Quality Assurance of Ultrasound-Guided Radiotherapy: TG 154

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Task Group Charge

- Produce a guidance document for clinical medical physicists describing QA procedures for US-guided EBRT.
  - Focused
  - Brief
  - Summarize literature and state of the art
  - Basic US physics
  - QA considerations
  - Describe existing commercial systems
  - Describe simulation, treatment planning and delivery considerations
  - Develop recommended QA tests, frequencies, tolerances

TG 154

- Formed in 2007
- In review

Contents

- Background
  - History of commercial development
  - US accuracy verification studies
  - Comparison to gold seed alignment
  - Inter-user variability
  - Pressure-induced target displacement
  - Intra-fraction motion
  - Physics of US
  - Tissue heterogeneity
  - Inter-imaging modality dependence

Contents

Basic Physics of US

$$Z = c \times \rho$$

- Z = acoustic impedance
- c = speed of sound (propagation medium dependent)
- ρ = medium density

US physics

$$\alpha_t = \frac{4Z_1 Z_2}{[Z_1 + Z_2]^2}$$

- Power transmission coefficient, α_t
- Reflection only occurs at the interface of media with differing acoustic impedances
- = 1 for Z1=Z2, < 1 all else
- Fundamentally, US is a boundary detector

Acoustic properties

	Density (kg/m³)	Sound Speed (m/s)	Acoustic Impedance (kg/m²s)
Water	1000	1480	1.48
Muscle	1070	1542-1626	1.65-1.74
Liver	1060	1566	1.66
Lung	400	650	0.26
Kidney	1040	1567	1.62
Fat	920	1446	1.33
Brain	1030	1505-1612	1.55-1.66
Bone	1380-1810	2070-5350	3.75-7.38
Blood	1060	1566	1.66
Air	1.2	333	0.0004

Beam formation

- Up to 200 array elements
- Phased arrays progressively excite individual elements
- Image information derived from time-of-flight and receiver element

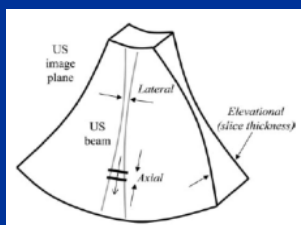


Figure : Ultrasound beam geometry

Figure : A phased transducer array

US physics

$$P(x,f) = P_0\, e^{-\alpha(f)x}$$

- P_o = initial power amplitude
- α = attenuation coefficient, proportional to frequency
- α / f = 0.5 dB/(cm Hz)
- x = penetration depth

- TGC: Time/gain compensation applied in order to equalized image intensity at various depths

US image formation

$$r = \frac{c\tau}{2}$$

- r = range
- τ = travel time of US pulse
- Image information
  - Array element (determines fan beam)
  - Time (determines depth)
  - Intensity of received pulse (determines grey scale)

Tissue Heterogeneity

- Speed of sound typically assumed to be 1540 m/s
- For prostate localization, acoustic pulse travels through
  - Fat (c = 1446 m/s)
  - Muscle (c = 1542-1626)
  - Urine (blood) (c = 1566)
- Salter et al measured 0.7 mm/cm fat
- Szpala measured average -2.7 mm shift
- Results in apparent depth > actual depth through fat
- Path length through muscle compensates

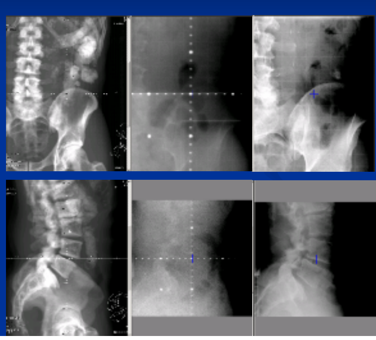
Abdominal Pressure

- Measured by comparing to
  - CT
  - Gold markers
  - MR
  - Electromagnetic tracking
- Magnitude ranges most typically up to 5 mm
- Can be mitigated through the use of reference US image (i.e., intra-modality alignment)

Soft tissue imaging for localization

- US is a good soft tissue differentiator
- Planar kV imaging is very limited (in terms of soft tissue differentiation)
- 3D CT (kv or MV) is capable of soft tissue differentiation but is limited
- MR best
  - Impractical for daily set up

2D kV imaging yields superior soft tissue contrast compared to 2D MV imaging



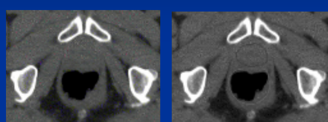
Comparison of:

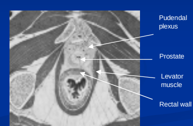
DRR/MV/kV

DRR/MV/kV

- Soft tissue contrast is not usefully increased
- Boney anatomy is enhanced
- Decreased penetration creates dead areas (need for large dynamic range imagers)
- Not even all bones are imaged well

kVCT differentiation of prostate capsule is limited





Artist's rendering taken from B. L. Carter, J. Morehead, S. M. Wolpert, S. B. Hammerschlag, H. J. Griffiths, and P. C. Kahn, Cross Sectional Anatomy: Computed Tomography and Ultrasound Correlation, Appleton-Century-Crofts, New York 1977, Section 41.

US-guided localization v. implanted marker seeds

- Multiple publications have revealed differences between US and gold marker seed localization
- The underlying assumption in most of these studies is absolute accuracy of marker seeds (i.e., few include error analysis of seed localization)
- All difference is attributed to US error
- Large body of US verification studies indicate accuracy within 5 mm.

US-guided localization v. implanted marker seeds

- Error analysis of marker seeds would include
  - CT/DRR resolution
  - kV/MV image system accuracy
  - Migration, deformation (1-2 mm)
- Legitimate US errors
- Legitimate differences in interpretation
  - Align to center of mass
  - Align to interfaces
  - Compromise

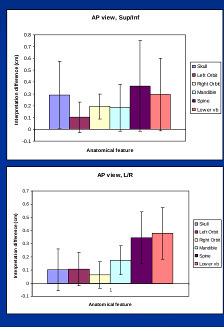
User variability study

Reference DRR Daily kV set-up image

- Varied anatomy used in matching
- Compared to 'reference match'
- Averaged 5 data sets

Data courtesy Michelle Taylor. MS Medical Physics candidate

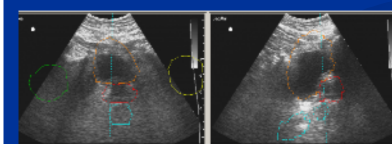
User variability study



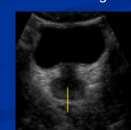
- Localization reproducibility is limited to 2-5 mm
- Spine and vertebral bodies have decreased reproducibility
- Will be exacerbated for thoracic and abdominal targets

Soft tissue imaging for localization

- US, at its best, is an excellent soft tissue differentiator
- Contrast resolution is a function of the design of the US system



Raw image



Compounded image

Intra v. Inter modality alignment

- Soft tissues appearance is imaging modality dependent
- Residual spatial errors may be resolved/reduced via intra-modality alignment

Table 2. Differences (in millimeters) in the paired 217 CMVM and IMVM prostate displacements in the lateral (RL), anteroposterior (AP), and superoinferior (SI) directions

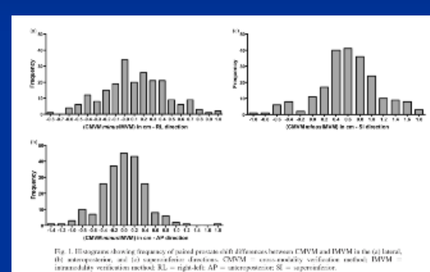
	CMVM minus IMVM		
	RL	AP	SI
Mean	0.9	0.1	6.0
SD	3.4	4.2	5.1
p value	<0.0001	0.604	<0.0001

Abbreviations: CMVM = cross-modality verification method; IMVM = intramodality verification method; SD = standard deviation.

Int. J. Radiation Oncology Biol. Phys., Vol. 66, No. 5, pp. 1562–1567, 2006

Intra v. Inter modality alignment

- Largest average discrepancy between CT/US and US/US alignment in SI direction (6 mm)

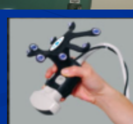


Early spatial registration methods for US/US alignment

Available technology

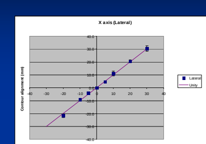
- BAT (B-mode acquisition and targeting system)
  - Articulating arm technology (original)
  - Optical marker tracking
- Sonarray (Varian Medical Systems)
  - Optical marker tracking
  - 3D
- Clarity (Resonant Medical)
  - Optical marker tracking
  - 3D
  - Simulation/reference US
- I-Beam (CMS)
  - Transducer-mounted camera, backlit calibration plate

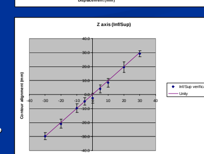
Technologies



Uncertainty propagation

- Lasers
  - Simulation suite
  - Table sag
  - Drift
- CT imaging
  - Pixel size (400mm FOV/512 = 0.8 mm)
  - ***Slice thickness***
  - Soft tissue contrast (technique, dose, noise)





Uncertainty propagation

- Contouring
  - User precision, esp in sup/inf dimension
  - Treatment planning contours v. alignment contours
- US image resolution/quality
  - Function of depth, esp. for 3D systems
  - Non-isotropic
  - Noise
  - Compromised penetration depth
  - Artifacts
- US spatial registration/calibration
  - Mechanics (phantom, camera, arm, transducer/holder integrity)
  - User upkeep
- Target deformation, mobility

Recommended QA procedures Geometric/Spatial Accuracy

- Laser alignment (daily)
  - 1 mm
  - Treatment room and simulator suite
  - Especially true for Sonarray (camera calibration directly dependent on laser alignment)
- Positioning constancy (daily)
  - 2 mm
  - Test over range of interrogation angles
  - Specifics are vendor dependent

Recommended QA procedures Geometric/Spatial Accuracy

- Basic US unit controls (daily)
  - TGC, brightness/contrast
- IR camera verification (daily)
  - Typical 60 minute warm up required
  - < 4 mm deviation prior to warm up
  - Mechanical stability
- Phantom stability (quarterly)
  - Desiccation
  - Mechanical trauma
  - < 1 mm
  - Repeat CT scan

Recommended QA procedures Geometric/Spatial Accuracy

- Positioning constancy (monthly)
  - Performed by physicist
  - Helps ensure skill maintenance
  - Separate and overt camera calibration verification
  - Observe gradual shifts that may go undetected daily
  - < 2mm
- Phantom offset test (monthly)
  - Performed by physicist
  - Offset in 3 dimensions and verify that alignment procedures return it to correct position.
  - May be done daily
  - < 2mm

Recommended QA procedures Geometric/Spatial Accuracy

- Laser offset test (monthly)
  - Simulation suite, if applicable
  - Verifies proper alignment and transfer of isocenter information for systems used in the simulation suite
  - Phantom is offset from zero position by a clinically appropriate distance
  - Isocenter is set at this new position
  - Co-registration of CT/US image sets should produce good alignment
  - Alternate between zero and non-zero offsets

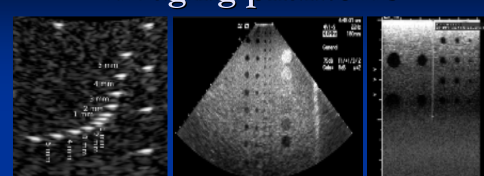
Recommended QA procedures Geometric/Spatial Accuracy

- End-end testing (annually)
  - Acquire reference CT (and reference US if applicable)
  - Structure segmentation
  - Set up in treatment room using lasers
  - Perform US alignment
  - < 2mm
  - Test for objects near isocenter and those displaced from isocenter by at least 3 - 5 cm.

Image quality checks

- Did not provide *quantitative* guidelines
- Frequency is semi-annual, consistent with ACR practices
- All criteria are in comparison to baseline
  - Spatial resolution
  - Low contrast resolution
  - Sensitivity
  - Hardware degredation

Imaging phantoms



- Highly reflective markers for spatial resolution
- Low contrast targets
- Uniform area or low contrast targets at depth for sensitivity determination

Process considerations

- Patient selection
  - Body habitus
    - Very large patients *may* not image well (but they might)
    - Very thin patients may not image well
    - Unfavorable relative locations of targets and obstructions
    - Unfavorable tissue acoustics (very dense tissues)
  - Prescreen patients for suitability
  - Inability to maintain moderately full bladder

Process considerations

- CT simulation and target delineation
  - Structures must be contoured for dosimetric treatment planning and (separately?) for alignment
  - Asymmetric planning target volumes could lead to confusion during US alignment
  - Consider that US alignment may emphasize boundaries. Contrast and attention to sagittal views is important for sup/inf alignment
  - Acquire CT scans with as small a slice spacing as practical

Process considerations

- Treatment planning
  - Yields beam arrangements and isodose configurations
  - If isodose contours used for patient alignment need to remain mindful of possible deliberate asymmetries
- Patient positioning and treatment
  - Need departmental policies regarding management of unacceptable images (bladder refilling, alternative imaging modalities (MV, kV imaging)
  - Need departmental policies regarding minimum and maximum shifts.

Training

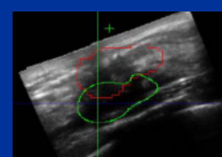
- Experienced users
  - have improved reproducibility
  - Better structure recognition
- Initial manufacturer training
  - Trainers should have significant clinical experience
  - Involve local US experts during initial training and clinical implementation period
- Continuing Clinical Training
  - Define regular meeting schedule for quality improvement/image review
  - May want to keep user log of number of cases

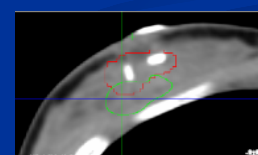
To do US right

- Use matching contours, not treatment planning contours
- High resolution CT, esp in the Sup/inf dimension
- Consider whether interfaces or prostate center of mass is the desired matching objective
- Screen patients at sim and do not use for patients that don’t image well
- Find prostate using lots of probe pressure, then back off until just visible
- Consider benefits of intra-modality (US/US) alignment
- Do a lot of it

Other applications

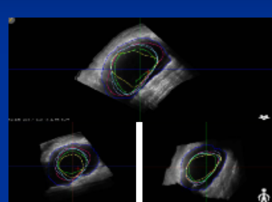
- Abdominal targets
- Liver, pancreas
- Breast





PBI

- US for treatment planning target definition
- Daily image guidance
- Monitor GTV/CTV changes



Conclusions

- US localization can be accurate and provide good soft tissue detail not available with other systems
- Accuracy depends on details of total clinical procedure train
- Frequent use and training are key