Ultrasound Instrumentation: An Important Focus for the Medical Physicist

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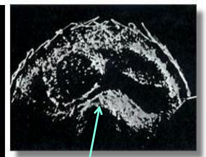
Picker Ultrasound Scanner (1971)
(Charles Kelsey, UW-Radiological Sciences)

Single element transducer moved manually over the scan plane, slowly tracing the anatomy.

"Bi-stable" B-mode images formed on a storage oscilloscope.

Today's most common Radiology systems


- Small-mid-size scan console.
- Linear, curvilinear, phased array transducers, supported by digital beam formers, in the console or in the probe, provide real-time 2D images.
- 3D imaging capabilities via motorized oscillation of the array or 2D array.
- Very good gray-scale performance, brightness prop. to echo amplitude.

Focus: Role of the Diagnostic Physicist


- Traditional medical physics support (QA, based on accreditation requirements)
- Do relevant, "advanced" testing
  - Example, resolution using realistic targets
  - Example, Doppler
- Support important emerging quantitative areas of ultrasound,
  - Example, shear wave detection and display

QA Information From US Accreditation Bodies

- Ultrasound Accreditation Program Requirements, Am College of Radiology, http://www.acraccreditation.org
- ACR-AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Real Time Ultrasound Equipment. http://www.acr.org/~/media/ACR/Documents/PGTS/standards/MonitorUSEquipment.pdf
- AIUM 1998, American Institute of Ultrasound in Medicine, Routine Quality Assurance for Diagnostic Ultrasound Equipment. http://aium.s3.amazonaws.com/resourceLibrary/rqa.pdf

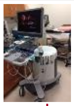
Annual Surveys, Routine QA (ACR)

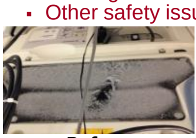
- Physical and and mechanical inspection; sterility
- Image display performance
- Image Uniformity
  - Element "dropout" and other sources on non-uniformity
- System sensitivity and/or penetration capability
- Geometric measurement accuracy (during program initiation; optional, but still included on acceptance tests (optional))
- 6-month Routine QC: optional
- Annual surveys: required
- Contrast resolution, spatial resolution: optional items for annual survey.

http://www.acraccreditation.org/Modalities/Ultrasound

Physical and Mechanical Inspection, ACR

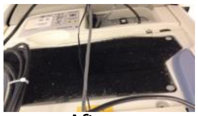
- Console
  - Air filters
  - Lights, indicators
  - Wheels, wheel locks
  - Proper cleaning (are procedures in place?)
  - Viewing monitor, keyboard clean
  - Other safety issues





Before

Air filters on back of console

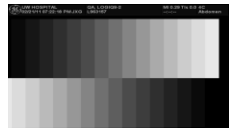


After

Image Display (Scanner and PACS)

- Important for monitor on machine to be set up properly to view all echo levels available and entire gray bar pattern.
  - Set up during acceptance testing
  - Take steps to avoid casual adjustments (mark or inscribe contrast and brightness controls)
- Most machines provide one or more gray scale test patterns for setup and for routine QC.
  - are all gray bars visible?

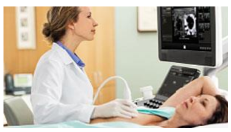
www.philips.com

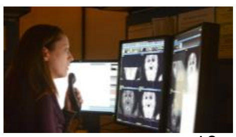


Gray bar on GE Logiq 9

Image Display (Scanner and PACS)

- Gain and sensitivity adjustments done using system monitor
- Intrepretation most often done on a PACS workstation.
- Important that there is agreement between image features viewable on PACS and the features seen on the system monitor.
- We were finding that the 15 gray bar pattern built into some machines was not sensitive enough to subtle, but important faults in monitor agreement.





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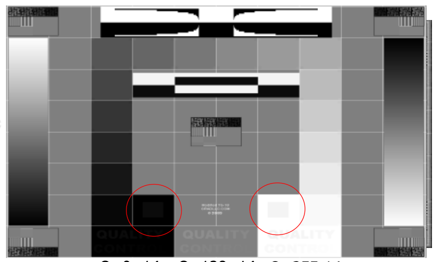
SMPTE, TG18 or Other Gray Scale Test Pattern

- Available on most scanners
- 0% to 100% gray bar pattern
- Squares for detecting geometric distortion
- Are all gray transitions visible?
- Is the 0-5% transition visible?
- Is the 95-100% transition visible?



TG18: Q=0+14 I=1 Q=128+14 I=129 Q=255-14 I=254

AAPM Task Group: TG 316

- Proposed goals: develop evaluation methods to assess the performance of ultrasound image-display systems and the harmonization between the PACS-display and the ultrasound scanner-display.
- Test methods: Visual evaluation with test patterns and quantitative evaluation with photometers.
- Expected outcome: Criteria, based upon the guidelines in the report of AAPM TG-270, expanded specifically to ultrasound imaging tasks.
- Timeline: Getting underway Summer, 2018.
- Interested? contact ZhengFeng Lu, Univ of Chicago

Routine QA: Transducers

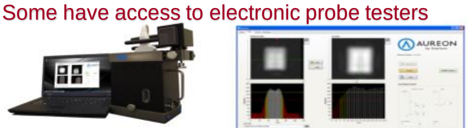
- Check all transducers on the system
  - (most facilities have many interchangeable probes that float among systems; a systematic approach to evaluate all probes should be in place.
- Transducer Inspection Delaminations
  - Frayed cables
  - Proper cleaning

www.providian.com

Transducer Tests

- Most facilities use phantoms for transducer imaging tests and further system evaluation

- Some have access to electronic probe testers



Tests using phantoms. Current materials:

- Water-based gels
  - Advantages:
    - Speed of sound = 1540 m/s
    - Attenuation ~ proportional to frequency (specific attenuation expressed as 0.5 or 0.7 dB/cm-MHz)
    - Backscatter
  - Disadvantages:
    - Subject to desiccation (?)
    - Must be kept in containers
    - Requires scanning window

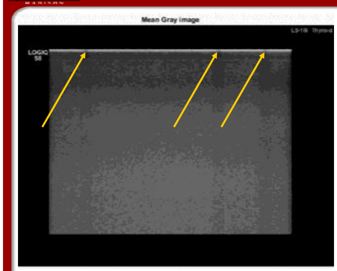
Tests using phantoms. Current materials:

- Solid, non-water-based materials (urethane)
- Advantages:
  - Not subject to desiccation
  - No need for scanning window; possibility for soft, deformable scanning window
  - Produce tissue-like backscatter
- Disadvantages:
  - C= 1430-1450 m/s
  - Attenuation ~ proportional to $f^{1.6}$
  - Surface easily damaged if not cleaned regularly to remove gels

Check for non-uniformities caused by element dropout

- Most frequent fault seen in QA testing
- Image a phantom using good coupling
- Search for "shadows" emanating from the transducer
- Common in new and old probes!
- (This transducer is functioning well.)

Check for non-uniformities caused by element dropout



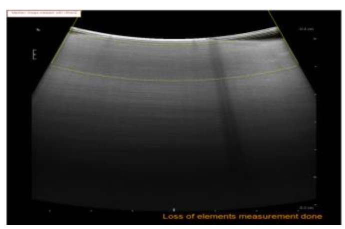
- Most frequent fault seen in QA testing
- Image a phantom using good coupling
- Search for "shadows" emanating from the transducer
- Common in new and old probes!
- (This transducer has 3 obvious areas of dropout.)

Recommended Testing Technique

- Use a single (shallow) transmit focal distance
- Use persistence; translate transducer to reduce effects of speckle. (make a cine loop)

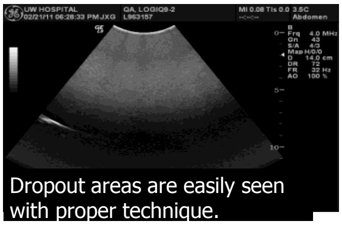
Median image made from a cine loop, acquired while transducer was moving.

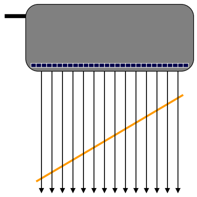
("UltraIQ" from Cablon Medical)



Recommended Testing Technique

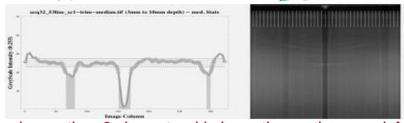
- Use a single (shallow) transmit focal distance
- Use persistence; translate transducer to reduce effects of speckle.
- Disable spatial compounding (Sea Clear; X beam, etc)





Objective Criteria being developed

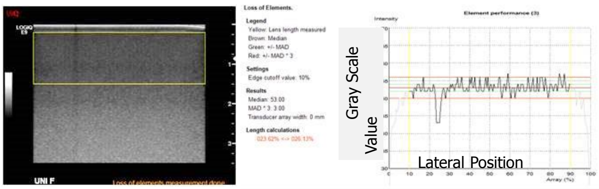
- IEC 62736 Ultrasonics (2016) – Pulse-echo scanners – Simple methods for periodic testing to verify stability of an imaging system's elementary performance
- AAPM Ultrasound Subcommittee Task Group
- Record a cine loop while translating the transducer ⊥ to the image plane.
- Compute the **'median'** image for this (~100) image loop
- Plot a lateral intensity profile from a ~3-10 mm axial range



Median image

- A dip >3dB and more than 2 elements wide is worth counting as a defect of possible concern. (IEC 62736)

Image Uniformity(Automated QC Software)



Median Image

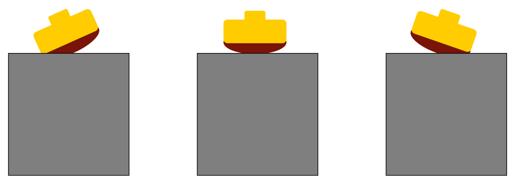
UltraiQ

cablon medical

Dip magnitude and width analyzed in uniformity assessment

Uniformity tests with curvilinear arrays

- Solution 1: rock transducer from side to side



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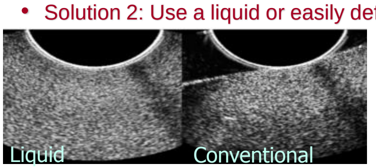
Uniformity tests with curvilinear arrays

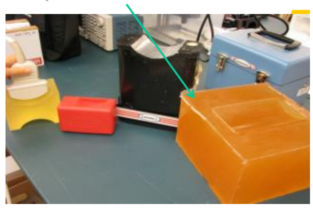
- Solution 2: Use a liquid or easily deformable TM material



King et al, Evaluation of a low-cost liquid ultrasound test object for detection of transducer artifacts. Phys. Med. Biol. 55 (2010) N557-570.

Uniformity tests with curvilinear arrays

- Solution 3: Use a phantom having concave windows (Goodsitt et al, AAPM Ultrasound Task Group work)



Transducer worksheet part of UW Report

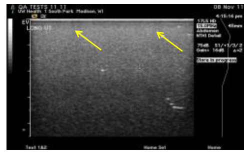
Instructions, uniformity ratings (UW-Madison, not other groups, such as AAPM):
- 1=uniform
- 2=minor inhomogeneity (no more than 2 minor dips)
- 3=Significant inhomogeneities; transducer is functional, but consider replacing
- 4=Immediate repair or replacement recommended

Data table (1 line for each transducer)

Transducer ID/Serial Number	Cables/ cracks/ delaminate		Uniformity, dropout		Sensitivity (Depth of Penetration) (MHz/cm)	Geometric Accuracy H: cm/actual cm V: cm/actual cm	Conclusions and recommendations
	OK	No	OK	No			
C1-5 79635YP9	☒	☐	☒	☐	5MHz/13.71cm H5MHz/10.6 cm	H: 5.81/6 V: 8.01/8	Uniformity Rating 1 DOP ≈ to previous results ☒ Yes ☐ No Click here to enter comments.

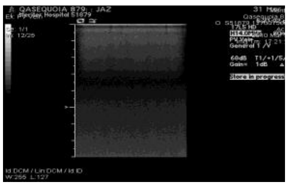
Transducer Recommendations

- Rating of “2”: 1 or 2 minor defects seen. Continue to use (watch and wait).



Transducer Recommendations

- Rating of “3”: Significant inhomogeneities; transducer is functional, but look to replace it ASAP.



Transducer Recommendations

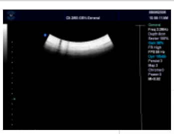
- Rating of “4”: Immediate repair or replacement recommended.

The left half of the array is faulty, with numerous dropout areas.

There is a single, large dropout areas in the middle of the array.

Transducer Tests on the System

- A few systems can do a self test that evaluates the transducer response or the electrical impedance for each element.
  - Machine sequences through each channel measuring the signal while the transducer is “in air.”
- AIUM’s Technical Standards Committee and FDA working to make self test modes available to qualified users.
- (Especially needed for phased arrays. 2 D arrays)

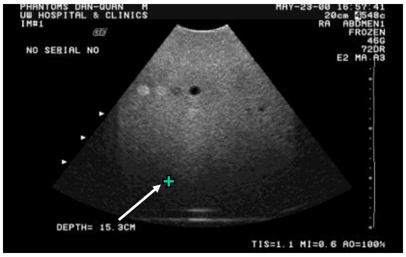


Sensitivity, Maximum Depth of Penetration

- Considered by many as a good overall check of the integrity of the system
- FOV set to match the phantom height or the maximum visualization depth of the transducer
- Output power (MI) at max
- Transmit focus at deepest settings
- Gains, TGC for visualization to the maximum distance possible

Maximum "Relative" Depth of Penetration

How far can you see the speckle pattern in the material?



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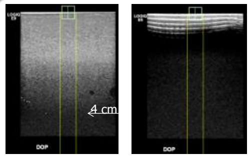
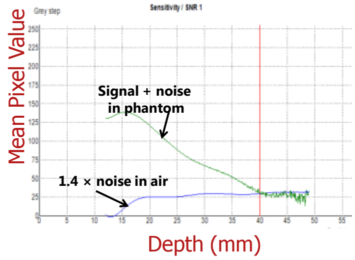
DOP testing: Objective methods are becoming available





Compute mean pixel value vs. depth for phantom (signal+noise).

Do the same for "air" image (noise) acquired using the same settings.

Depth where (signal + noise) equals 1.4 x (noise) =DOP (IEC 62736, 2016)

UW Report Transducer worksheet (page 3)

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Distance Measurement Accuracy: Vertical

- Actual 8.0 cm
- Measure 7.94 cm
- error 0.75%
- Acceptable

*Action: >1.5mm or 1.5%

*Defect: >2mm 0r 2%

*Goodsitt M M *et al* 1998 Real-time B-mode ultrasound quality control test procedures. Report of AAPM Ultrasound Task Group No. 1 *Med. Phys.* **25** 1385

Routine QA (ACR General US Program)

- Distance Measurement Accuracy tests
  - Necessary? ("Scanner is a transducer tied to a computer.")
  - May be important for specific uses
    - Images registered from 3-D data sets
    - Workstation measurements
    - Radiation seed implants

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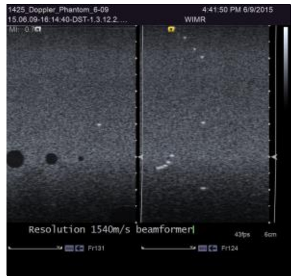
4-year Experience with a clinical ultrasound quality control program (phantom-based tests)

(Hangiandreou et al., Ultrasound Med Biol 37, 1350-1357, 2011)

Evaluation Method	# of detected "failures"	% of detected "failures"	Recommendation (Hangiandreou)
Mechanical Integrity	47	25.1	Quarterly
Image uniformity	**124**	**66.3**	Quarterly
Distance Accuracy	0	0.0	Annually
DOP (penetration)	3	1.6	Annually, (if done with software)
Clinical Problems	13	7.0	Sonographer's daily inspections
TOTAL	**187**	**100.**	

Spatial Resolution?

- Not done routinely
  - 2 image sets, each taken with a different speed of sound assumption in the beam former
  - Targets not agreed on universally
    - Anechoic objects get fuzzy with poorer resolution
    - Line targets get wider
  - Requires standardized gain settings to make meaningful
  - Enhance using computational methods to measure point spread function width?



Involvement with Protocols

- "What's wrong with our machine? We scanned a patient having a palpable breast mass, and it appeared suspicious enough to warrant a biopsy. But the machine used to perform the biopsy showed a different property of the mass, much more like a cyst."
- Both machines are from the same manufacturer.
  - Logiq E9, Logiq S8 from GE
  - Both are equipped with a multi-row linear array transducer, commonly used for breast imaging.

Problem: Solid mass?

Transmit foci:
1.35 cm
2.05 cm

Mass looks much more like a cyst

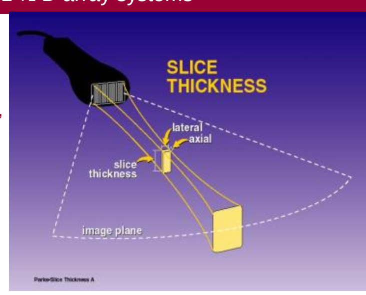
- No internal echoes
- Clear borders

Transmit foci:
0.75 cm
1.25 cm
(A bit above the lesion)

Beyond "Routine QC:" Assessment of 1 ½ D array systems

Slice thickness effects in medical ultrasound

- Systems apply electronic focusing in the scan plane, maintaining optimal lateral resolution
- Elevational (slice thickness) focusing may be done using a fixed focal length lens



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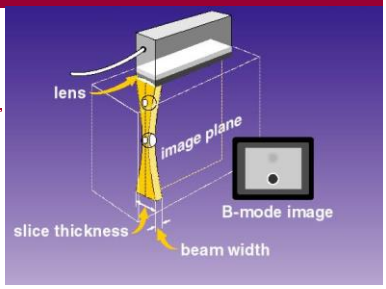
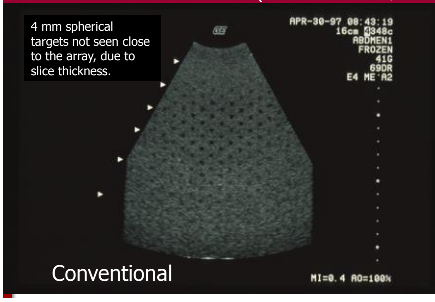
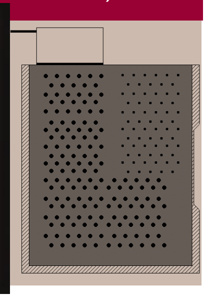


4 mm diameter spherical lesion phantom (Gammex 408, CIRS 040GSE)

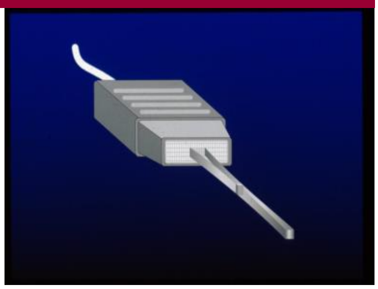




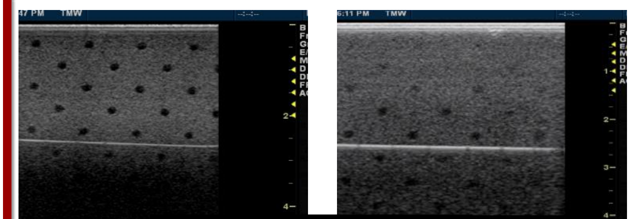
Beyond "Routine QC:"
Assessment of 1 ½ D array systems

Slice thickness effects in medical ultrasound

- Systems apply electronic focusing in the scan plane, maintaining optimal lateral resolution
- Matrix (1 ¼ or 1 ½ D) probes provide additional control of elevational focusing.
  - Aperture size control
  - Focusing time delays



High Frequency Breast Imaging Probes

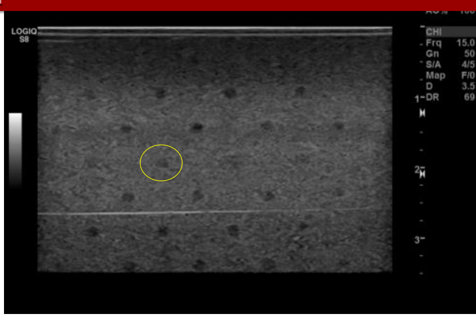


2 mm spherical, anechoic targets

1 ½ D or Multi-row

1-D, or single row with mechanical lens

Duplicated findings with a 2mm spherical lesion phantom.



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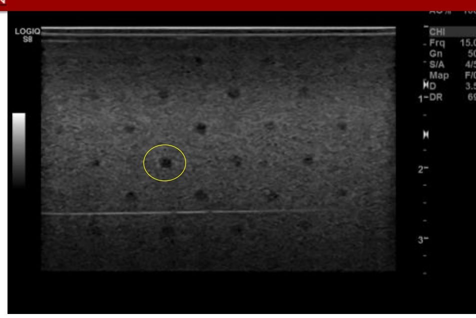

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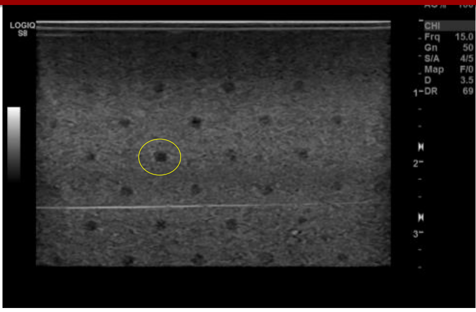
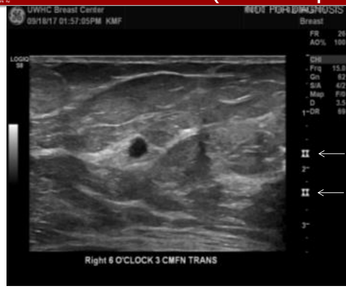


Issue (work in progress)



The elevational aperture control vs. transmit focus is built into the system presets.

Users need to be made aware of these results.

Tests using "advanced" phantoms can aid development of better, more robust control of the elevational focus.

Currently working to achieve concordance among system presets.

Beyond "Routine QC:" Important Areas for Medical Physics Involvement

- Protocol development using more advanced phantom testing
- Doppler evaluations
  - Velocity accuracy
  - Volume flow, (QIBA)
  - Directional Discrimination; gate accuracy, etc.
- Elasticity, shear wave (SW) imaging
  - QIBA work on SW velocity in liver (advanced stages)

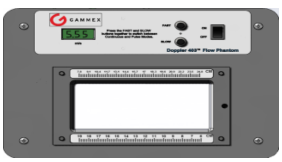
Doppler Testing: Blood Velocity is Important!

Common Carotid Artery

60 cm/s

Consensus criteria used to diagnose stenosis of the internal carotid artery based on blood velocity measurements. ICA blood velocities of less than 125 cm/s are considered normal, as are ratios of the velocity in the internal carotid artery to that in the common carotid artery of less than 2. Specific values of these Doppler spectrum-based parameters are associated with different degrees of stenosis. (From http://www.slideshare.net/shaffar75/doppler-ultrasound-of-carotid-arteries)

Doppler 403 Flow Phantom

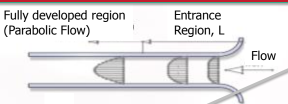


Scan surface and flow control, with volume flow readout. Can be run in continuous or pulsed mode. Volume flow rates from 1-12.5 ml/s (continuous)

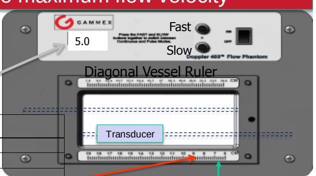
Doppler 403 Flow phantom, with transducer holder

Medical Physics Dept.

Gammex 403 Flow Phantom: uses a calibrated volume flow meter Estimates are made of the maximum flow velocity



Phantom Display (ml/s)	System Display (ml/min)	Average Vmean	Peak Velocity at Parabolic Flow Vmax	Entry Length to achieve Parabolic Flow
1	60	5.1	10.2	1.76
2	120	10.2	20.4	3.51
3	180	15.3	30.6	5.27
4	240	20.4	40.7	7.03
5	300	25.5	50.9	8.79
6	360	30.6	61.1	10.54
7	420	35.7	71.3	12.30
8	480	40.7	81.5	14.06
9	540	45.8	91.7	15.81
10	600	50.9	101.9	17.57
11	660	56.0	112.0	19.33



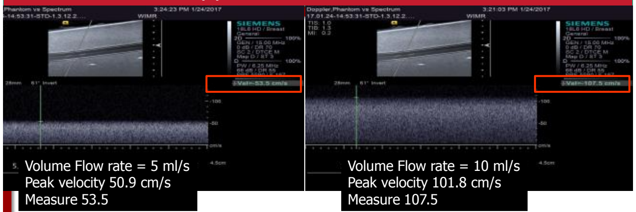
Horizontal Vessel Ruler

$$v_{mean} = \frac{Q}{Area} = \frac{Q}{\pi D^2/4}$$

$$v_{max} = 2\, v_{mean}$$

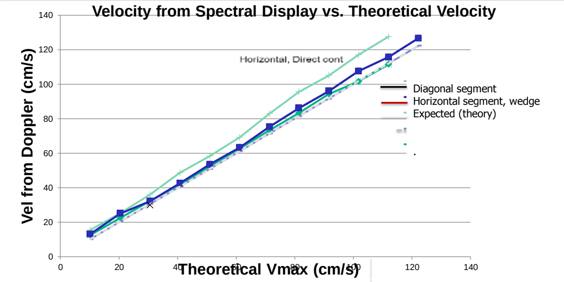
$$L = 0.06\, D\, Re$$

Doppler 403 Flow Phantom

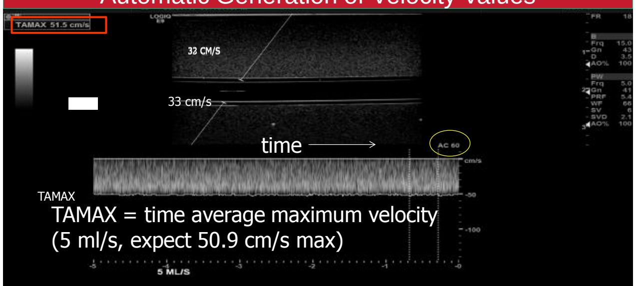


With a wedge offset, tilting the transducer to enable a 60° Doppler angle.

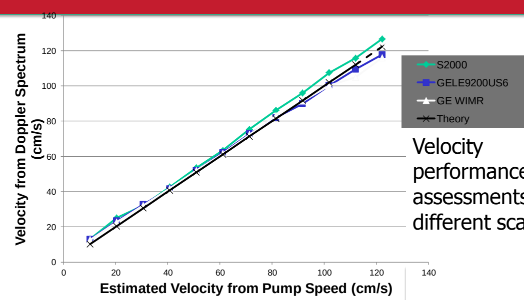
Doppler 403 Flow Phantom, Siemens S2000



Doppler 403 Flow Phantom, GE Automatic Generation of Velocity Values



Doppler 403 Flow Phantom, GE LE9, Automatic Generation of Velocity Values (TAMAX)



Velocity performance assessments for 3 different scanners

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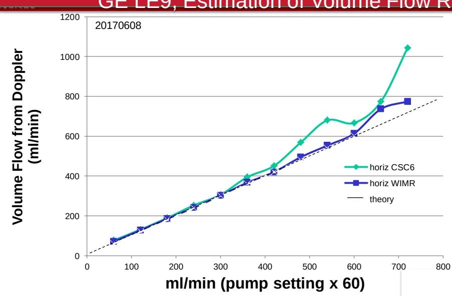
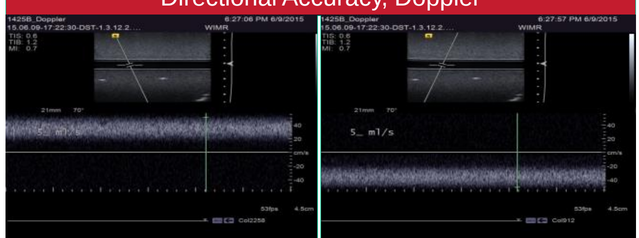
Doppler 403 Flow Phantom GE LE9, Estimation of Volume Flow Rate



Directional Accuracy, Doppler



System with good directional detection

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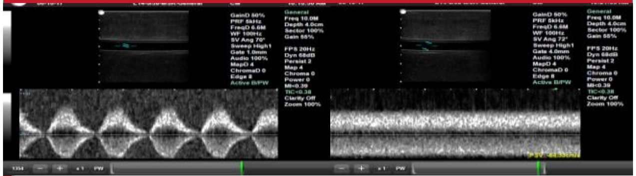
Directional Accuracy, Doppler



Pulsed flow Continuous flow

System with <u>poor</u> directional detection. Flow appears to be bidirectional, even though it is only from right-to left..

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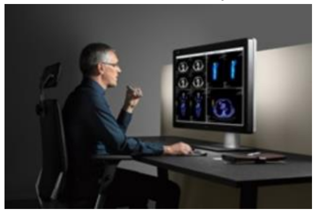
Liver Tissue Stiffness

"And on the basis of shear wave measurements, the liver exhibits a stiffness of 13.4 kilopascals."

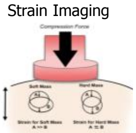


- Strain and shear wave imaging is built into most radiology machines.
- Important area of medical physics involvement
  - Support testing
  - Radiology resident education
  - QIBA work

Liver Tissue Stiffness

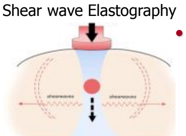
Strain imaging: push transducer
Shear wave imaging: track a shear wave that is imparted, such as by vibrating the transducer or by ARF Results are <u>quantitative!</u>

Strain Imaging



Display strain after a push

Shear wave Elastography



Quantitative cm/s or kPa

- Strain and shear wave imaging is built into most radiology machines.
- Important area of medical physics involvement
  - Support testing
  - Radiology resident education
  - QIBA work

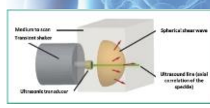
Transient Elastography: the Fibroscan

- 50 Hz Mechanical push ("Fibroscan") generates a spherical compression wave as well as a spherical shear wave.
- Track shear wave tissue displacement in the axial direction using a 2.5 or a 3.5 MHz single element ultrasound transducer. Use signal correlation methods to get c_T
- Convert c_T to elastic modulus E using

$$E \cong 3G = 3\rho(c_T)^2$$

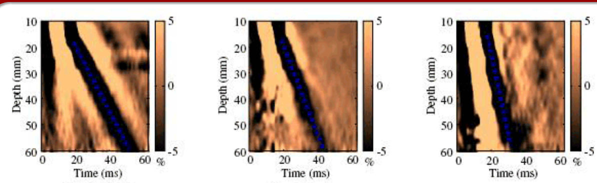
where G is the shear modulus.

- E is in kPa when c_T is in m/s (assuming the density is 1,000 kg/m³ and Poisson's ratio is 0.5)



www.echosens.com
Gennisson et al., Ultrasound elastography: principles and techniques, Diagnostic and Interventional Img. 94(5): 487-495 (2013)

Transient Elastography: the Fibroscan



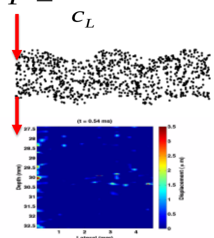
V_s = 1.0 m/s	V_s = 1.6 m/s	V_s = 3.0 m/s
E = 3.0 kPa	E = 7.7 kPa	E = 27.0 kPa
F0	F2	F4
Normal Liver		Significant Fibrosis

https://www.racgp.org.au/afp/2013/july/fibroscan/

Tissue Stiffness: Shear Wave Speed

- Most Ultrasound SWE systems use Acoustic Radiation Force, or ARFI
- Use conventional imaging transducers
- "Push" tissue remotely with long duration (100μs), high intensity ultrasound pulse
  - Typical ultrasound B-mode pulse is sub-microsecond
  - Force excites a shear wave
- Track tissue displacement (wave motion) perpendicular to push

$$F = \frac{2\alpha I}{c_L}$$

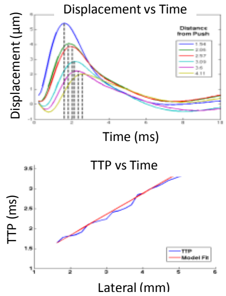


Courtesy of L Drehfal and TJ Hall, UW Madison

Tissue Stiffness: Shear Wave Speed

- Push tissue remotely with long duration (100μs), high intensity ultrasound pulse
  - Typical ultrasound pulse is sub-microsecond
  - Force excites a shear wave
- Track tissue displacement (wave motion) perpendicular to push
- Time-to-peak at each lateral location is used for SWS estimate

Courtesy of L Drehfal and TJ Hall, UW Madison



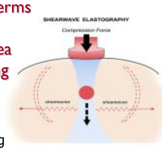
Tissue Stiffness: Shear Wave Speed

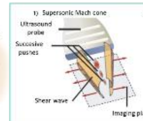
- Differences between ARFI systems in terms of shape of push pulse, number of push pulses used (point measurements vs area measurements), and shear wave tracking methods.

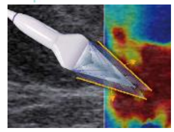
Nightingale et al., Shear-wave generation using acoustic radiation force: in vivo and ex vivo results, Ultrasound Med Biol 29(12): 1715-1723 (2003).

Gennisson et al., Ultrasound elastography: principles and techniques, Ultrasound Med Biol 94(5): 487-495 (2013)

www.supersonicimagine.com

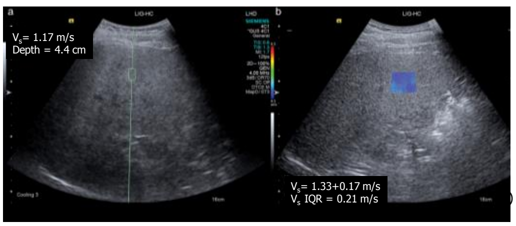






Tissue Stiffness: Shear Wave Speed

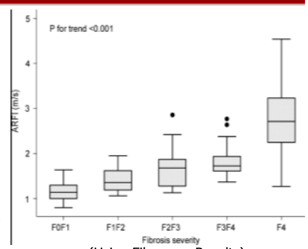
- Liver example



Kennedy et al., Quantitative Elastography Methods in Liver Disease: Current evidence and Future directions, Radiology 286: No 3 – March 2018.

Tissue Stiffness: Shear Wave Speed

- This paper compares ARFI imaging using a Siemens S3000 system with results of the Fibroscan system, where most of the clinical work has been done.
- Notice, ARFI results are reported in m/s, and were not converted to Young's modulus.
- Experts (see QIBA, next slide) point out that results are complicated by dispersion, excitation of different shear wave frequencies by different methods (Fibroscan, SWE, MRE), etc.



(Using Fibroscan Results)

Tung-Hung Su et al, Acoustic Radiation Force Impulse US imaging: liver stiffness in patients with chronic hepatitis B with and without antiviral therapy. Radiology 2018 Mar 27: 171116 (Epub ahead of print)

QIBA Effort: Shear Wave Speed in Liver

QIBA Profile* ***Ultrasound Measurement of Shear Wave Speed for Estimation of Liver Fibrosis.*** If successful, shear wave assessments might be used for:

- patient treatment decisions
- monitor progression, response to treatment

QIBA Profile: Places requirements on:

- Acquisition Devices,
- Technologists, Radiologists, training, actions
- **Image Data Acquisition**, Image Data Reconstruction,
- Image QA and Image Analysis.

*Currently in draft form only. Committee heads: Brian Garra, MD, Tim Hall, Ph.D., Andrej Milkowski, MS.

QIBA Effort: Shear Wave Speed in Liver

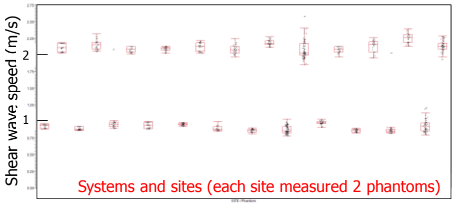
QIBA Profile* ***Ultrasound Measurement of Shear Wave Speed for Estimation of Liver Fibrosis.*** Role for physics technical support

- Standard QA tests listed by AIUM and ACR
- In-house SWE phantom testing is an important component.
- Elastic phantoms, ~2 m/s and ~ 0.9 m/s
- Standard properties of QA phantoms
  - 0.5 ± 0.1 dB/cm-MHz
  - SOS 1540 ± 30 m/s
- Procedure for verifying phantom stability

*Currently in draft form only. Committee heads: Brian Garra, MD, Tim Hall, Ph.D., Andrej Milkowski, MS. Phantom courtesy of CIRS Inc.

QIBA Effort: Shear Wave Speed in Liver

QIBA Profile* ***Ultrasound Measurement of Shear Wave Speed for Estimation of Liver Fibrosis.*** Role for physics technical support



Tim Hall et.al., RSNA/QIBA: Shear wave speed as a biomarker for liver fibrosis staging. IEEE Ultrasonics Symposium Proceedings, 2013.

Summary

- Setting up, maintaining an ultrasound equipment QA program is straight forward
- The ACR listed procedures form a useful, basic QA program
  - Transducer uniformity problems, element dropout, a frequent fault in today's scanning machines
  - Computational methods can be incorporated for objective tests
- Physicists can contribute to provide more detailed assessments of resolution
- Doppler testing should be considered by sites
- Quantitative assessments of shear wave speed are an important, new focus for clinical physicists. QIBA group is making rapid progress on developing a profile that should provide reproducible results in different systems.