation relating the native coordinate systems of the two datasets.

Registration:

"...the determination of a one-to-one mapping between the coordinates in one space and those in another, such that points in the two spaces which correspond to the same anatomical point are mapped to each other."

(C.R. Maurer and J.M. Fitzpatrick, "A Review of Medical Image Registration," in Interactive Image Guided Neurosurgery, R.J. Maciunas ed., A.A.N.S., 1993.)

Registration: find transformation between primed and unprimed coordinate systems such that corresponding anatomical points are mapped onto one another.

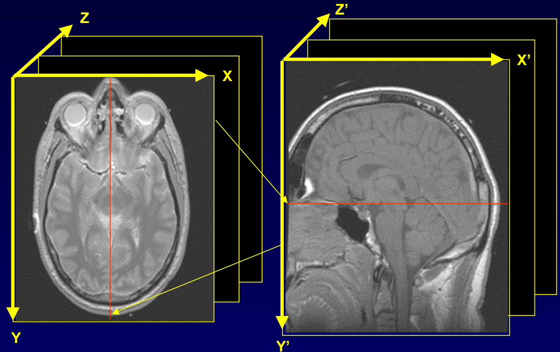
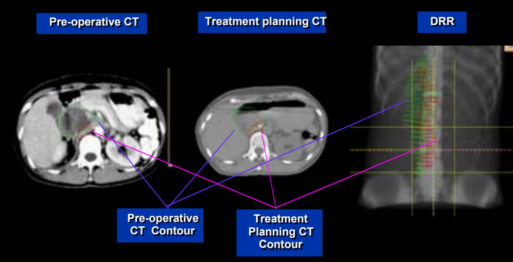


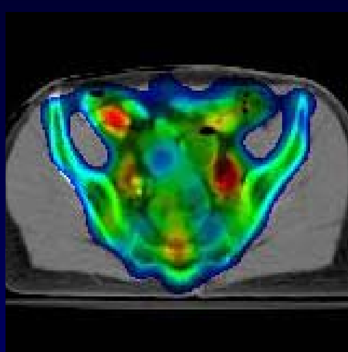
Image source: NLM Visible Human Proje



Scott Sailer, Julian Rosenman - UNC

Merged CT and SPECT by surface matching of large blood vessels

RJ Hamilton, UC
M Blend, UIC



Two Problems of Registration

- Register images to other images
- Register images to the real world
  - transfer image defined locations onto patient
  - transfer locations from patient to image model

Types of Data to be Registered

Class	Anatomic	Functional
3D	CT, MRI, US Digitized surface / point	PET, SPECT, fMRI EEG, MEG
2D Projection	Diagnostic radiograph Computed radiograph RT megavoltage image	Planar Scinitigraph
Multiple Projection	Biplane radiograph Stereo, angio	

Classification of registration methods

- What is matched? (which anatomical features)
- How is it matched? (cost function, parameter variation procedure, automatic vs manual)
- What kind of transformations are allowed? (linear, nonlinear, global, local)

A posteriori recovery of coordinate transformation

(Use information present in images to solve for required coordinate transformation)

Prospective - impose coordinate system on patient
- Stereotactic frame
  - rigidly fixed
  - on mask
- Applied fiducial marks
  - on patient
  - on mask

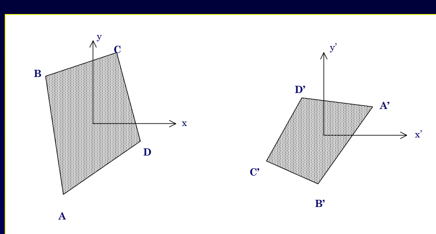
A posteriori recovery of coordinate transformation

Retrospective - attempt to use patient-intrinsic info

Feature based
- Point landmarks in 3D
- Curves, points on 2D projection images
- 3D shape properties
  - surfaces / volumes
  - cores (= shape descriptors of objects)
  - spatial moments
    - of features

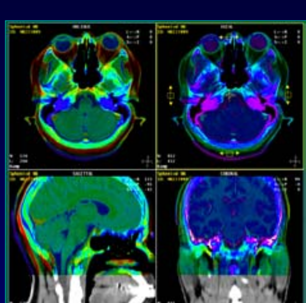
Dense field (voxel) based
- intensity distribution, texture

Point matching: Procrustes method



Point to point registration - AcQSim

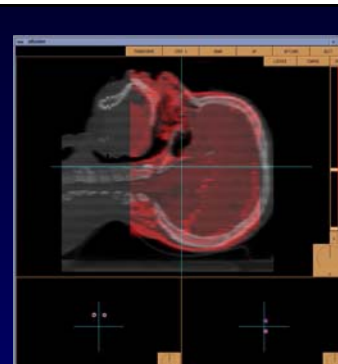
Multi-Modality
Interactive



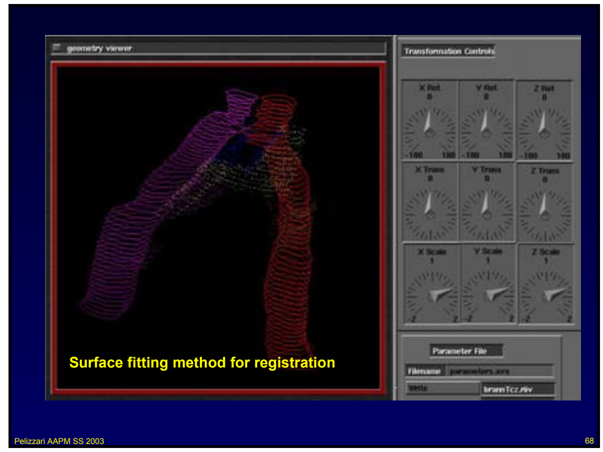
- Secondary study, shown as a colorwash overlay, is rotated and panned to match the primary CT simulation study

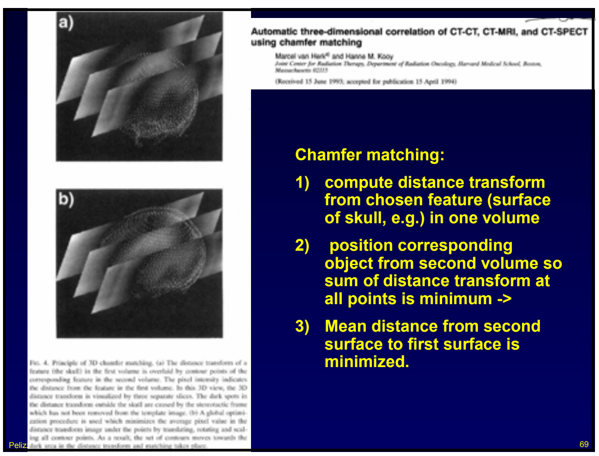
Slide: Marconi / Picker

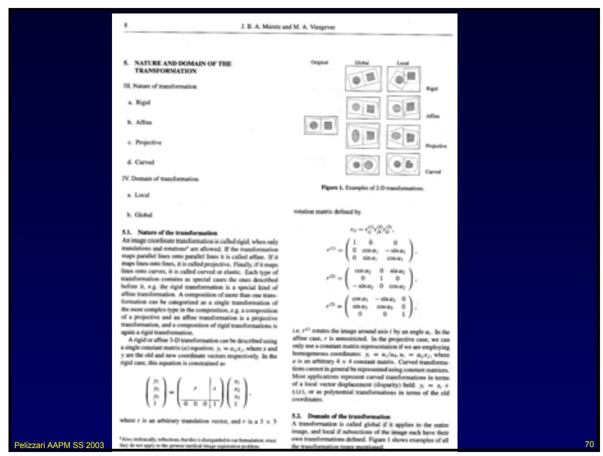
PlanUNC "Xfusion" interactive image registration tool

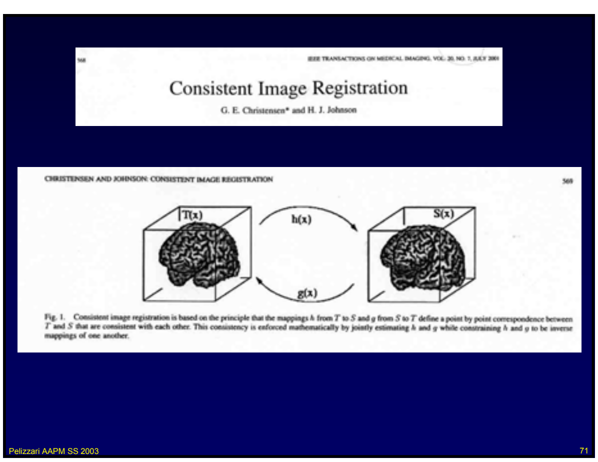


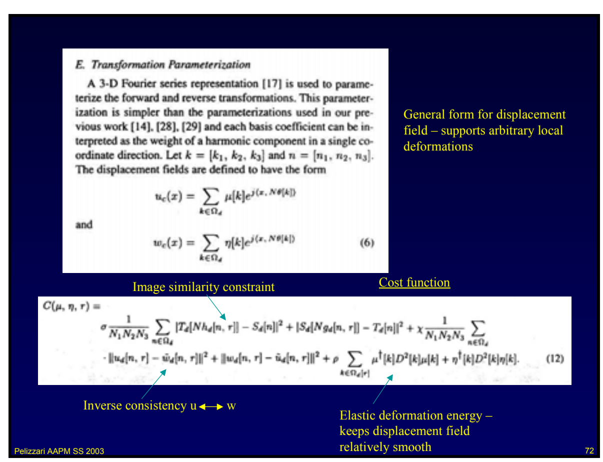

Xfusion:
images manually
overlaid
Pelizzari AAPM SS 2003
67


geometry viewer
Transformation Controls
X Rot
Y Rot
Z Rot
X Trans
Y Trans
Z Trans
X Scale
Y Scale
Z Scale
Parameter File
Filename
parameters.avs
Write
brainTcz.niv
Surface fitting method for registration
Pelizzari AAPM SS 2003
68


a)
b)
Automatic three-dimensional correlation of CT-CT, CT-MRI, and CT-SPECT using chamfer matching
Marcel van Herk and Hanna M. Kooy
Chamfer matching:
1) compute distance transform from chosen feature (surface of skull, e.g.) in one volume
2) position corresponding object from second volume so sum of distance transform at all points is minimum ->
3) Mean distance from second surface to first surface is minimized.
69


J. B. A. Maintz and M. A. Viergever
Pelizzari AAPM SS 2003
70


IEEE TRANSACTIONS ON MEDICAL IMAGING, VOL. 20, NO. 7, JULY 2001
Consistent Image Registration
G. E. Christensen* and H. J. Johnson
CHRISTENSEN AND JOHNSON: CONSISTENT IMAGE REGISTRATION
T(x)
h(x)
S(x)
g(x)
Fig. 1. Consistent image registration is based on the principle that the mappings h from T to S and g from S to T define a point by point correspondence between T and S that are consistent with each other. This consistency is enforced mathematically by jointly estimating h and g while constraining h and g to be inverse mappings of one another.
Pelizzari AAPM SS 2003
71


E. Transformation Parameterization
A 3-D Fourier series representation [17] is used to parameterize the forward and reverse transformations. This parameterization is simpler than the parameterizations used in our previous work [14], [28], [29] and each basis coefficient can be interpreted as the weight of a harmonic component in a single coordinate direction. Let k = [k1, k2, k3] and n = [n1, n2, n3]. The displacement fields are defined to have the form
and
(6)
General form for displacement field – supports arbitrary local deformations
Image similarity constraint
Cost function
(12)
Inverse consistency u ←→ w
Elastic deformation energy – keeps displacement field relatively smooth
Pelizzari AAPM SS 2003
72

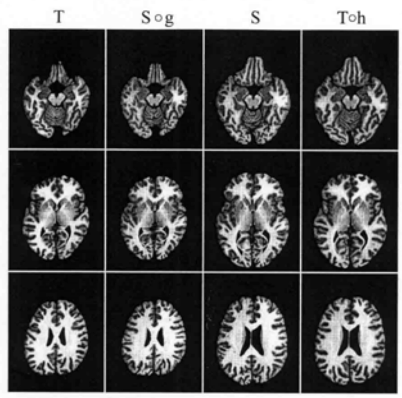


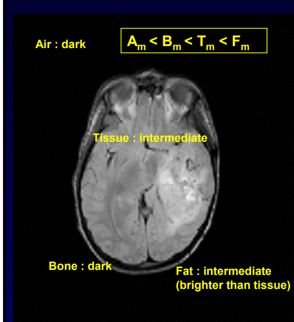
Fig. 6. Transverse slices 109, 135, and 165 (rows top to bottom) from the full resolution MRI-to-MRI registration experiment. The columns from left to right correspond to the template T, the deformed target $S \circ g$, the target S and the deformed template $T \circ h$. The intensities are on a range from 0 to 1.0.

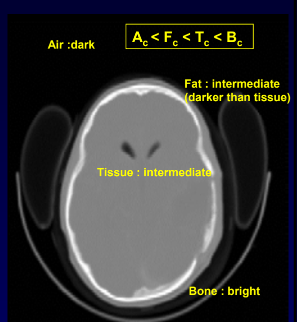
Pixel by pixel registration: maximization of mutual information

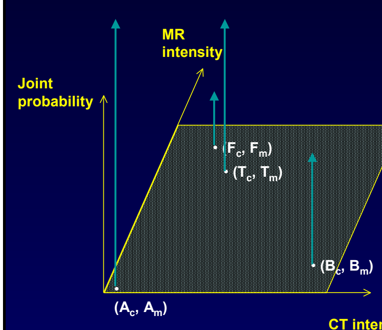
Principle: although anatomical regions may appear with different relative intensities in different modalities, these intensities are highly correlated.

Joint probability distribution when correctly registered is highly peaked; when misregistered, spread out. Peaked vs spread out nature is expressed formally in terms of entropy of the distribution.

Mutual information expresses the degree to which one image's intensities can be predicted given knowledge of the other - similar to correlation but more informative.





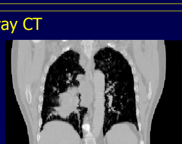


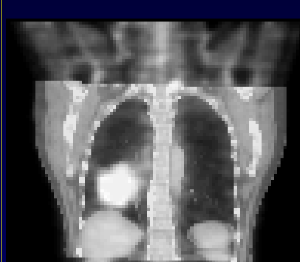
- When images are perfectly aligned, only 4 intensity pairings occur.
- Misregistration introduces other intensity pairings.
- Fewer pairings -> simpler distribution -> lower entropy when registered.
- Mutual information measures extent to which knowledge of CT intensity helps predict MR intensity

PET-CT Registration:
hybrid landmark / MI method

FDG PET

X-ray CT





PET – CT Fusion

M. Kessler, U. of Michigan

Assessment of accuracy

Problem with any method: how to get a case specific estimate of accuracy

Typical solution: visual evaluation
- **reformatted images**
  - **side by side / linked cursor**
  - **merge two data sets**
- **transformed VOIs**

Not quantitative but intuitively satisfying
Note requirement to manually verify 3 points when using FDA-cleared systems

Segmentation: it's a problem, isn't it?