



INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/638-18

**College on Medical Physics:
Imaging and Radiation Protection**

31 August - 18 September 1992

*Ultrasound Fundamentals
in Biomedical Applications*

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ULTRASOUND FUNDAMENTALS

elastic waves $f > 20 \text{ kHz}$

IN BIOMEDICAL APPLICATIONS:

FREQUENCY : $1 \leq f \leq 15 \text{ MHz}$

MEAN VELOCITY : $c \approx 1540 \text{ m/s}$

WAVELENGTH : $\lambda = \frac{c}{f}$ $1.5 \leq \lambda \leq 0.07 \text{ mm}$

ACOUSTIC IMPEDANCE : $z = \rho \cdot c$ $[\text{kg/m}^2\text{s}]$

where :

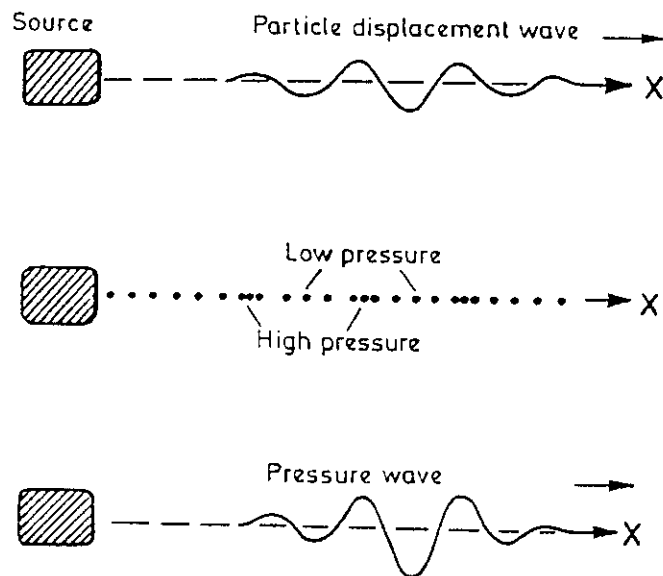
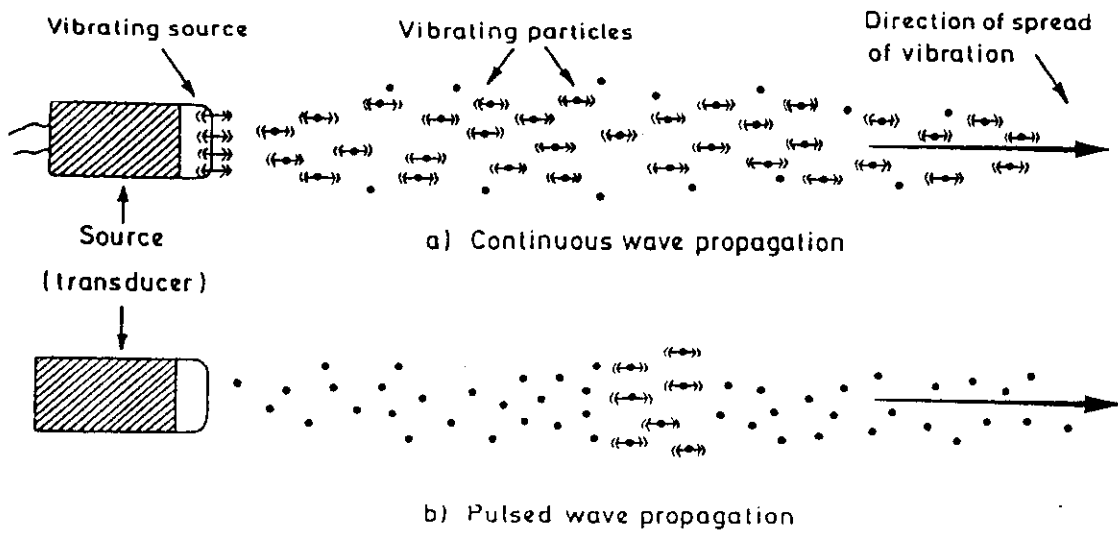
ρ = density of medium

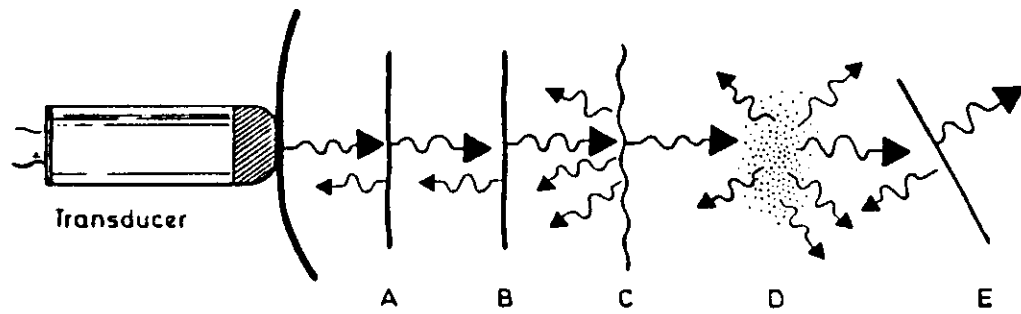
c = propagation velocity

$1.5 \cdot 10^6 \text{ kg/m}^2\text{s}$

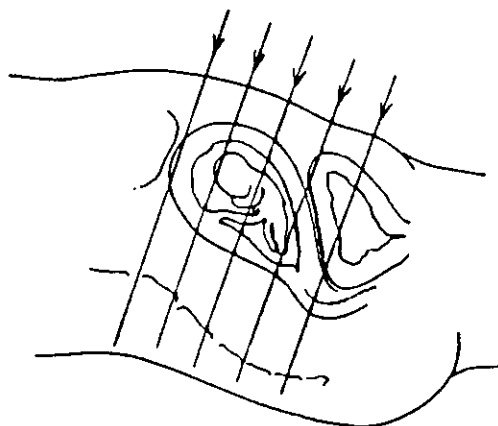
ATTENUATION IN BIOLOGICAL TISSUES :

$0.5 \div 1 \text{ dB cm}^{-1} \cdot \text{MHz}$

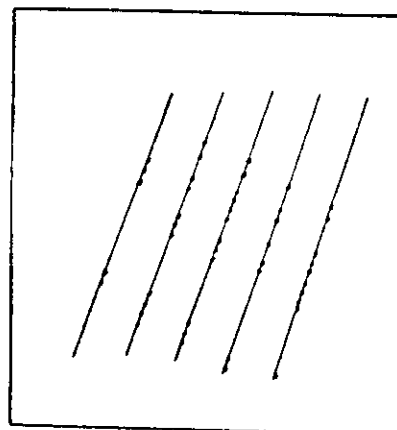




Sample beam directions



Sample lines of echo



Display screen

TABLE 1.1
Properties of some non-biological materials

Material	Density, ρ [kg m ⁻³]	Velocity, c [m s ⁻¹]	Characteristic impedance, Z [kg m ⁻² s ⁻¹] ($\times 10^{-6}$)	Absorption coefficient, α [dB cm ⁻¹] at 1 MHz	Approximate frequency dependence ^a of α
Air at STP	1.2	330	0.0004	1.2	f^2
Aluminium	2700	6400	17	0.018	f
Brass	8500	4490	38	0.020	f
Castor oil	950	1500	1.4	0.95	f^2
Mercury	13 600	1450	20	0.000 48	f^2
Polyethylene	920	2000	1.8	4.7	$f^{1.1}$
Polymethylmethacrylate	1190	2680	3.2	2.0	f
Water	1000	1480	1.5	0.0022	f^2

^a For frequencies below about 10 MHz.
Data chiefly from Kaye and Laby (1968).

TABLE 1.2
Field parameters for plane waves in water: values for 1 W cm^{-2}
at 1 MHz

Parameter	Value	Dependence
Heat equivalent	$0.24 \text{ cal s}^{-1} \text{ cm}^{-2}$	(intensity)
Peak particle acceleration, a_0	71 000 gravity	$(\text{intensity})^{1/2}$, (frequency) $^{-1}$
Peak particle displacement, u_0	$0.018 \text{ } \mu\text{m}$	$(\text{intensity})^{1/2}$, (frequency) $^{-1}$
Peak particle pressure, p_0	1.8 atmosphere	$(\text{intensity})^{1/2}$
Peak particle velocity, v_0	12 cm s^{-1}	$(\text{intensity})^{1/2}$
Radiation pressure, $\circ F$	0.069 g cm^{-2}	(intensity)
Velocity, c	1500 m s^{-1}	—
Wavelength, λ	1.5 mm	$(\text{frequency})^{-1}$

• For complete absorption
Data from Wells (1969).

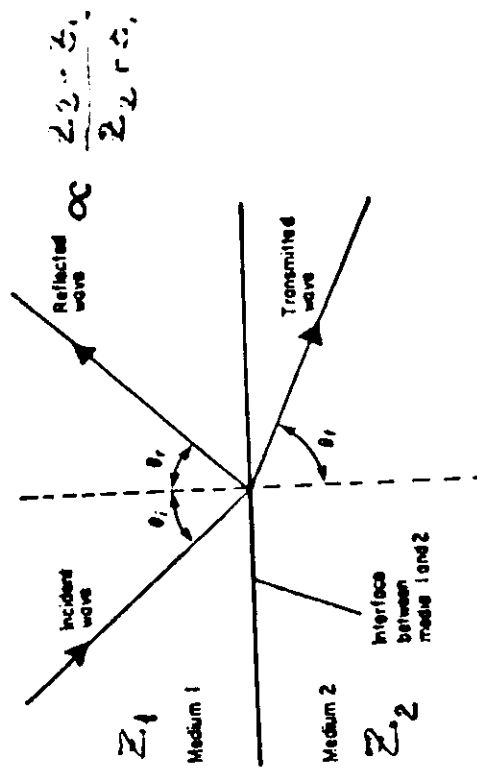
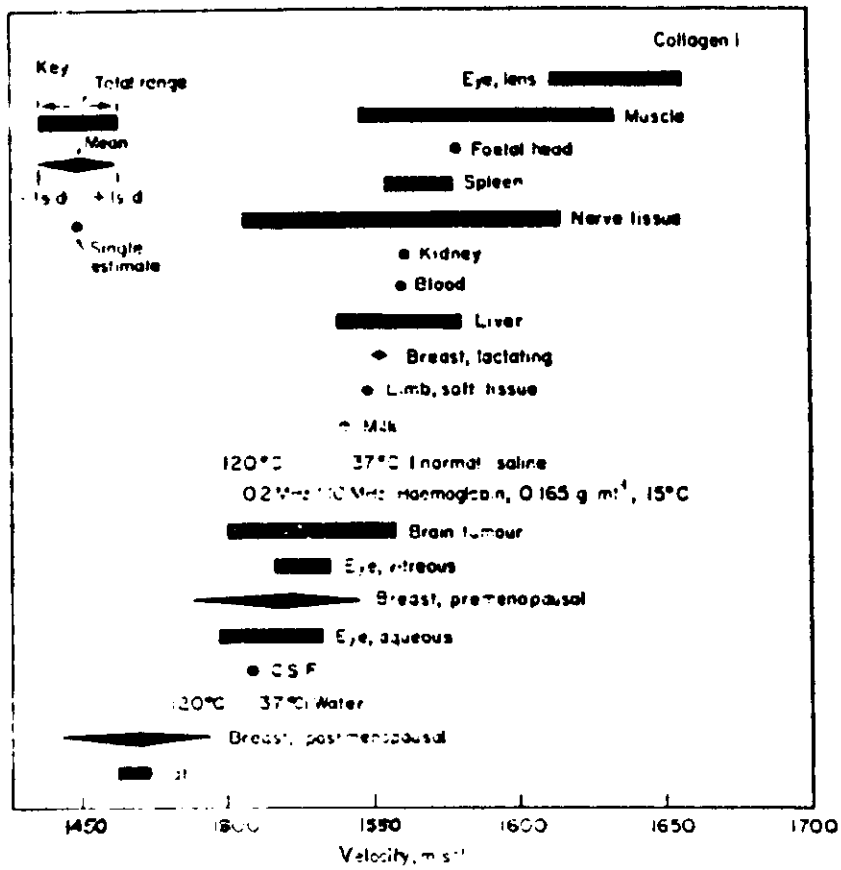


FIG. 1.8 The behaviour of a wave incident on the boundary between two media.

Amplitude of reflected wave

Densities and characteristic impedances of some biological tissues

Material	Density g ml ⁻¹	Characteristic impedance 10 ⁶ kg m ⁻¹ s ⁻¹
Blood	1.06	1.62
Bone	1.38-1.81	3.75-7.38
Brain	1.03	1.55-1.66
Fat	0.92	1.35
Kidney	1.04	1.62
Liver	1.06	1.64-1.68
Lung	0.40	0.26
Muscle	1.07	1.65-1.74
Spleen	1.06	1.65-1.67
Water	1.00	1.52



(b)

TABLE 4.2

Reflectivities of some plane biological boundaries, expressed in decibels below the level from a perfect reflector

Blood		Bone		Brain		Fat		Kidney		Liver		Lung		Muscle		Spleen		Water	
5	50	21	27	38	5	21	38	5	32	38	3	38	38	30	25	27	27	27	27
•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

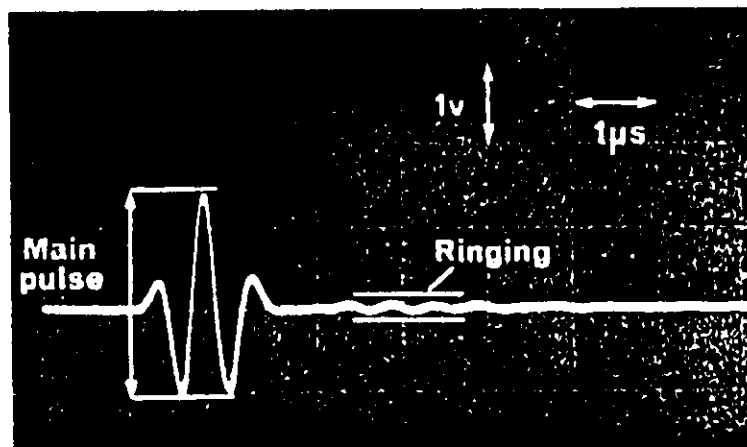
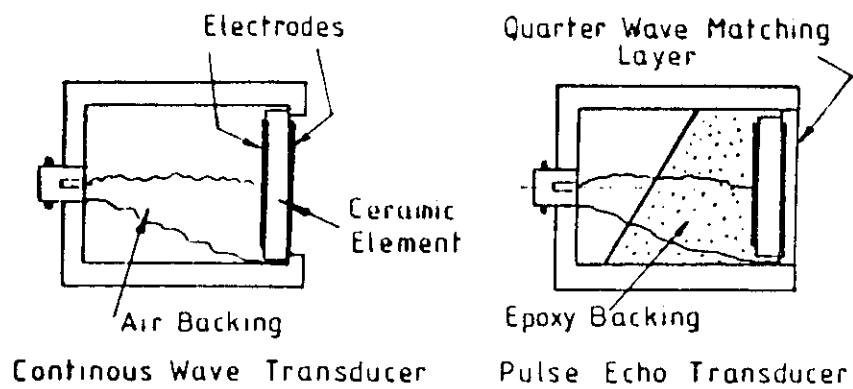
• Indicates that the corresponding boundary is unlikely to be of practical interest.
Based on data from Table 4.1.

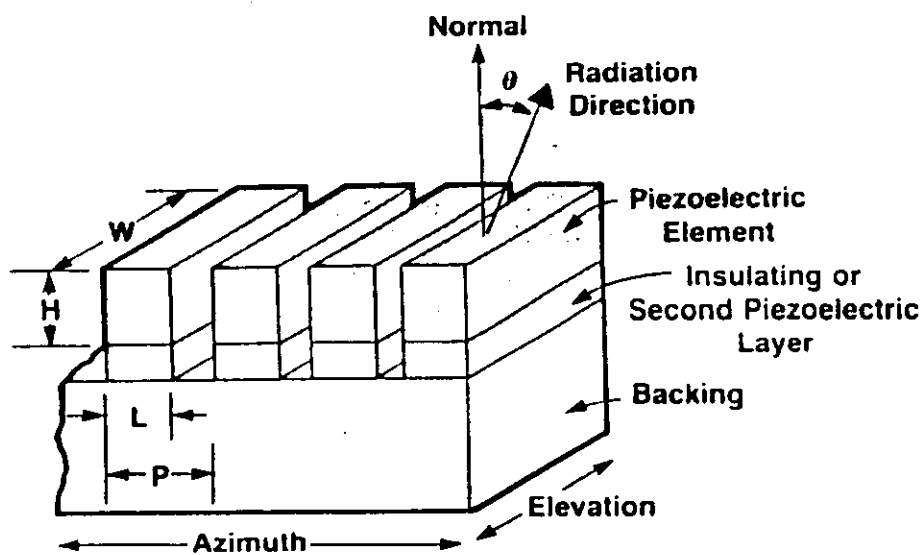
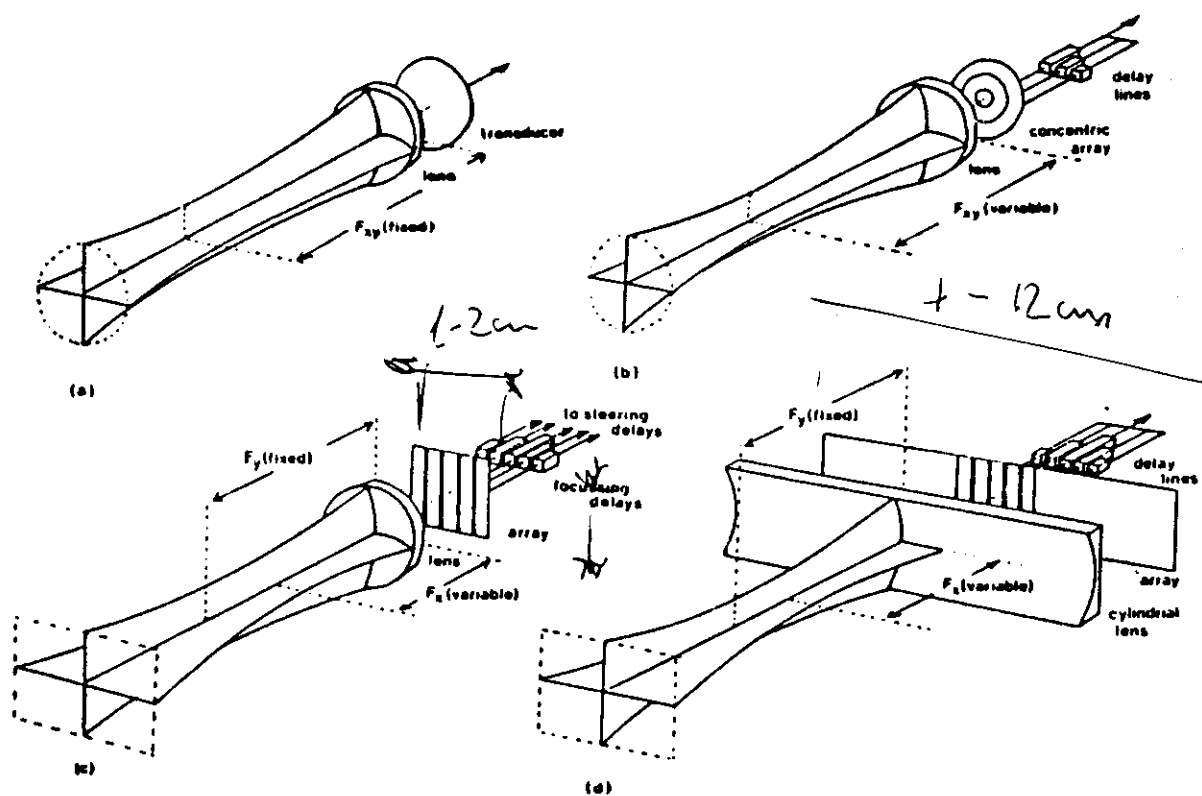
TRANSDUCERS

⑥ SINGLE ELEMENT

⑥ MULTIPLE ELEMENT

- LINEAR ARRAYS
- STEERED ARRAYS
- CONVEX ARRAYS
- ANNULAR ARRAYS

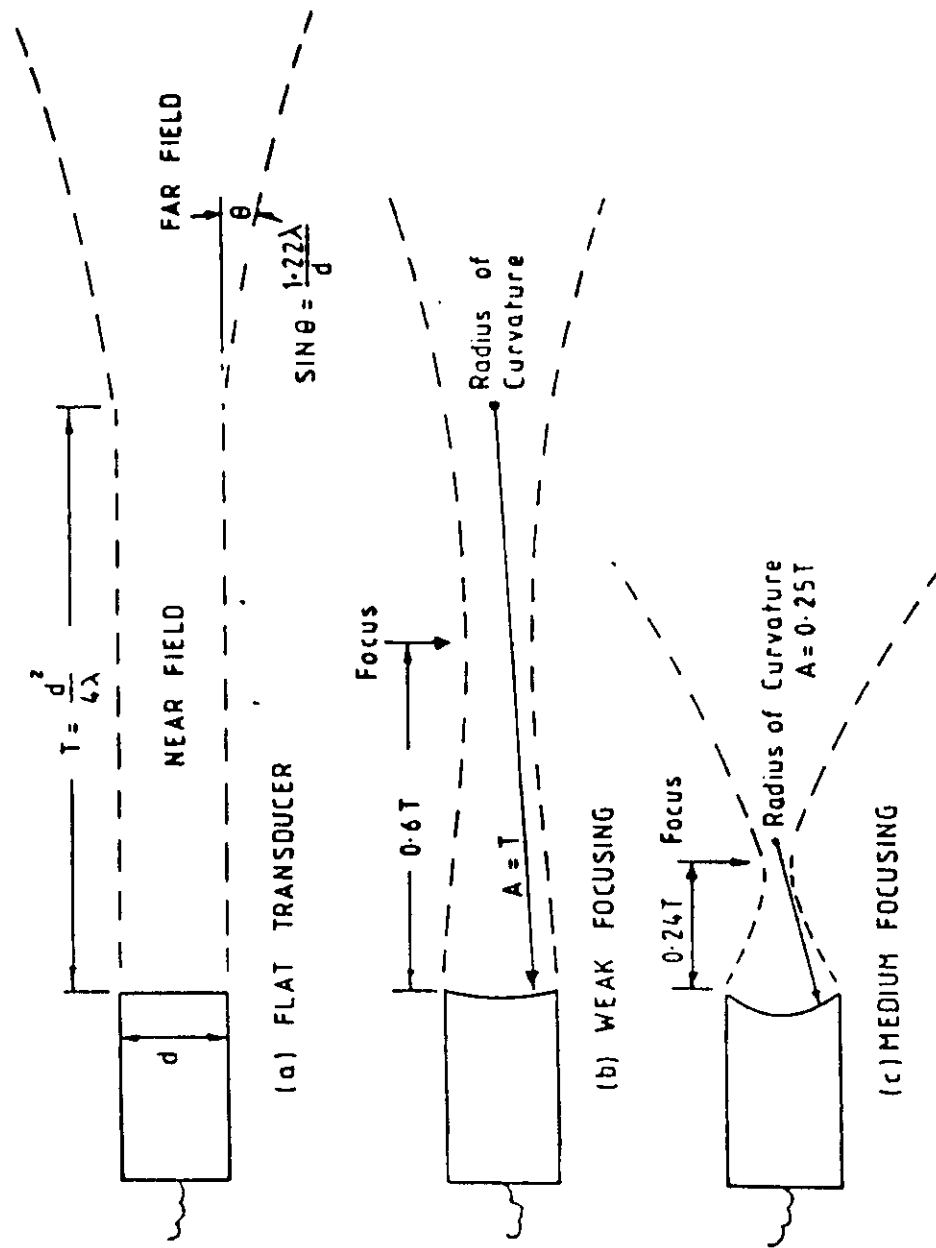


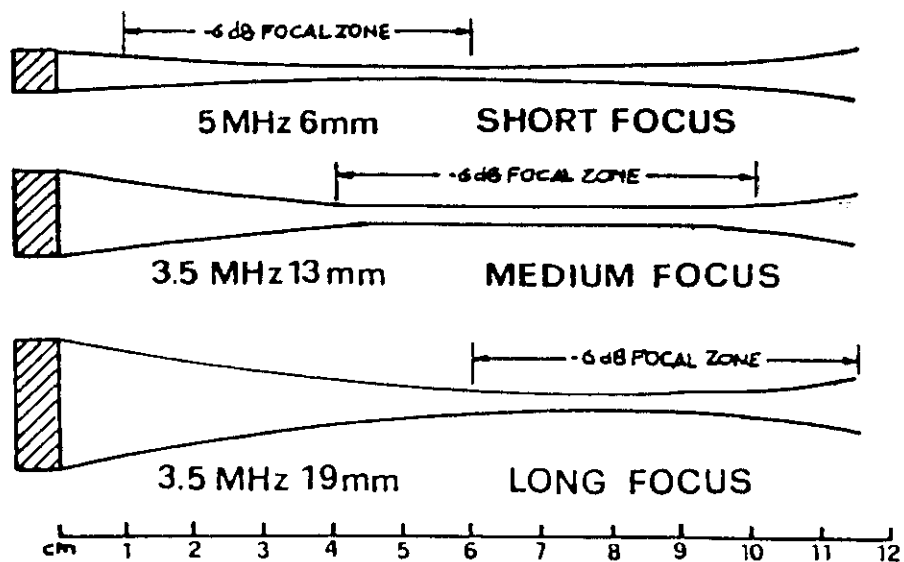
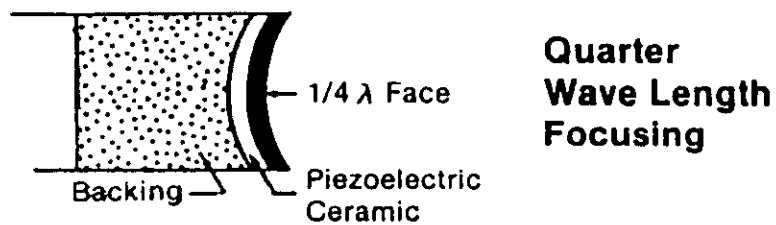
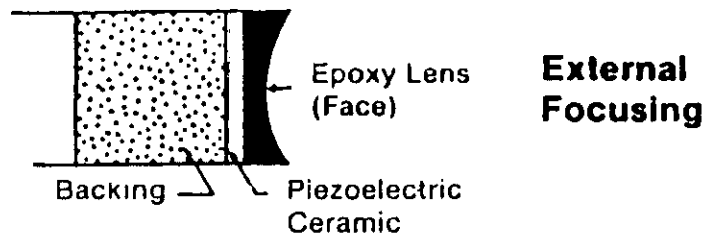
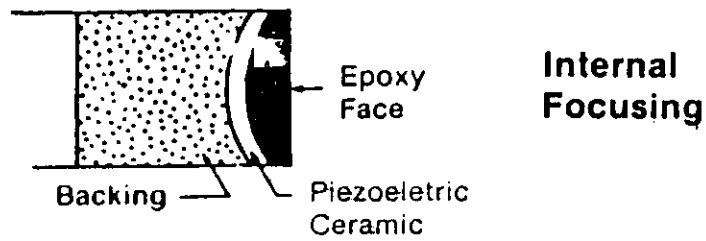


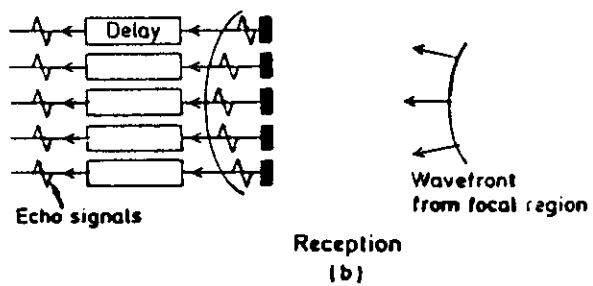
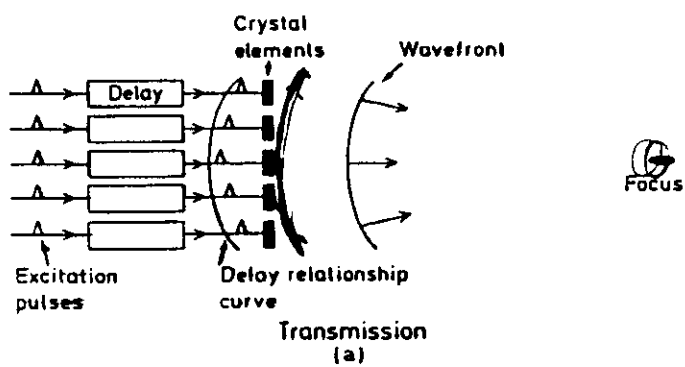
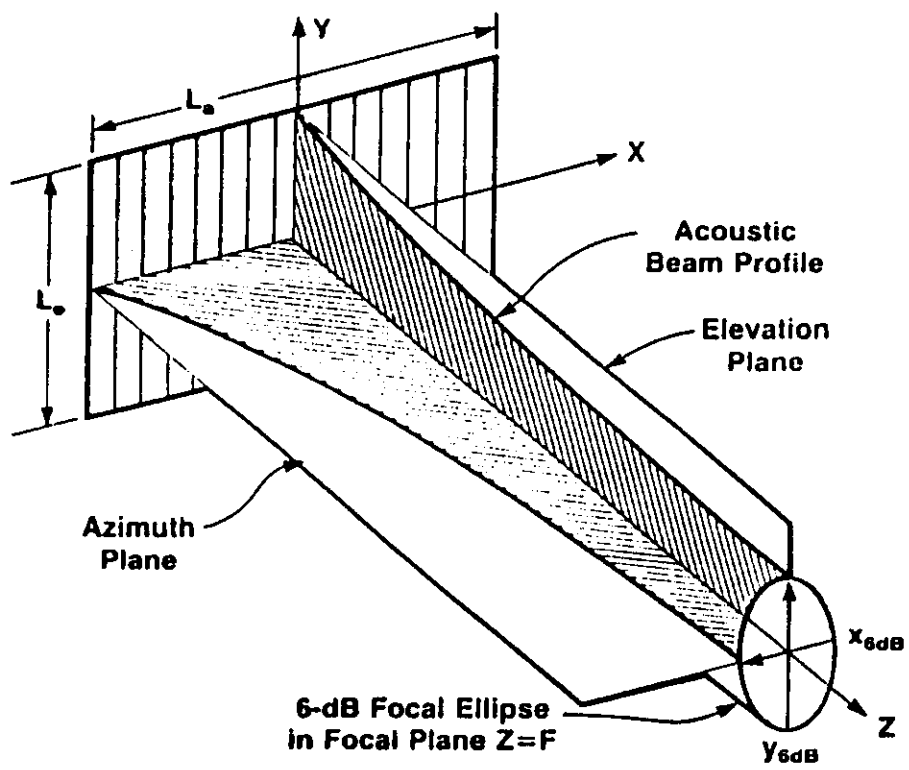
FOCUSSING TECHNIQUES

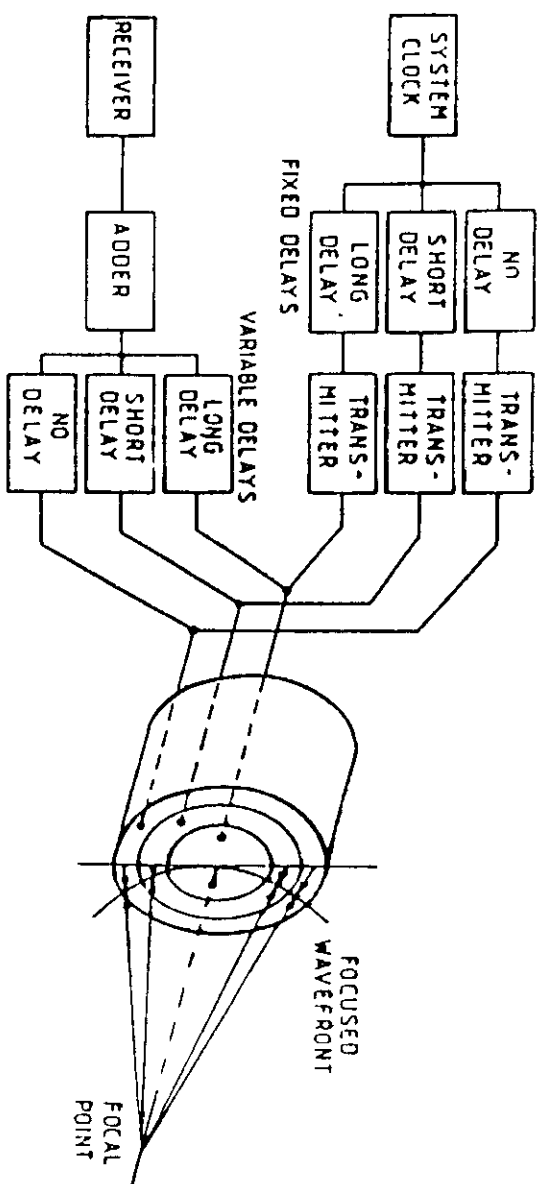
GOAL: To condense the radiated ultrasound energy into a beam of extremely narrow section.

- ACOUSTIC LENSES
(fixed focus)
- ELECTRONIC LENSES
(variable focus)







ELECTRONICS SYSTEMANNULAR ARRAY TRANSDUCER

USING ULTRASOUND TO OBTAIN
IMAGES . . .

- Diagnostic ultrasound scanners

SCANNING TECHNIQUES

- MECHANICAL SECTOR SCAN

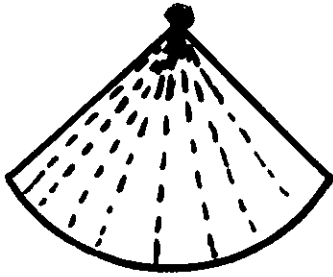
SINGLE OR MULTIPLE ELEMENT
ANNULAR ARRAY

- ELECTRONIC SECTOR SCAN

STEERED (PHASED) ARRAY

- LINEAR SCAN

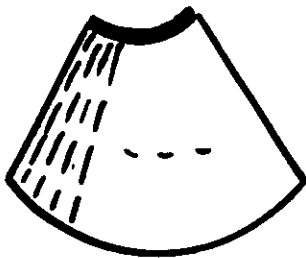
- CONVEX SCAN



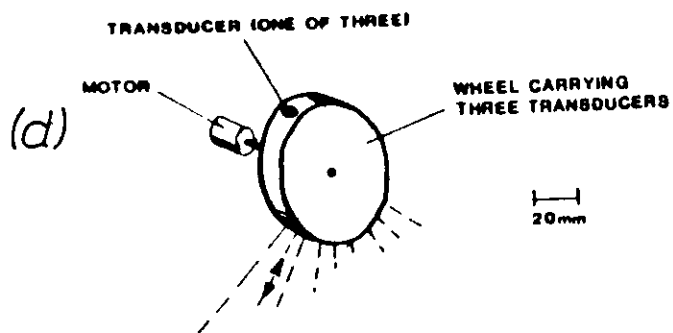
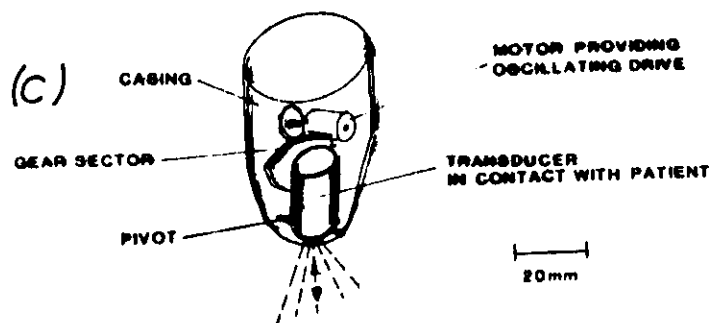
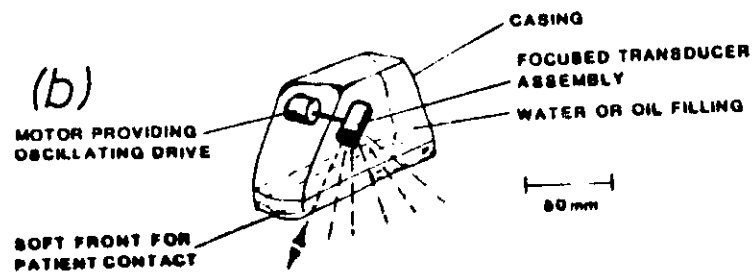
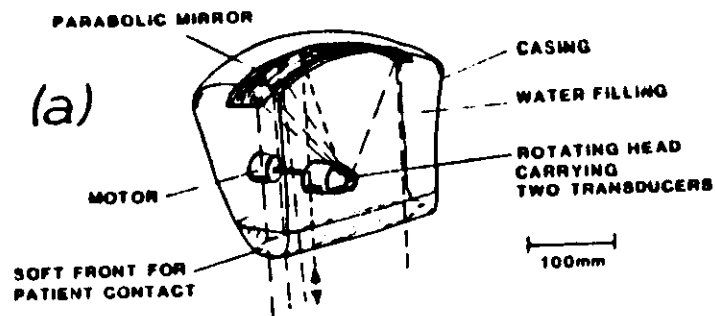
SECTOR SCAN



LINEAR SCAN



CONVEX SCAN



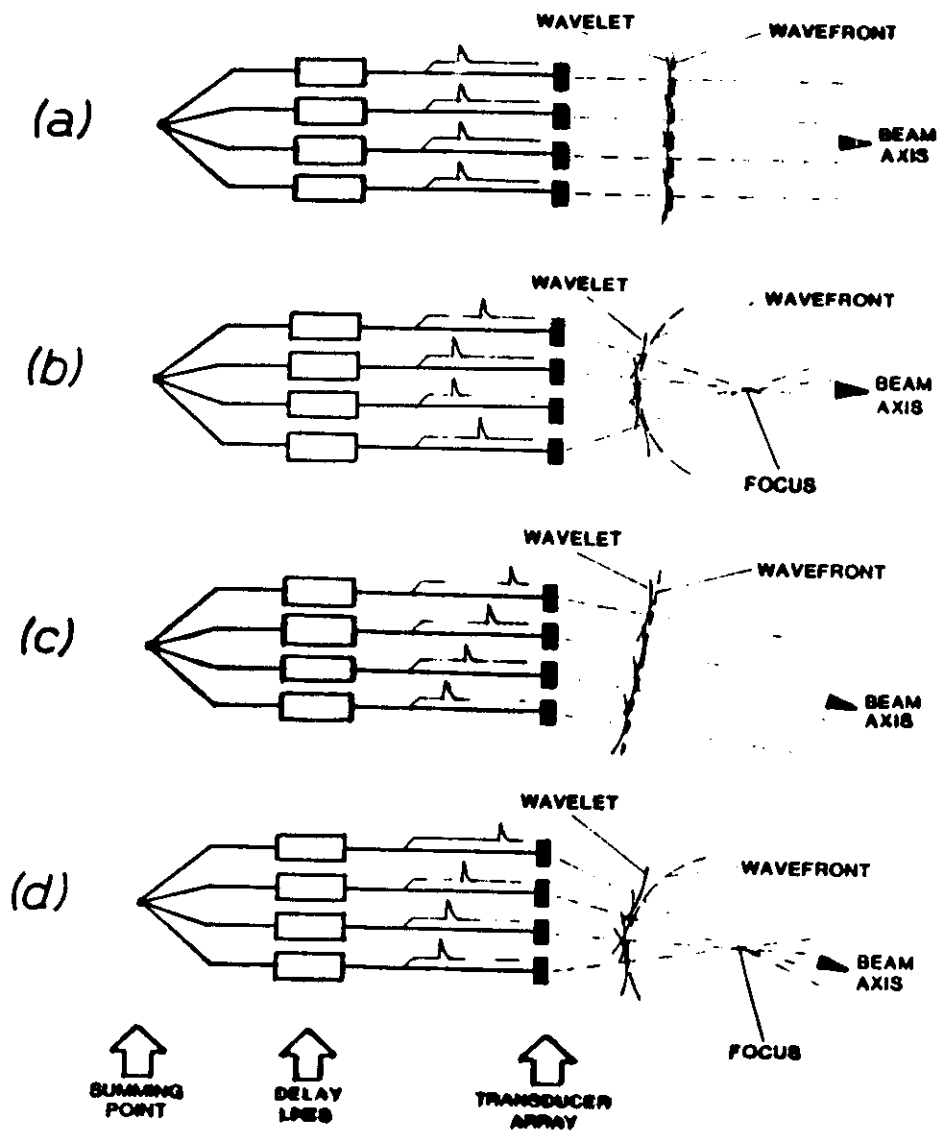


FIGURE 5.5. Synthetic focusing and steering of the ultrasonic beam produced by a transducer array. The long axes of the elements are normal to the plane of the diagrams; viewed in this direction, each element can be considered to emit a circular wavelet (a cross-section through a cylindrical wavelet) in response to electrical excitation. (a) When the elements are excited simultaneously (as indicated by the simultaneous "blips" associated with each electrical connection), the wavelets combine to form a wavefront of which the corresponding beam travels normal to the surface of the array. (b) When spherical time grading is used, the beam is focused. (c) When the elements are excited in sequence, the beam is deviated from the geometrical central axis. (d) When the time grading consists of combined spherical and linear distributions, the beam is simultaneously focused and deviated.

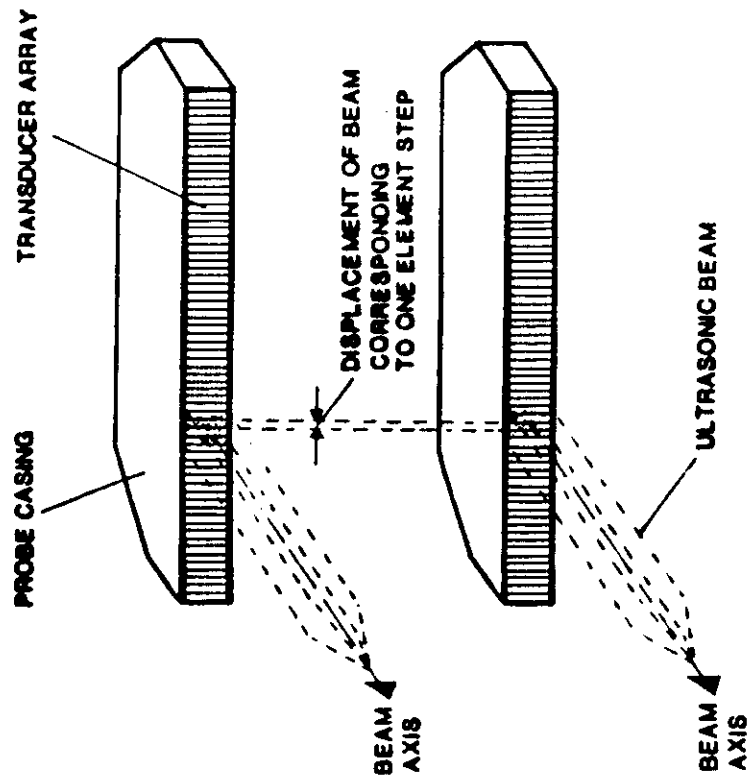
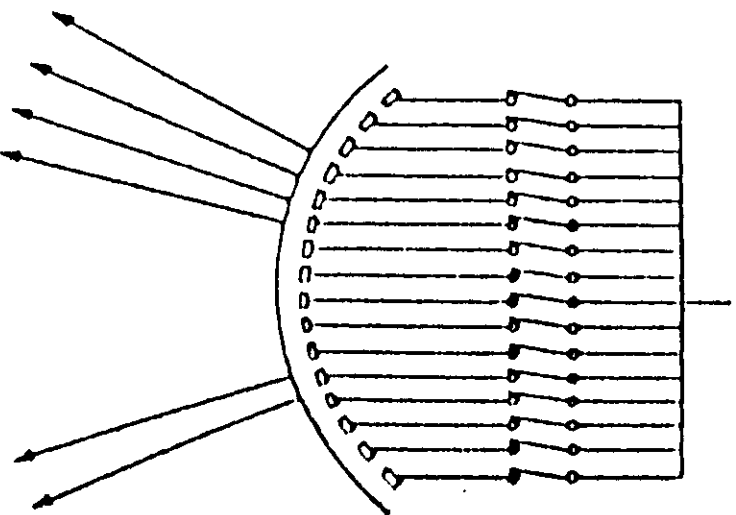
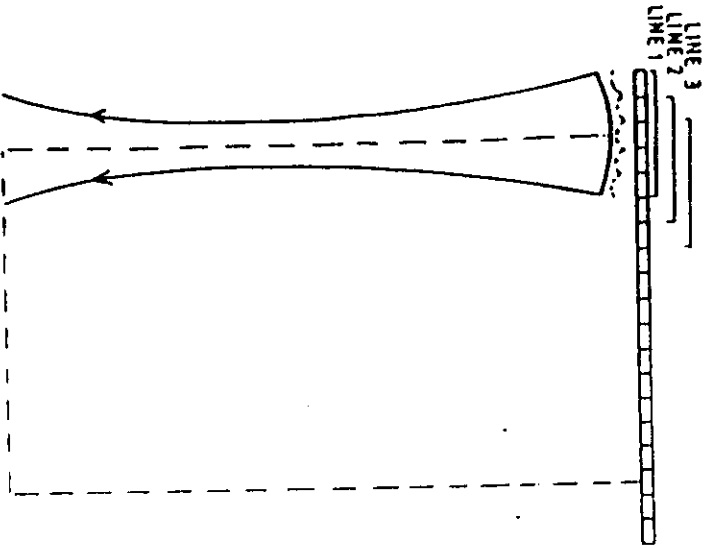
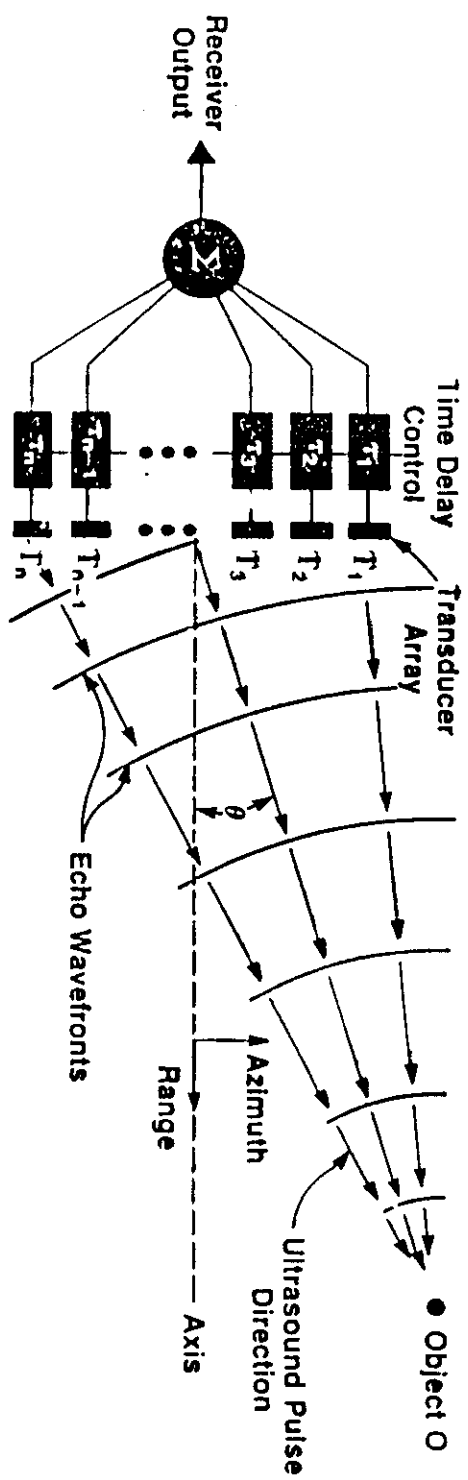
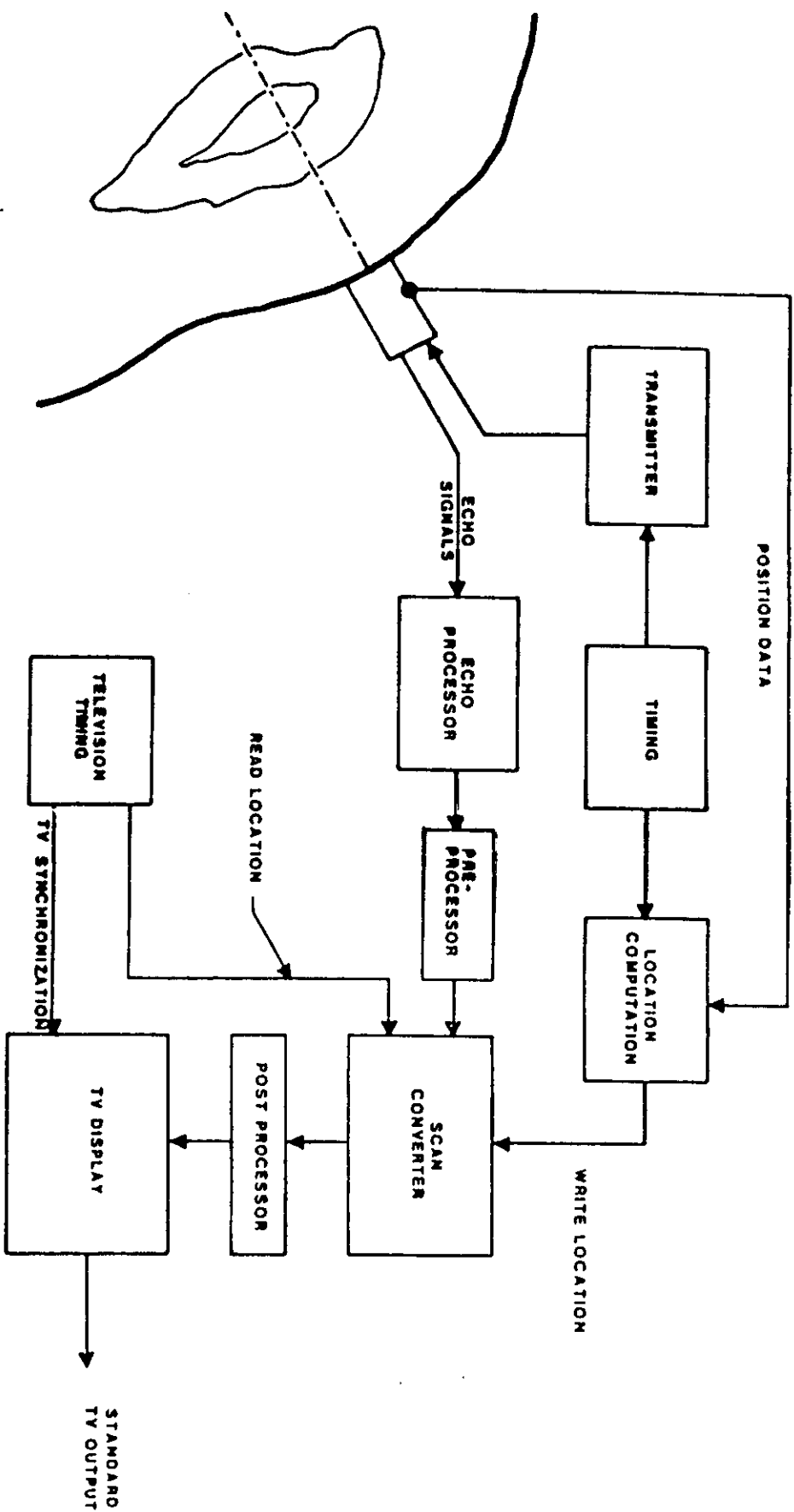


FIGURE 5.4. Linear transducer array operated in groups of four elements (to give an adequate aperture) stepped one element at a time (to give an adequate line density)





Or



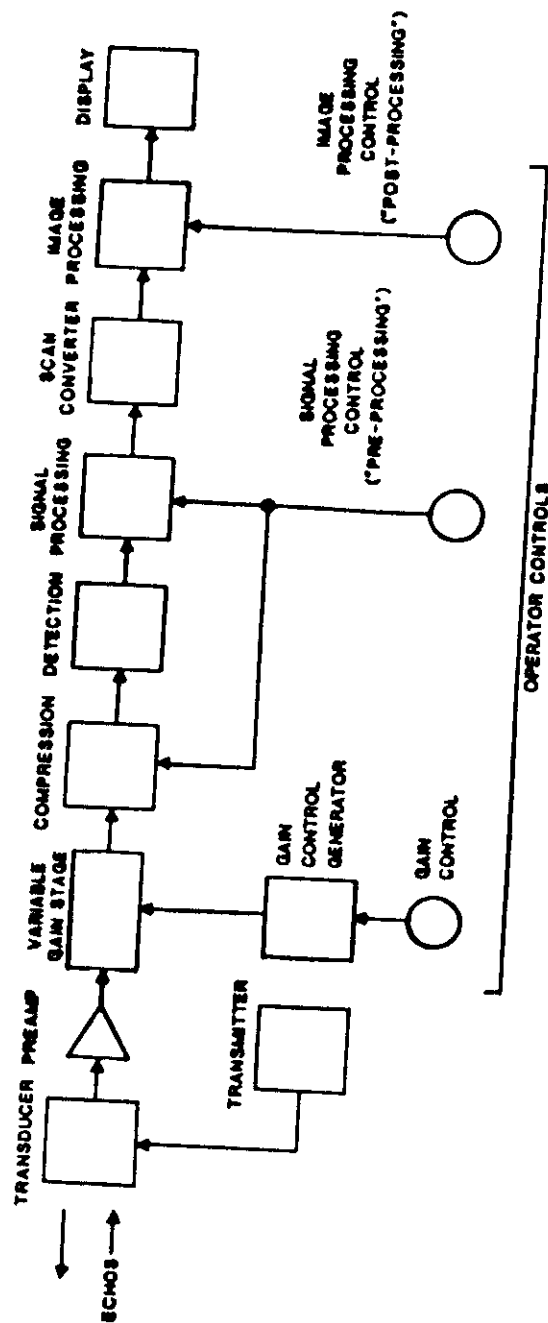


FIGURE 4.6 Echo signal path in imaging system

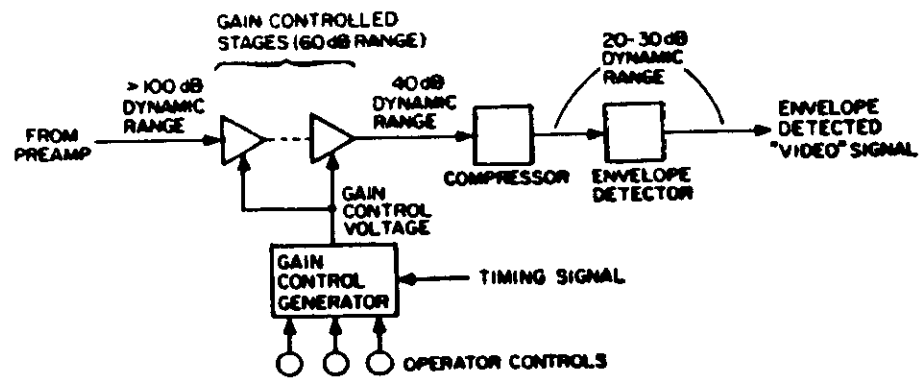


FIGURE 4.7. Variable-gain amplifier attenuation compensation

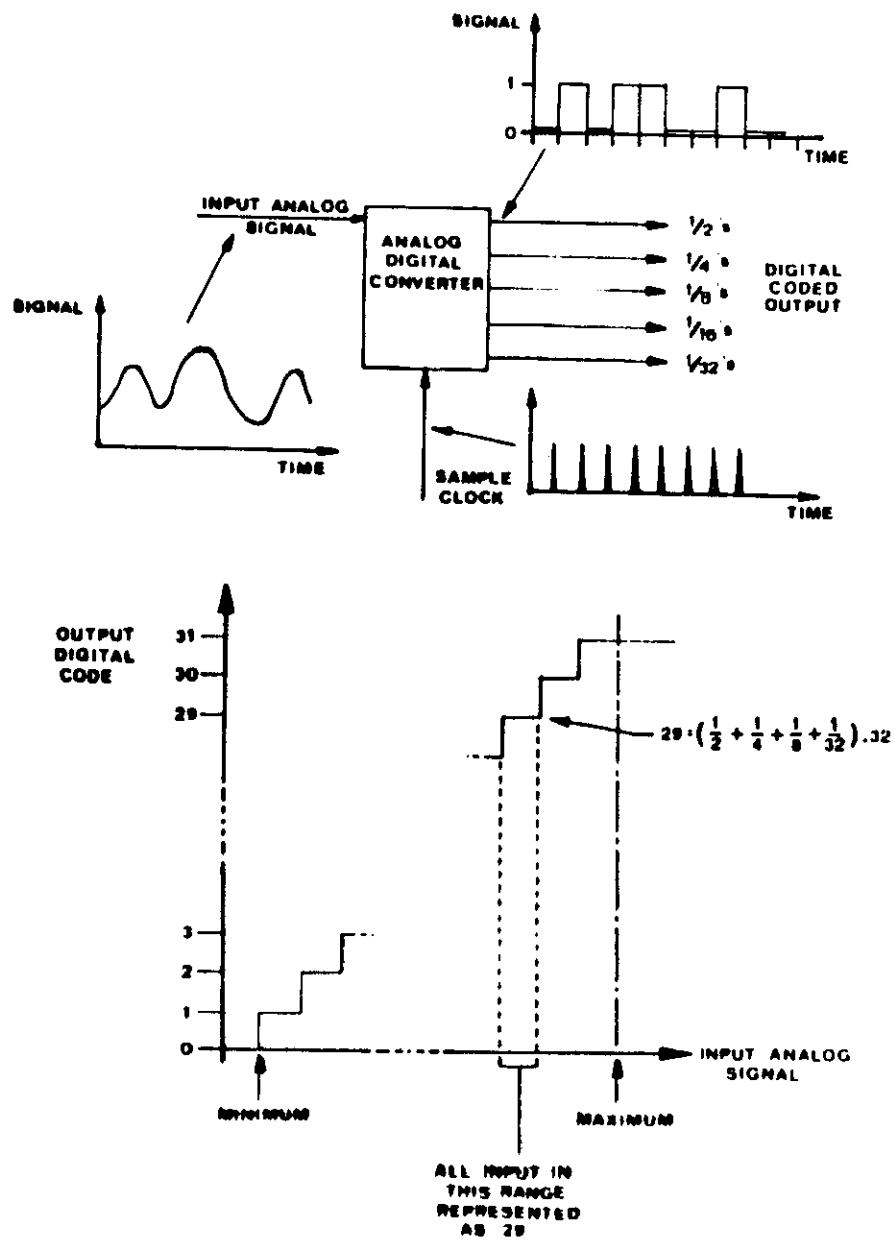


FIGURE 4.8. Quantization of continuous signal

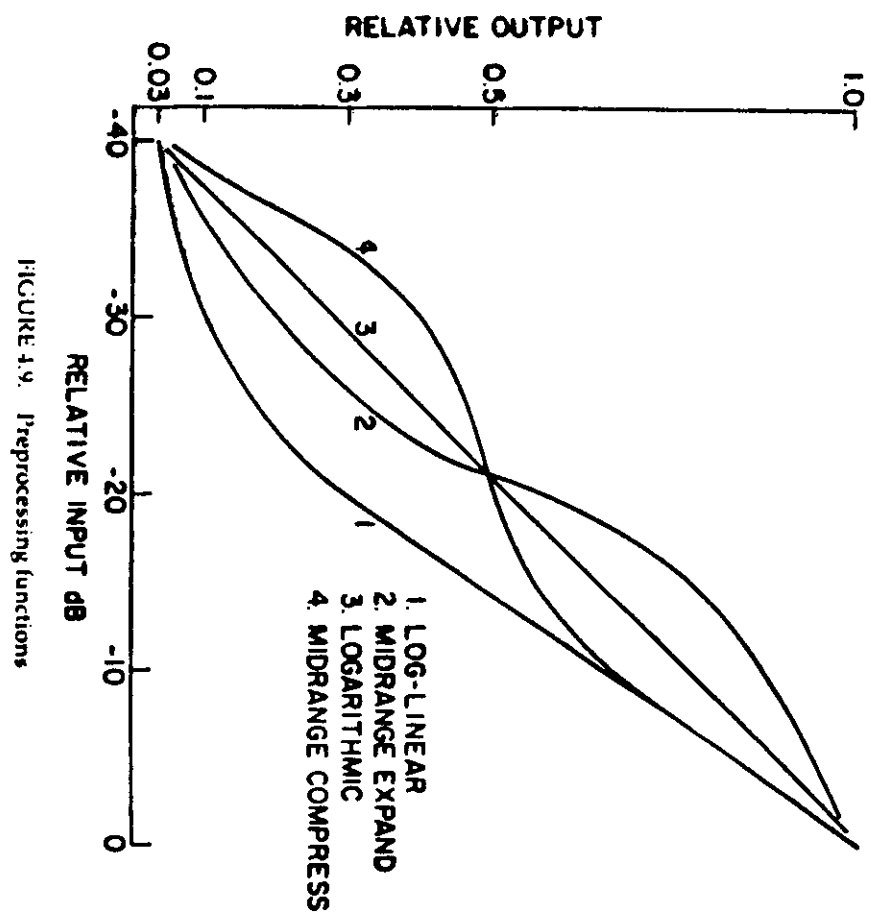


FIGURE 4.9. Preprocessing functions

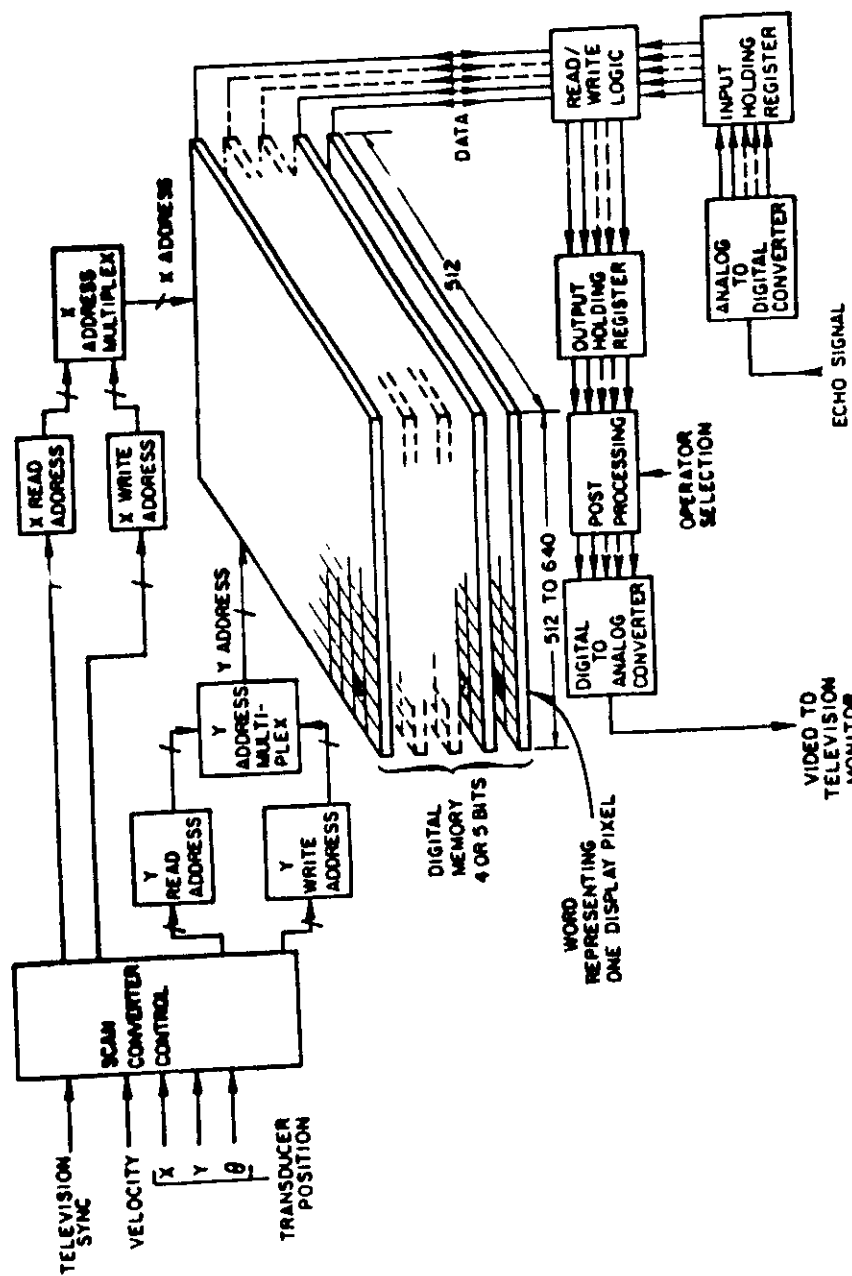
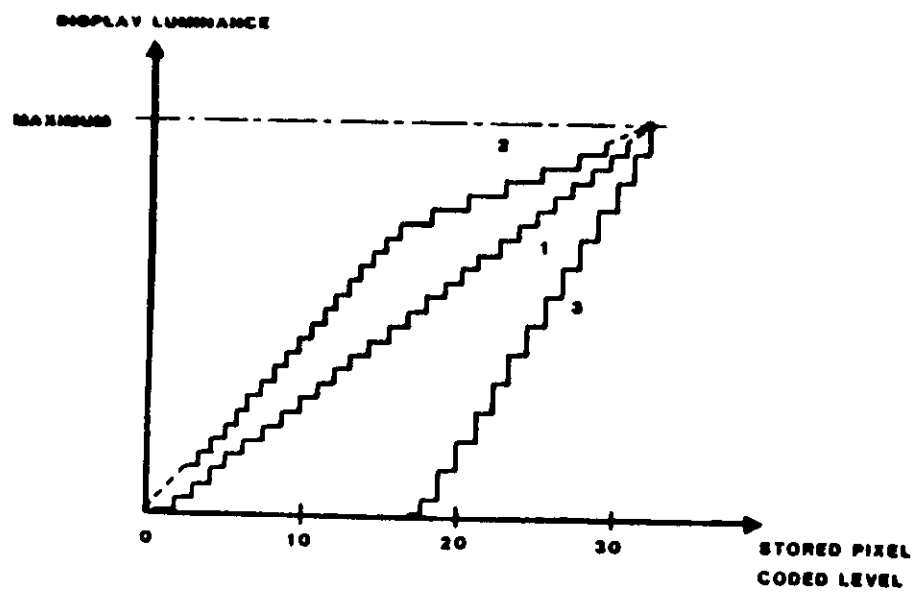


FIGURE 4.11. Digital scan converter construction



1. DIRECT TRANSFER
2. 'WEAR ECHO' EXPAND
3. REDUCED DYNAMIC RANGE

FIGURE 4.12. Post-processing amplitude functions

QUALITY PARAMETERS

- Geometrical resolution

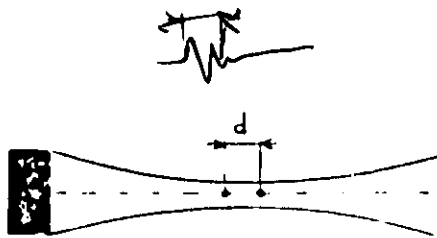
AXIAL RESOLUTION

LATERAL RESOLUTION

ELEVATION RESOLUTION

- Contrast resolution

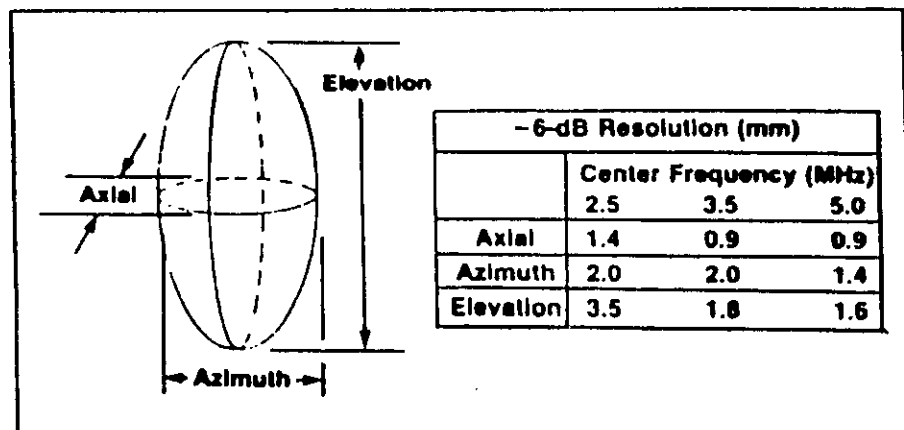
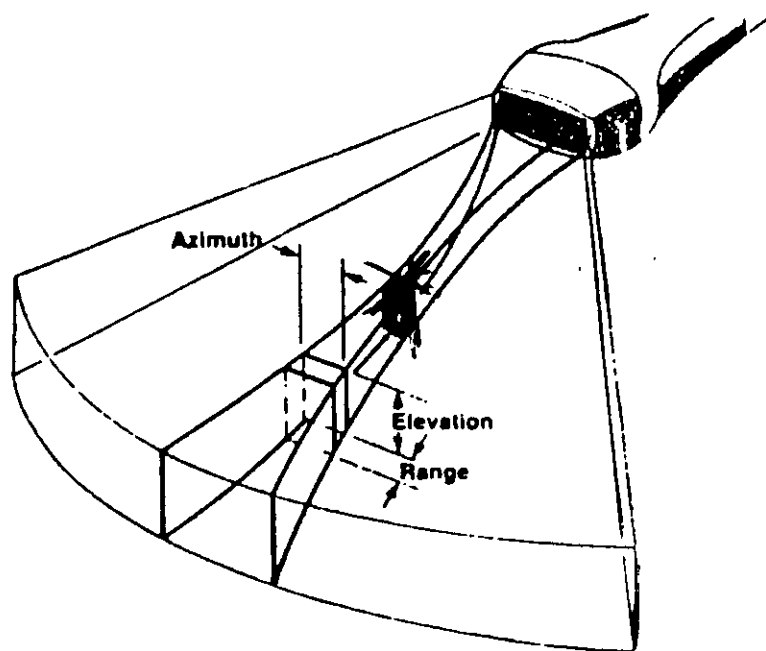
- Uniformity



AXIAL RESOLUTION



LATERAL RESOLUTION



QUALITY ASSURANCE

- THE PURPOSE IS TO ASSURE THAT THE EQUIPMENT IS OPERATING AT THE EXPECTED LEVEL OF PERFORMANCE.
- SOMETIMES IT MAKES POSSIBLE TO PREVENT FAILURES OF THE EQUIPMENT AND TO REDUCE DOWNTIME.

HOW TO DO Q.A. TESTS ?

- THE SAME TESTS MUST BE PERFORMED DURING EACH QUALITY CONTROL SESSION
- EACH TEST MUST BE DONE IN THE SAME MANNER (USING THE SAME TRANSDUCER AND WITH THE SAME EQUIPMENT ADJUSTMENTS)
- KEEP A LOG OF Q.A. TESTS, MALFUNCTIONS, AND PREVENTIVE MAINTENANCE CALLS
- A QUALITY CONTROL SESSION SHOULD BE PERFORMED AFTER ANY SERVICE CALL.

WHICH PARAMETERS ?

- DISTANCE CALIBRATION (HOR.-VERT.) NO VERT. AND HORIZ DISTORSION OF THE IMAGE
- DIGITAL CALIPER LEVEL OF PRECISION OF THE SYSTEM OF DISTANCE MEASUREMENT
- MAXIMUM SENSITIVITY AND THE DEEPEST ECHO SIGNAL UNIFORMITY YOU MAY DETECT AND DISPLAY AT OPTIMUM SETTINGS; UNIFORMITY OF THE SIGNAL AND OF THE IMAGE IN DIFFERENT AREAS
- GREY SCALE PHOTOGRAPHY HARD COPY FIDELITY
- SPATIAL RESOLUTION AXIAL AND LATERAL RES.
- CYST IMAGING CAPABILITIES DETECTION OF SOLID AND LIQUID CYSTS
- PHYSICAL ASPECT OF EQUIP. CABLES, FILTERS, TRANSDUCERS, CAMERAS, PROCESSOR

TEST OBJECTS

- TISSUE EQUIVALENT MATERIAL
IN ORDER TO TEST THE US EQUIP.
UNDER CLINICAL CONDITIONS

TYPICALLY ALL TISSUE MIMICKING PHANTOMS CONTAIN
A SOLUTION OF:

- AGAR (POLYSACCHARIDE GEL) (3%) ⊕
- WATER
- PROPANOL
- GRAPHITE

② H.H. BURLEW and others: "A NEW ULTRASOUND
TISSUE-EQUIVALENT MATERIAL" in RADIOLOGY
vol. 134 n. 2 pages 517-520; february 1980

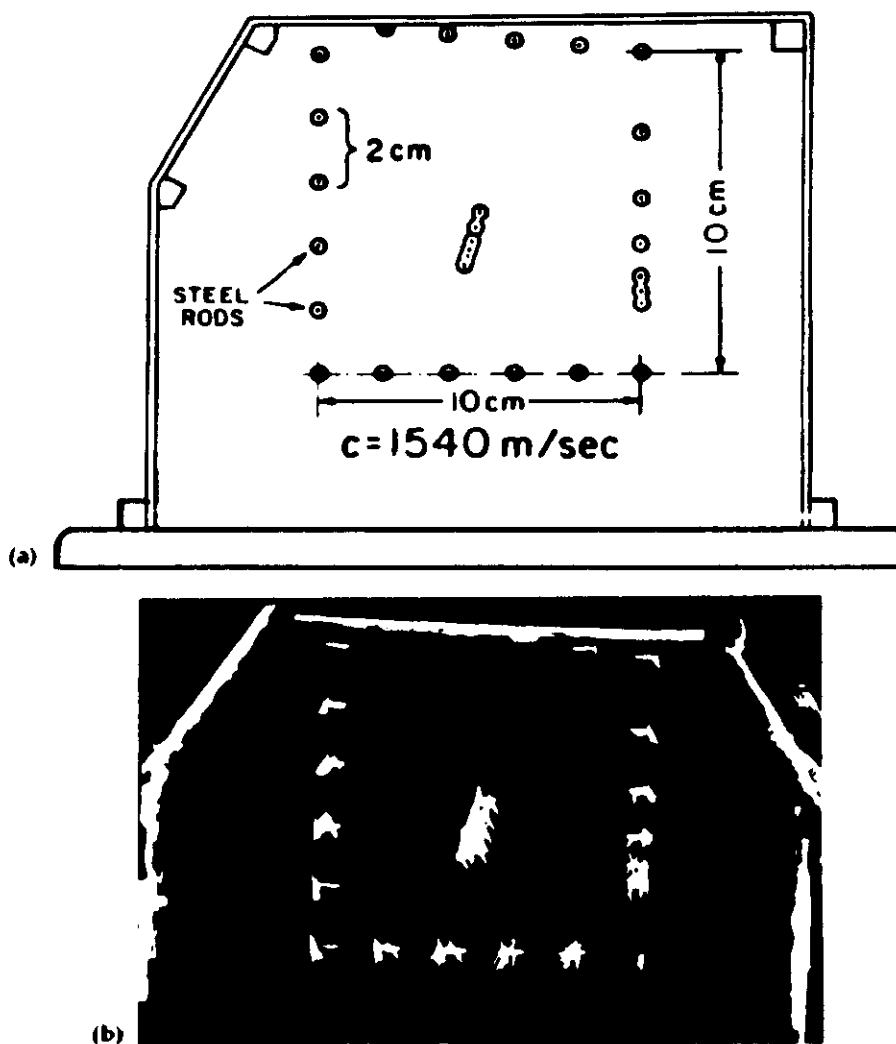


FIGURE 12.1. (a) Schematic of the American Institute of Ultrasound in Medicine Standard 100 mm Test Object.

(b) Image of the 100 mm test object. Vertical depth markers are compared to inter target spacings to test depth calibration. B mode registration accuracy is checked by imaging a single rod from four different sides of the test object.

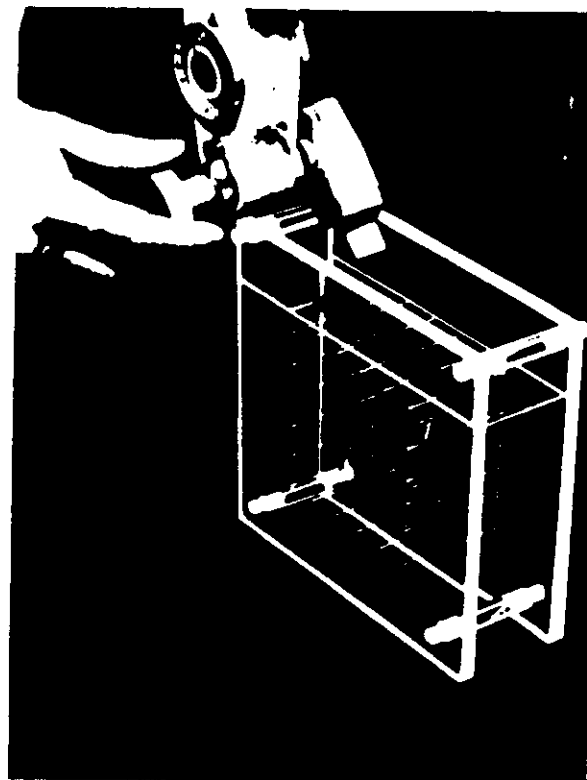


Figure A3-3. A.T.U.M. test object.

TABLE 12.1. Materials employed as tissue simulators

	Speed of Sound MS ⁻¹	Attenuation at		Reference
		1 MHz	dB cm ⁻¹	
Silastics				
Silicon rubber				16
Silicon fluid mixtures	950-970	~ 7		14
Wacker Silgel				
Plastisols				
Epoxy soya plastisol	1550	3		17
Urethane polymer	1554	1.5		18
Styrene-Butadiene Resin (3M flotation pad gel)	1455 1470	.22 .8		24 18,20
Water-based gels				
(with powder for attenuation)				
Gelatin	1500-1600	.2-1.5		20
Alginate acid				17
Agarose	1500-1600	.2-1.5		21

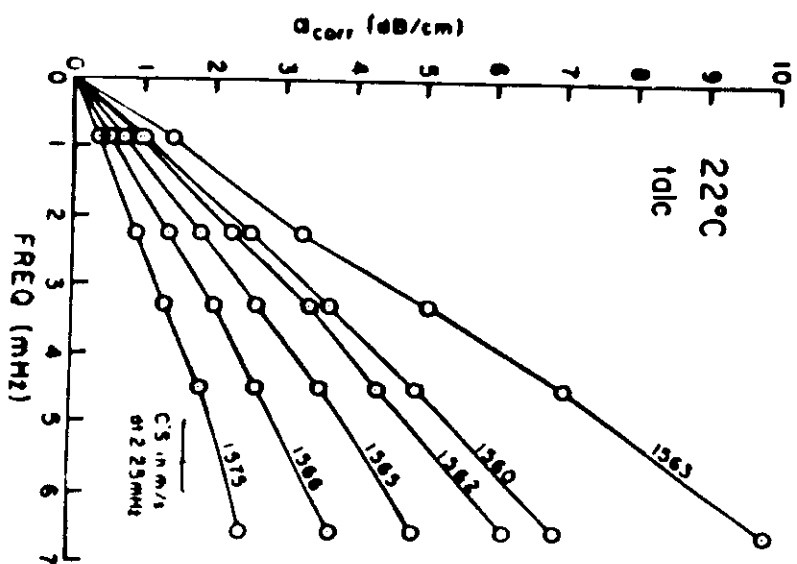


FIGURE 12.4 Attenuation vs frequency in different talc-gel samples. The speed of sound in the material is also shown on the curves.

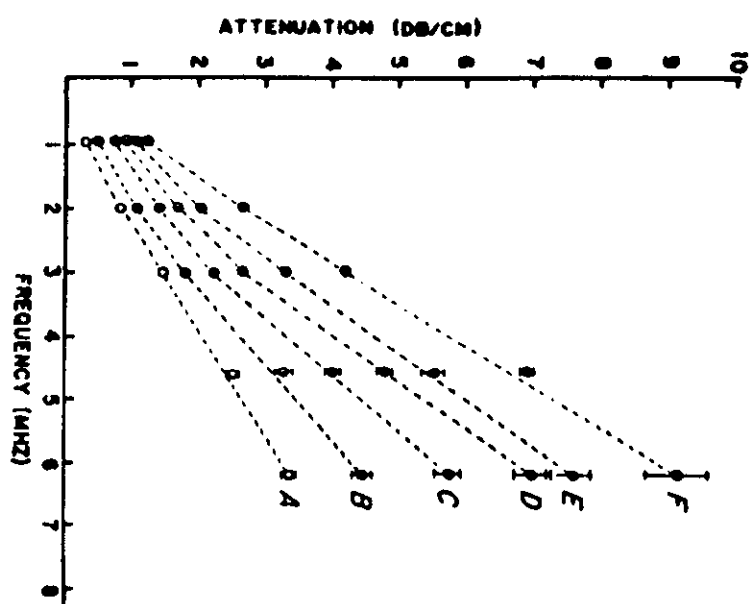


FIGURE 12.3 Attenuation vs. frequency in graphite-gel material for five different graphite concentrations ranging from 0.49 g cm⁻³ (A) to 0.187 g cm⁻³ (F).

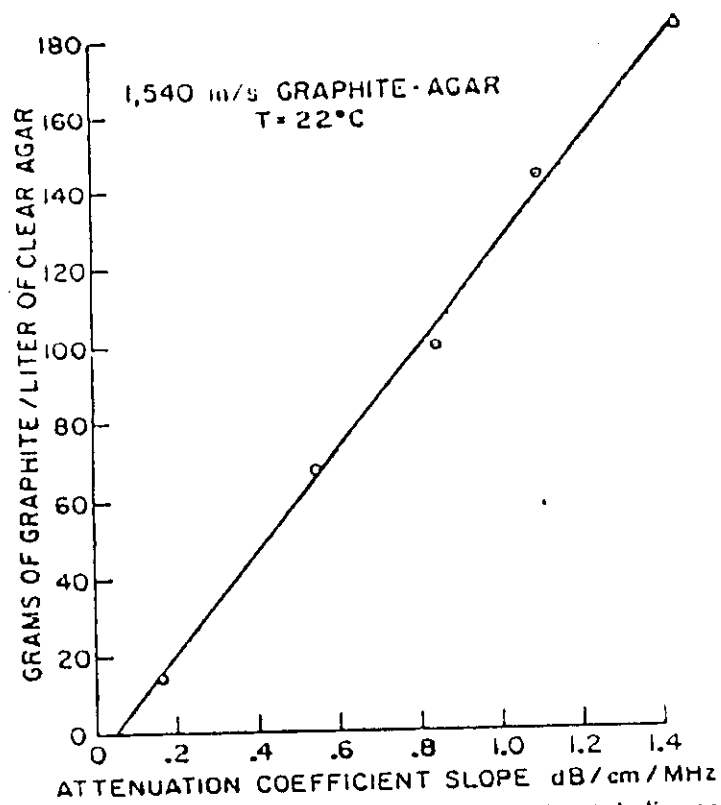


Fig. 2. This graph shows the approximately linear relation between the grams of graphite powder per liter of agar-water-propanol matrix material and the slope of the attenuation coefficient.

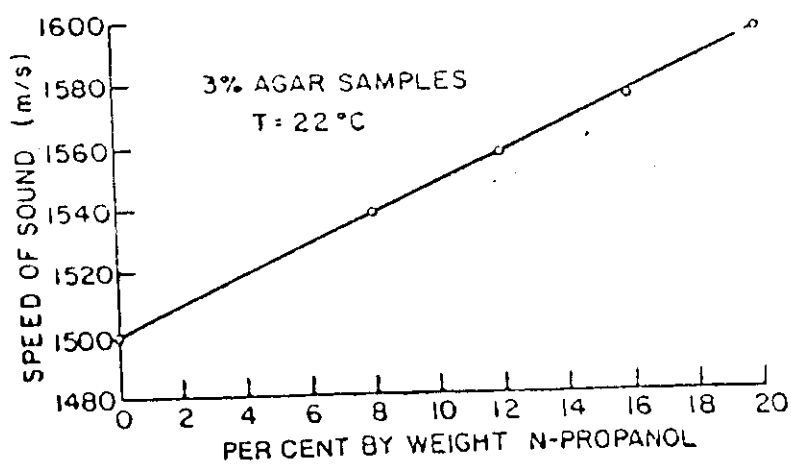
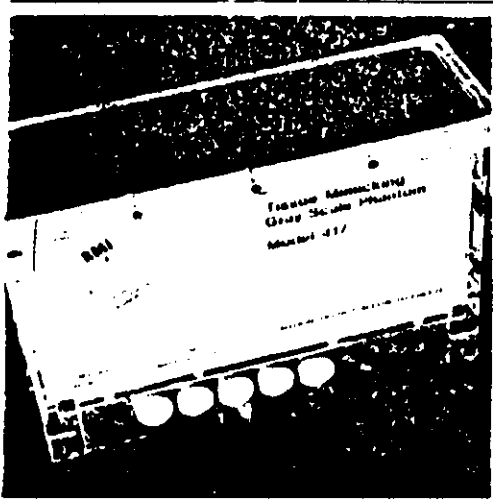
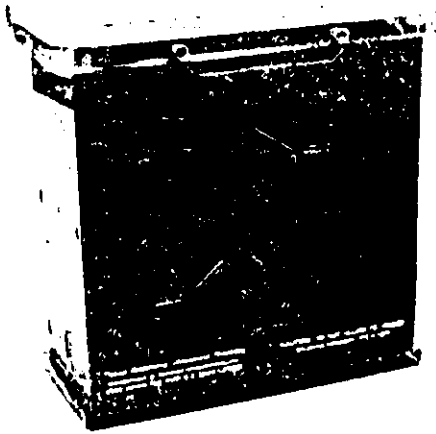


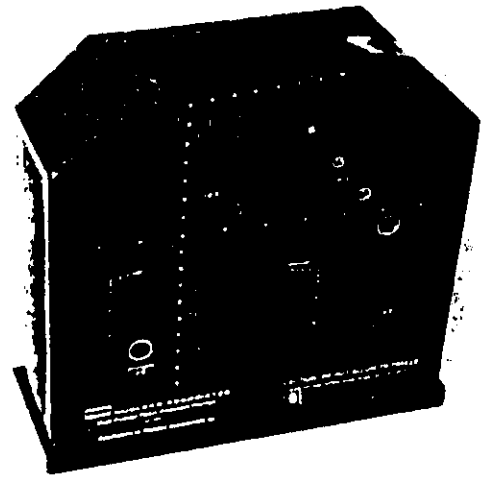
Fig. 4. Speed of sound vs. concentration of *n*-propanol at 22°C, showing a linear relation for sample D (TABLE I). Graphs for samples A through E are nearly identical.



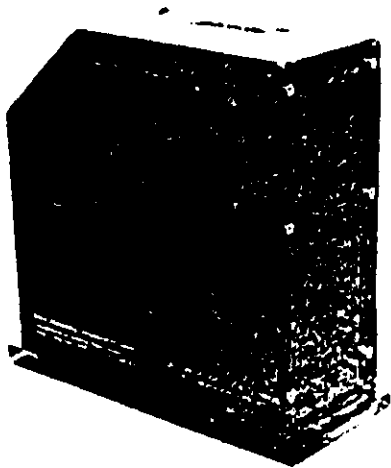
Model 417



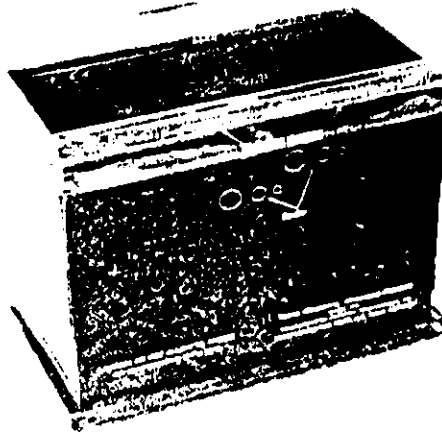
Model 413A



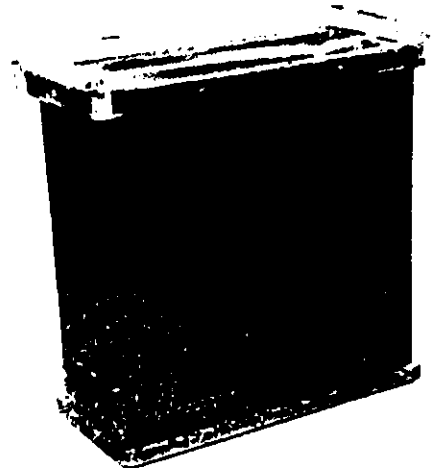
Model 84-317



Model 412A



Model 414B



Model 410B

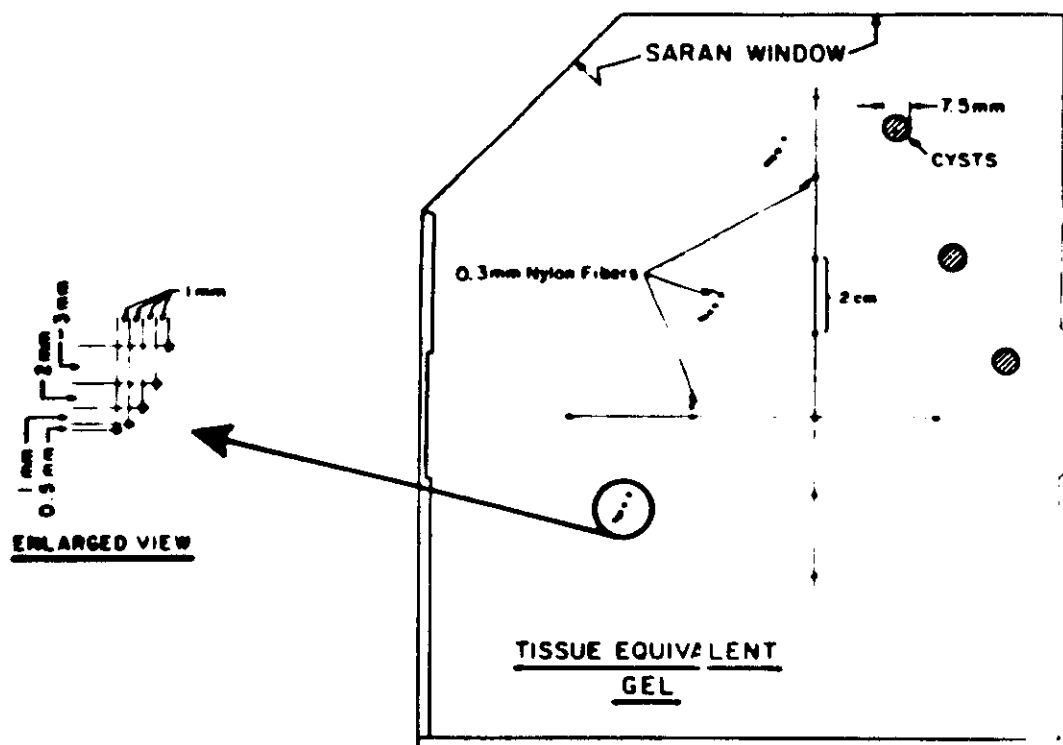


FIGURE 12.5. Test phantom for ultrasonic B-scanners. (Figure from Radiation Measurements, Inc., Middleton, Wisc.)

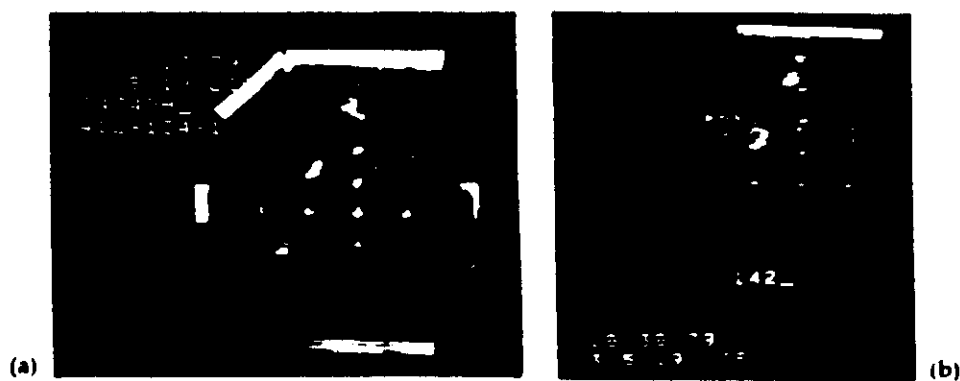


FIGURE 12.6. Images of phantom in Figure 5.
 (a) Line targets allow depth calibration, resolution and B-scan registration accuracy to be determined.
 (b) Texture allows depth of penetration to be estimated.

COMMON CHARACTERISTICS OF TEST OBJECTS:

- A TISSUE EQUIVALENT MATRIX OF AGAR AND GRAPHITE
- REFLECTORS MADE WITH NYLON WIRES (0.2, 0.3 mm)
- REFLECTORS ARRANGED IN DIFFERENT CONFIGURATIONS DEPENDING ON THE PARAMETER TO BE MEASURED
- INCLUSIONS OF GEL WITH DIFFERENT CHARACTERISTICS WITH RESPECT TO THE GEL OF THE MATRIX, IN ORDER TO SIMULATE LIQUID OR SOLID CYSTS.

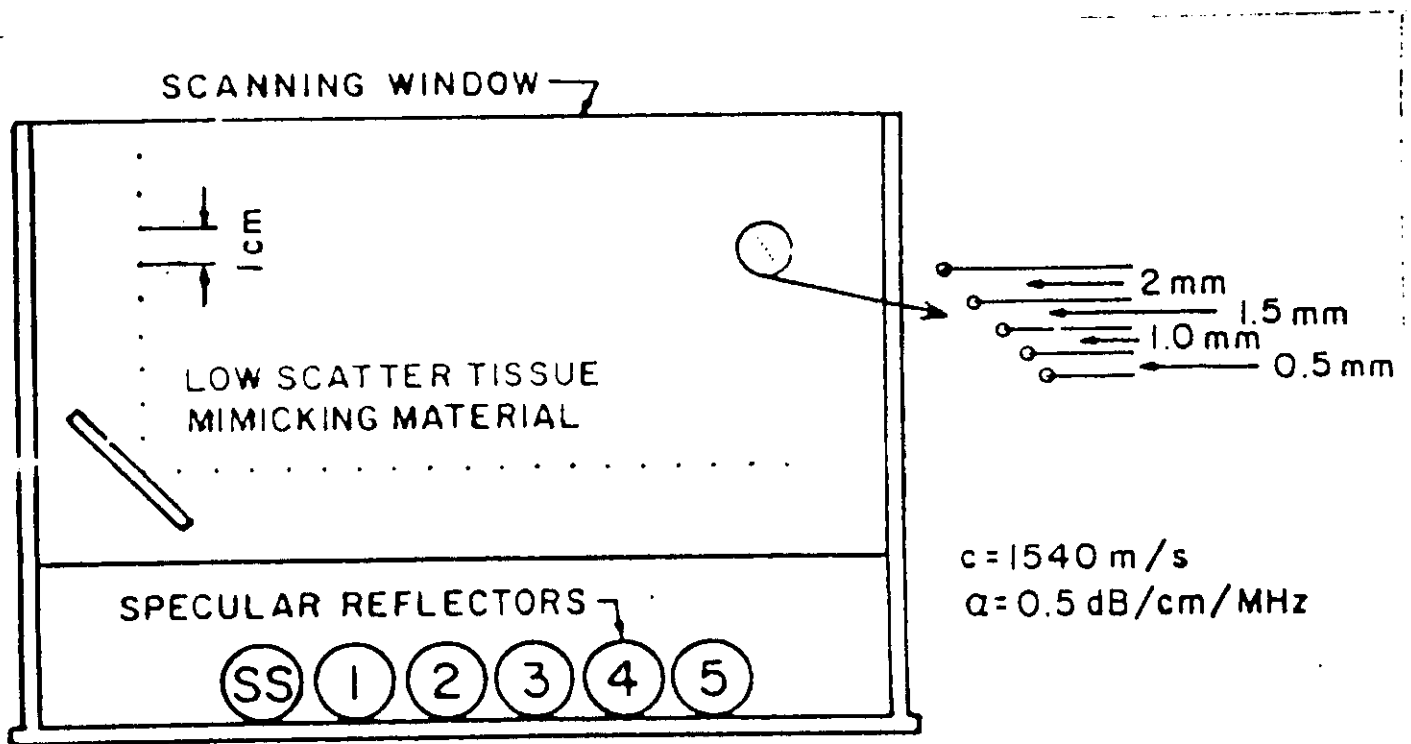
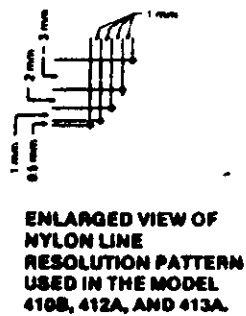
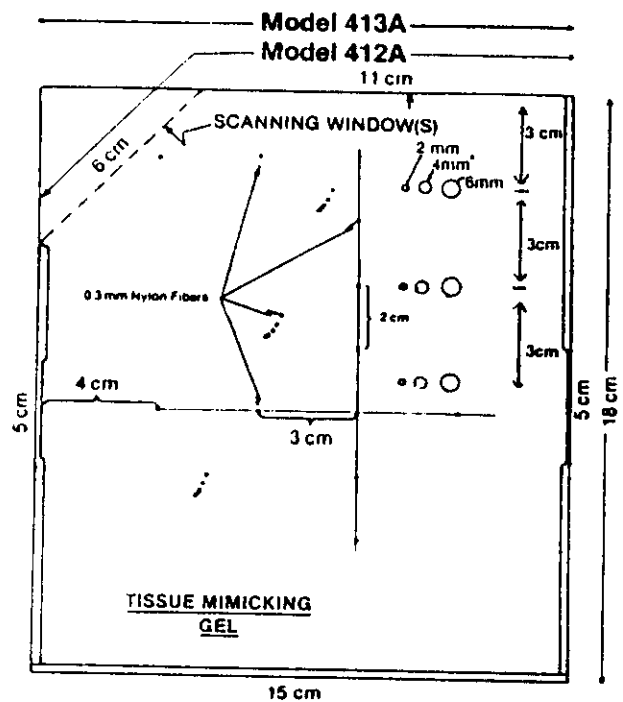
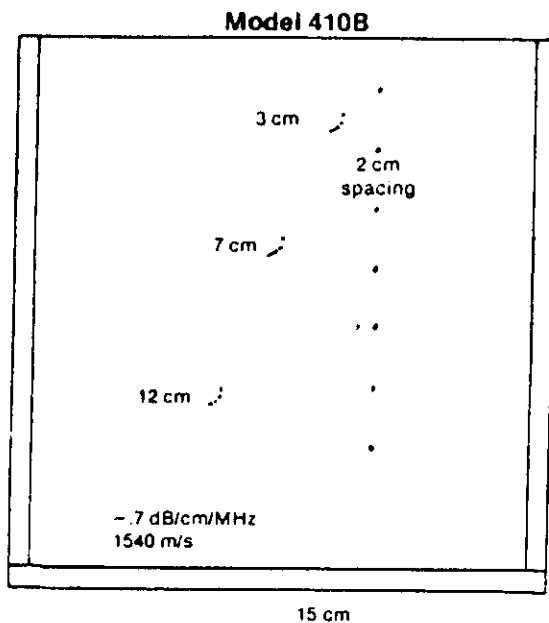


Fig. 2. Schematic of Gray Scale Ultrasound Phantom.

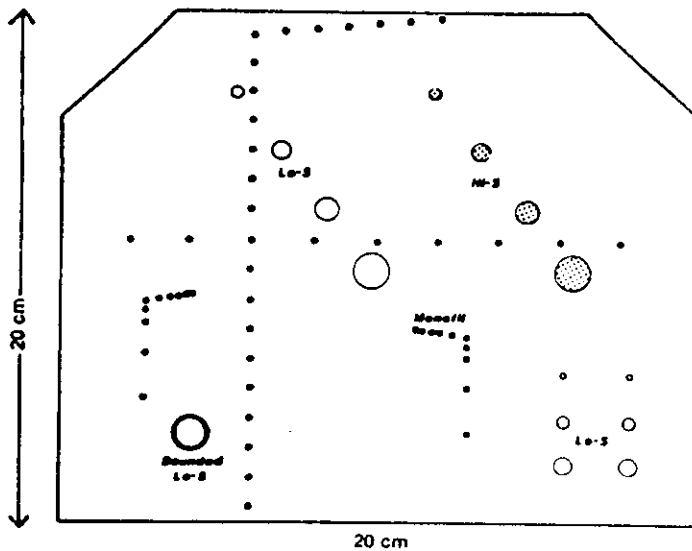
SCHEMATICS OF PHANTOM GEOMETRY



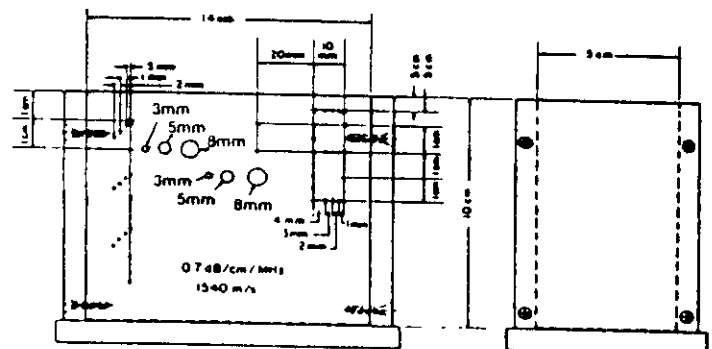
Note: Models 410B, 413A, 414B and 417 have water troughs. Models 412A, and 84-317 do not.



Model 84-317

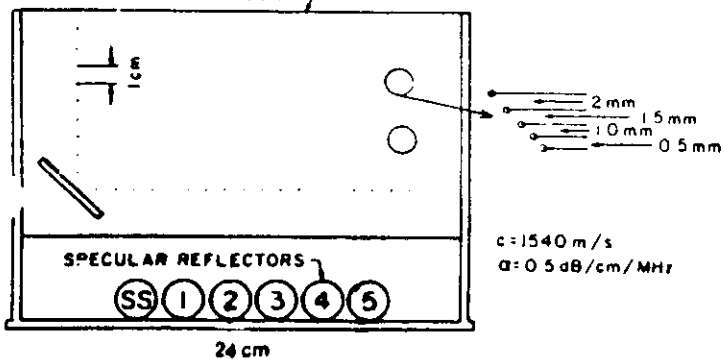


Model 414B

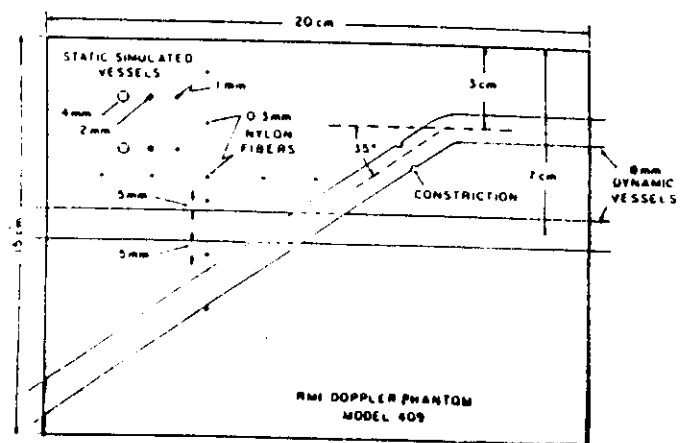


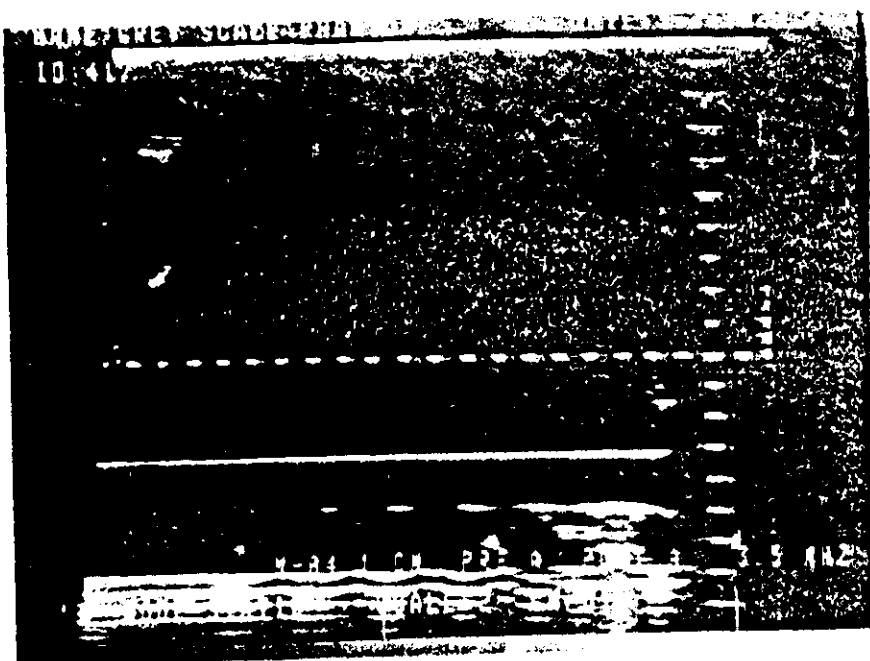
Model 417

SCANNING WINDOW

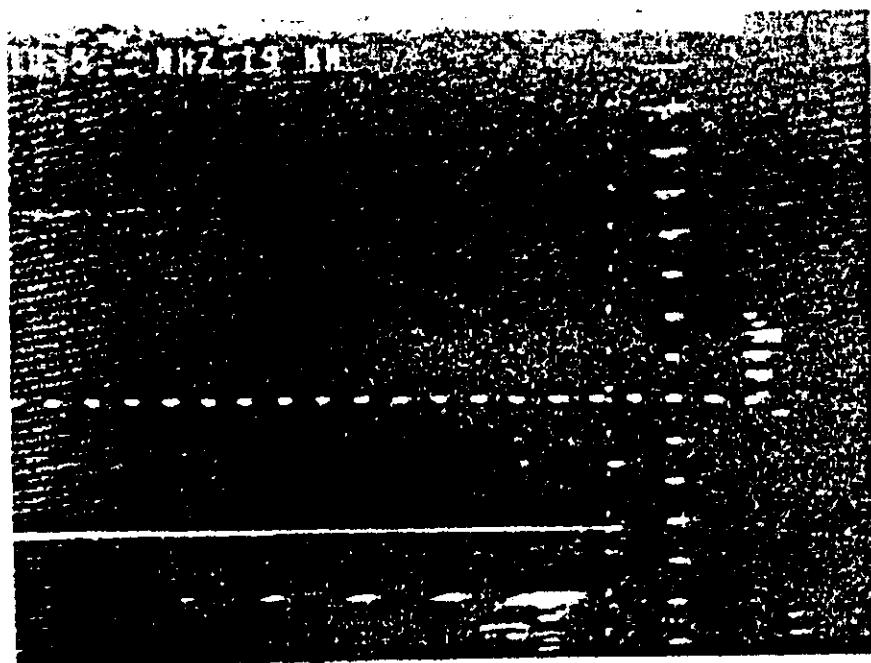


Model 409





7A



7B

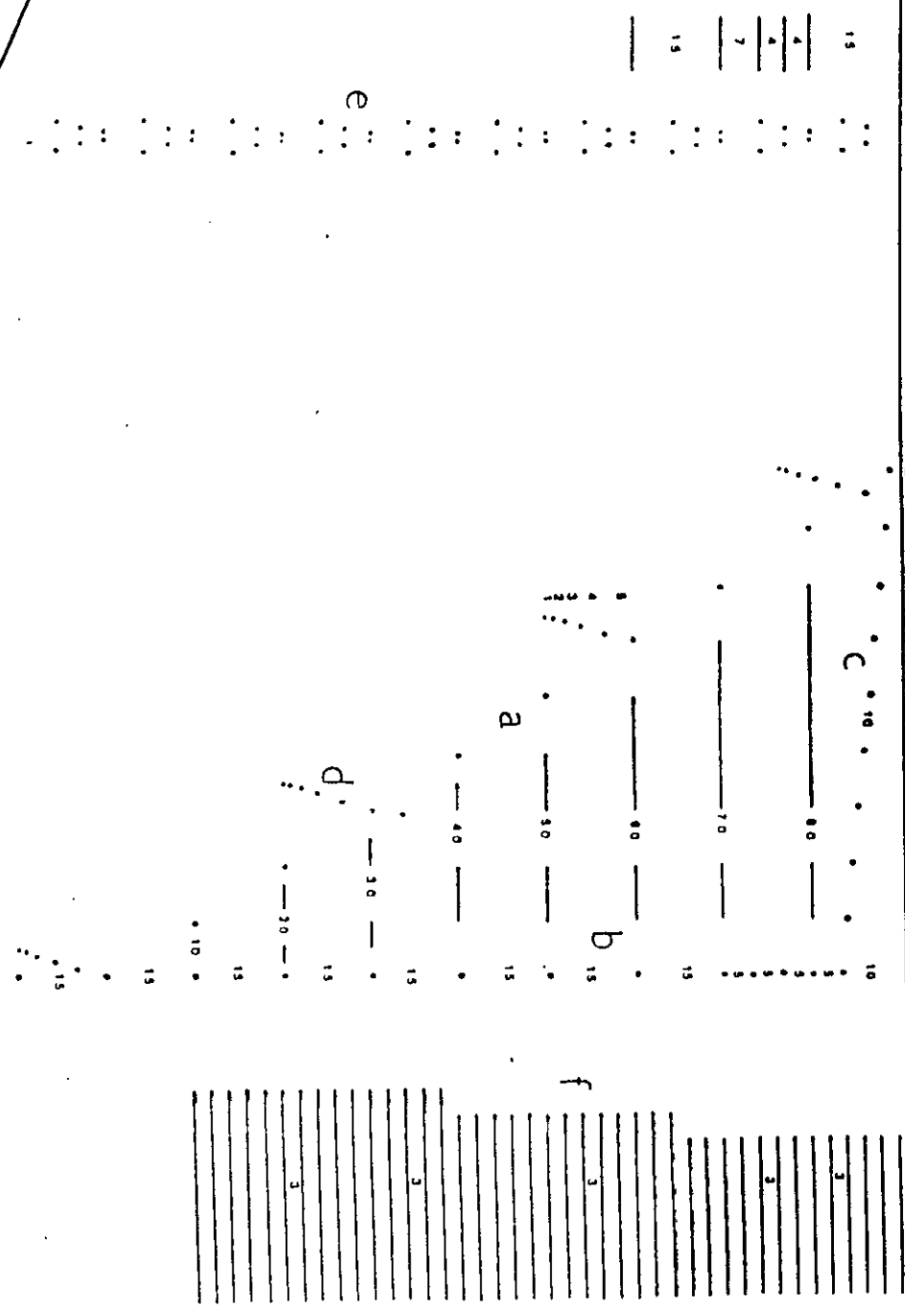
7. Scan using 3.5 MHz transducer (7A) and 5 MHz transducer (7B) showing line
 ets. Note the beam width pattern in the extended line target column.

RESOLUTION TEST OBJECT

scanning surface 1

1-2.5
2-5
5-10
lateral
spacing

scanning surface 2

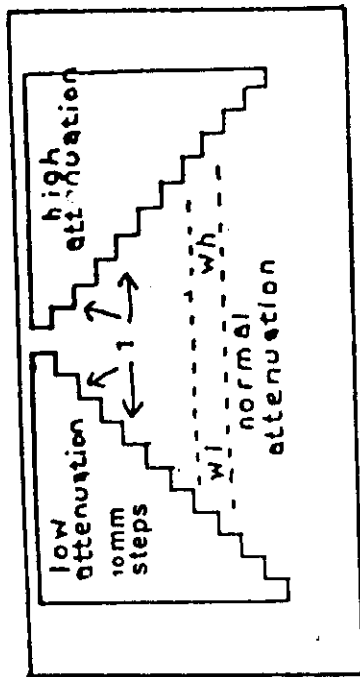


scanning surface 3

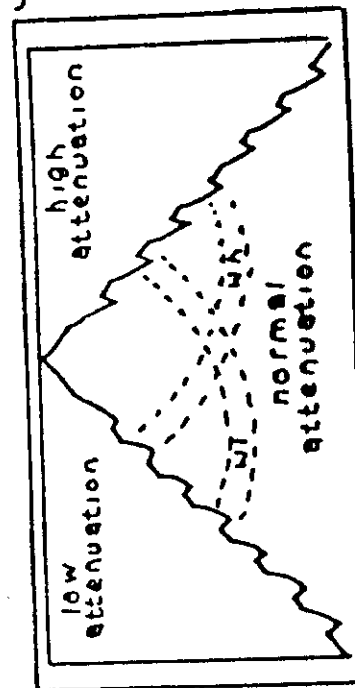
ACOUSTIC GREYSCALE TEST OBJECT

KEY

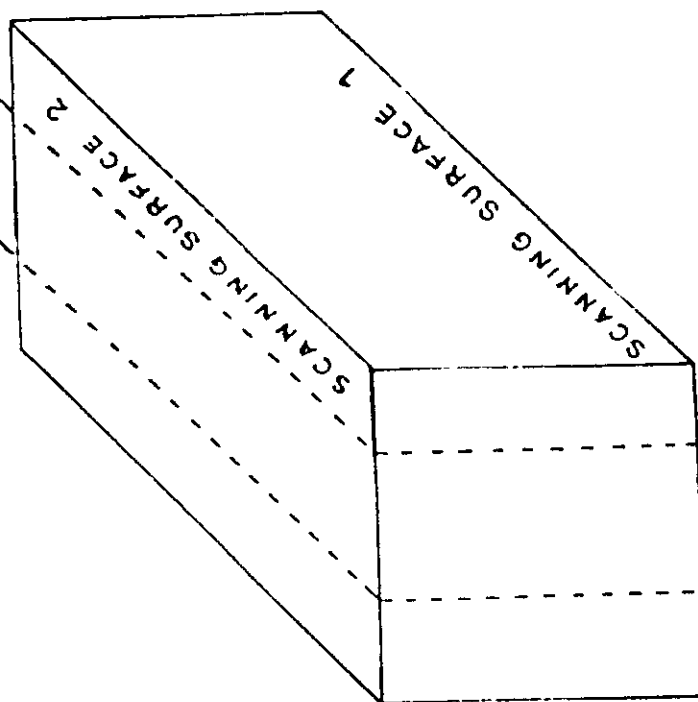
- wl wh areas of greyscale wedge
- 1 horizontal and vertical edges
- 2 arrowhead targets



Reference Plane 1 $4.5 < f < 8 \text{ MHz}$



Reference Plane 2 $2 < f < 4.5 \text{ MHz}$



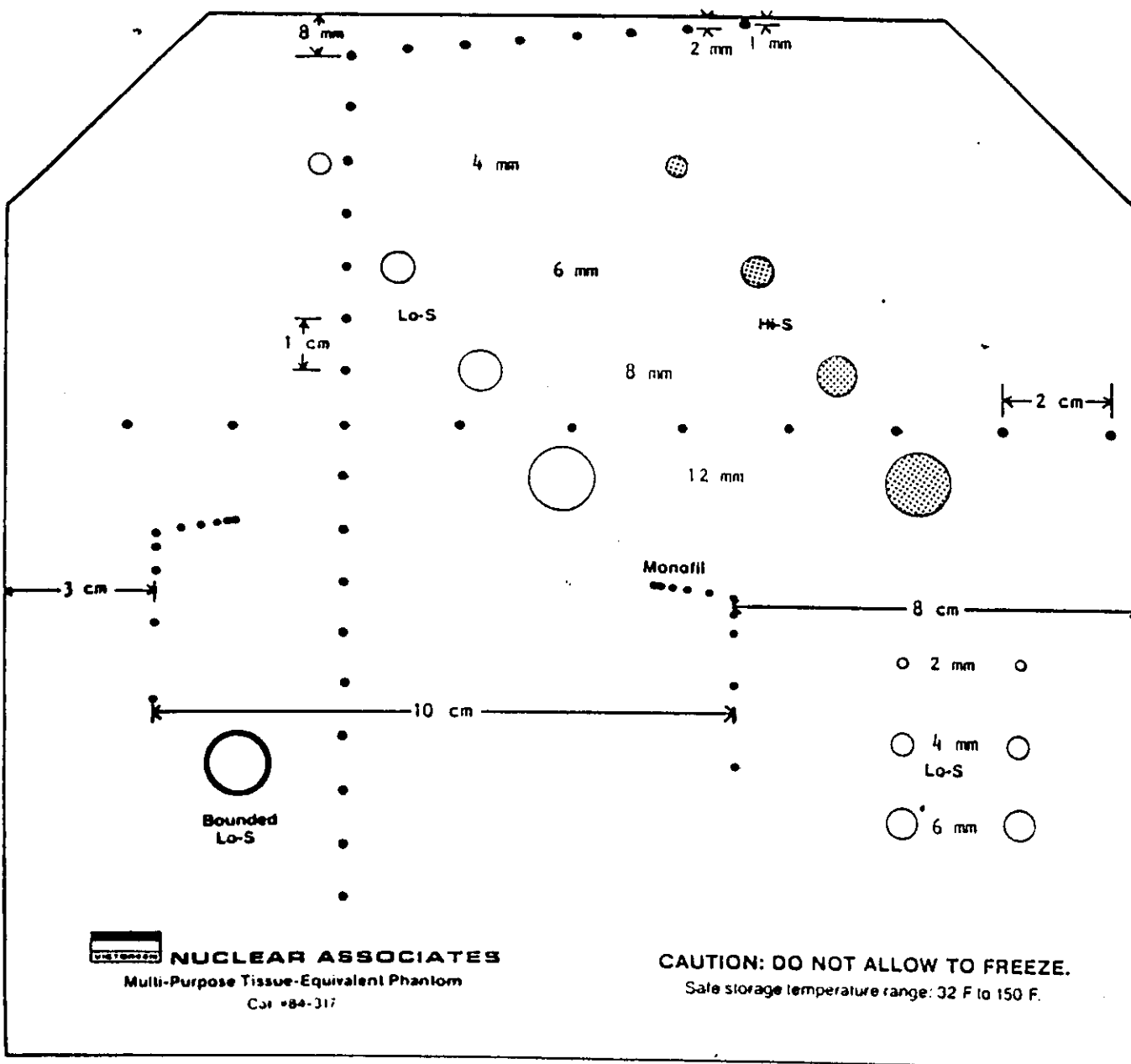


Figure 1.
Internal Targets of Multi-Purpose Tissue-Equivalent Phantom
(Shown 85% of full scale)

EVALUATION PROTOCOL

1. CHARACTERISTICS OF THE ACOUSTIC FIELD
 - 1.1 Sptp Intensity
 - 1.2 Sppa Intensity
 - 1.3 Space/Time Variation of Pulse Intensity
 - 1.4 Distribution of the Pulse Intensity Integral
 - 1.5 Distribution of Peak Intensity
2. PULSE CHARACTERISTICS
 - 2.1 Pulse Waveform
 - 2.2 Spectral Distribution
 - 2.3 Pulse Central (Working) Frequency
 - 2.4 Duty-Cycle
3. GEOMETRICAL CHARACTERISTICS OF THE BEAM
 - 3.1 Beam Shapes
 - 3.2 Variation of Acoustic Pressure along the Beam Axis
 - 3.3 Focal length
 - 3.4 Extent of Focal Zone
 - 3.5 Focal Area
4. SCAN CHARACTERISTICS
 - 4.1 Pulse Repetition Frequency
 - 4.2 Scan Frame Rate
 - 4.3 Number of Acoustic Lines per Scan
 - 4.4 Image Frame Rate
5. GENERAL CHARACTERISTICS
 - 5.1 Dead-Zone
 - 5.2 Axial Resolution
 - 5.3 Lateral Resolution
 - 5.4 Penetration in an Absorptive Medium
 - 5.5 Geometrical Distortion
 - 5.6 Imaging of Cyst-Type Structures
 - 5.7 Accuracy and Linearity of the Measurement System

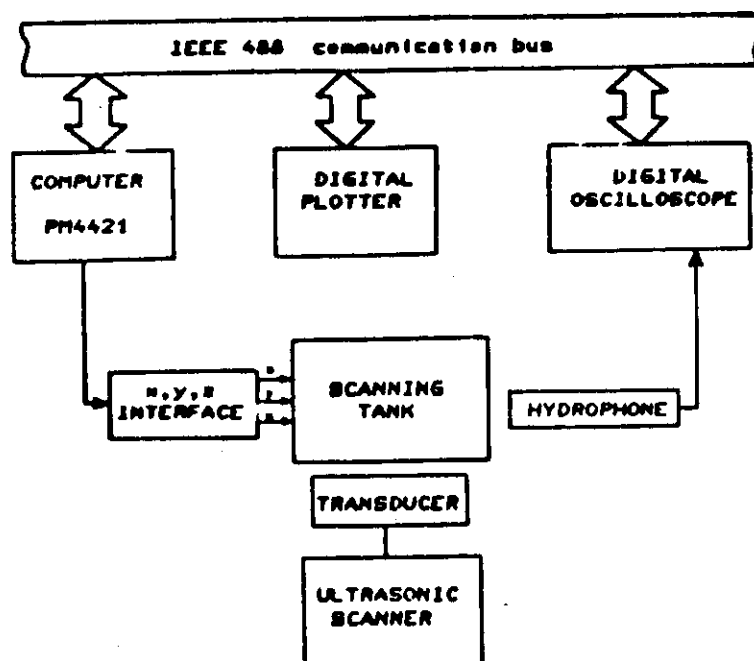


Fig. 1: Struttura del sistema per l'esecuzione delle misure di campo acustico.

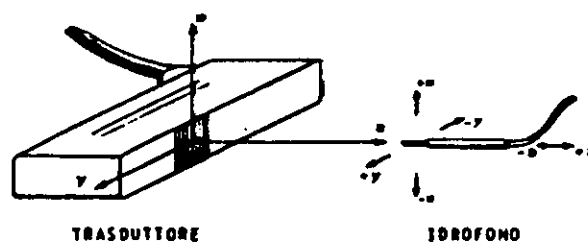


Fig. 2: Sistema di riferimento.

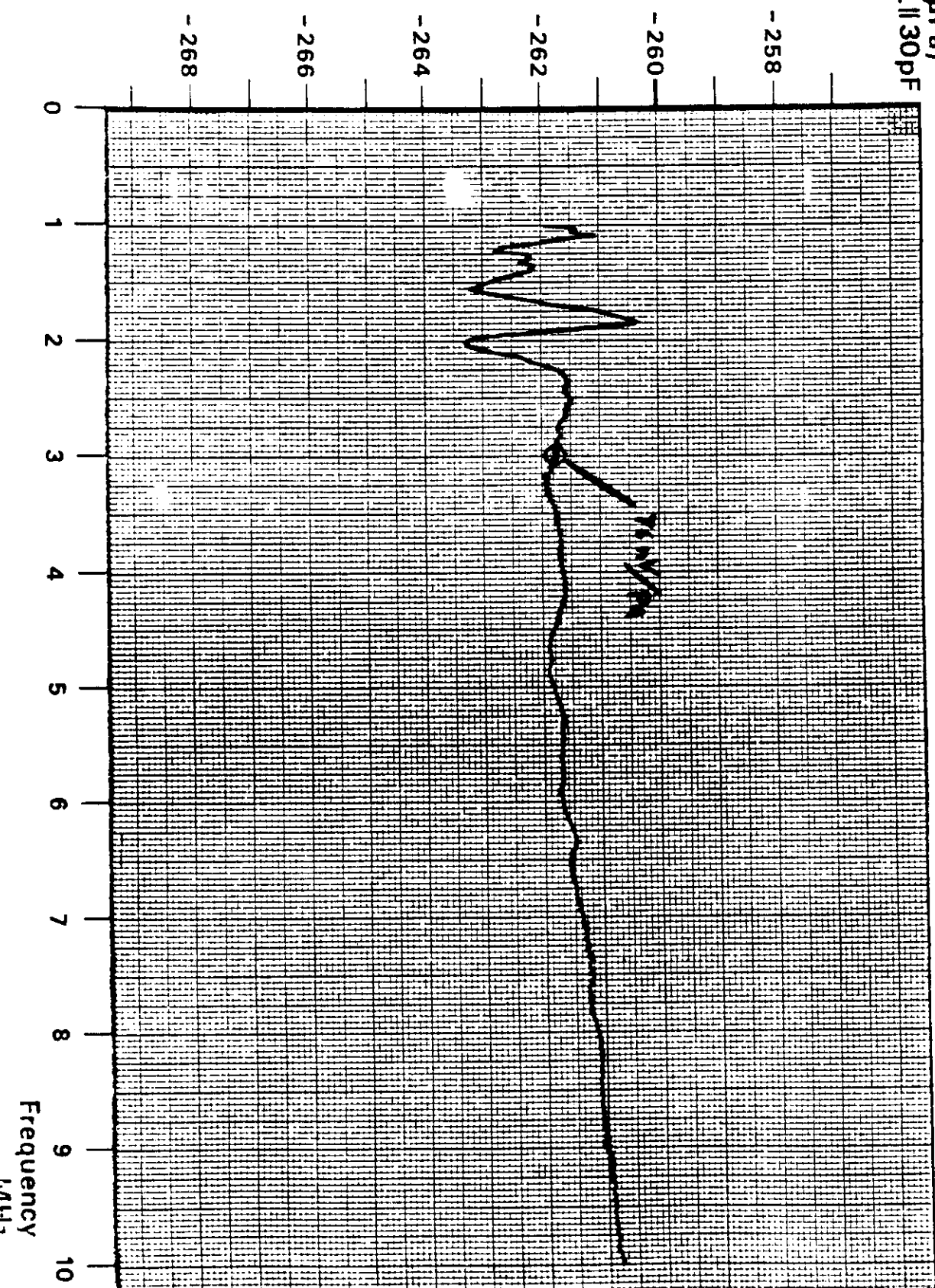


MEDICOTEKNISK INSTITUT
The Danish Institute of Biomedical Engineering

Calibration Chart for PVDF Ultrasonic Probe

Free Field Frequency Response

Impedance of Cable
Voltage Sensitivity
3 re 1V/ μ Pa)
Load 1M Ω || 30pF



0.1 μ V/Pa

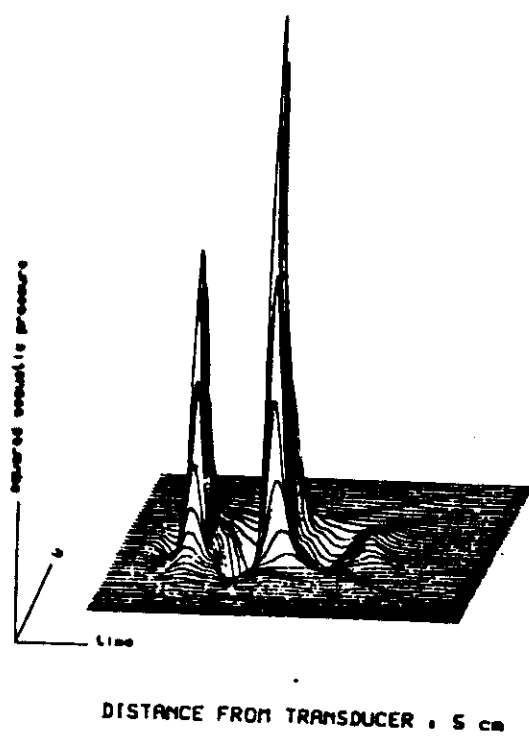
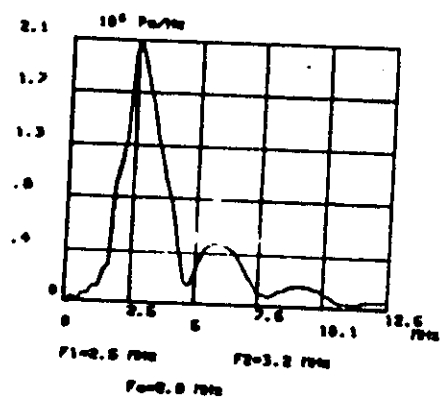
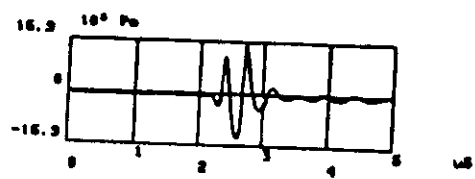
Serial no.: 668

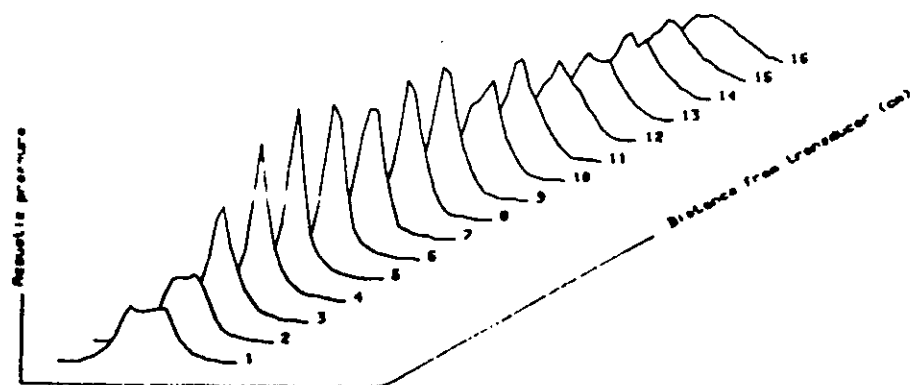
Date: 20. dec 87
Sign.: CAL

Water temp. °C: 25.0

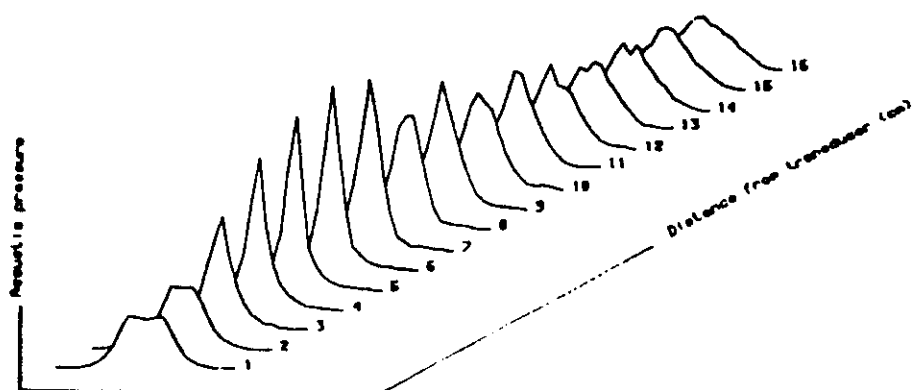
Diam.: 1.0 mm

End of cable
Capacitance
 $\pm 5\%$ at 1.6 MHz: 116 nF

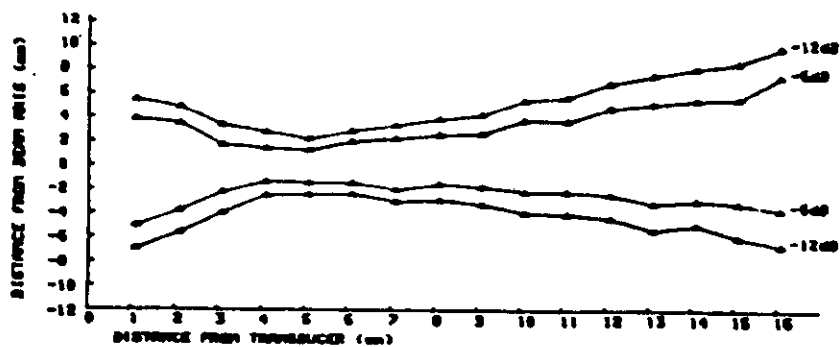




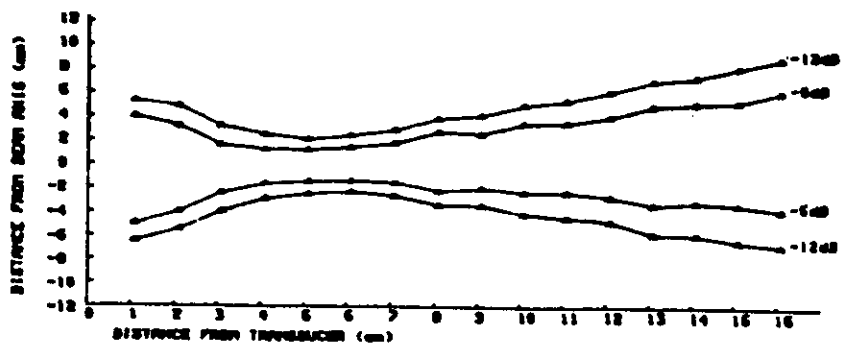
ACOUSTIC PRESSURE ON X-Z PLANE



ACOUSTIC PRESSURE ON Y-Z PLANE



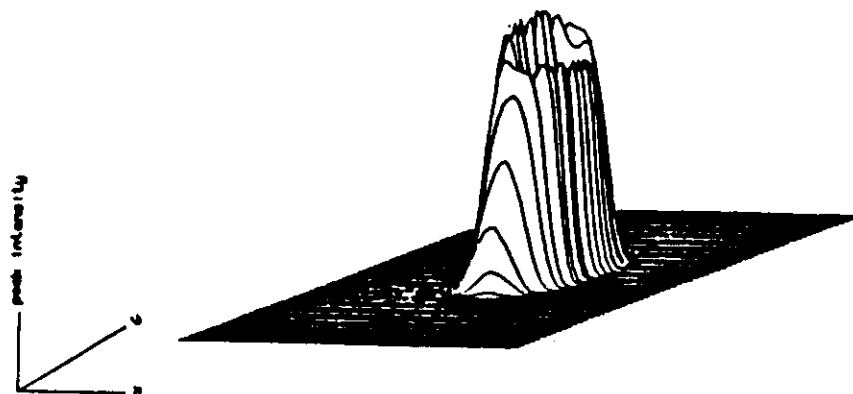
BEAM SHAPE ON ELEVATION PLANE (X-Z)



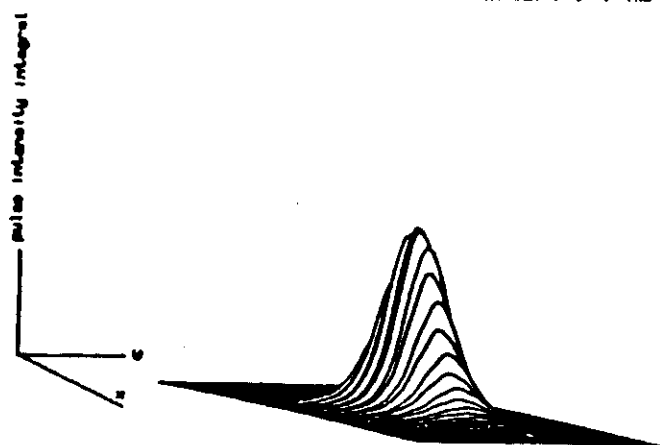
BEAM SHAPE ON SCAN PLANE (Y-Z)



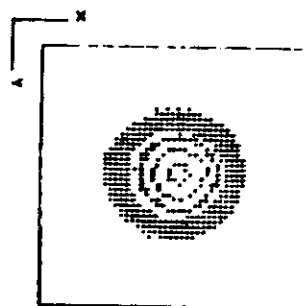
ACOUSTIC PRESSURE ON BEAM AXIS (Z)



DISTANCE FROM TRANSDUCER : 1 cm



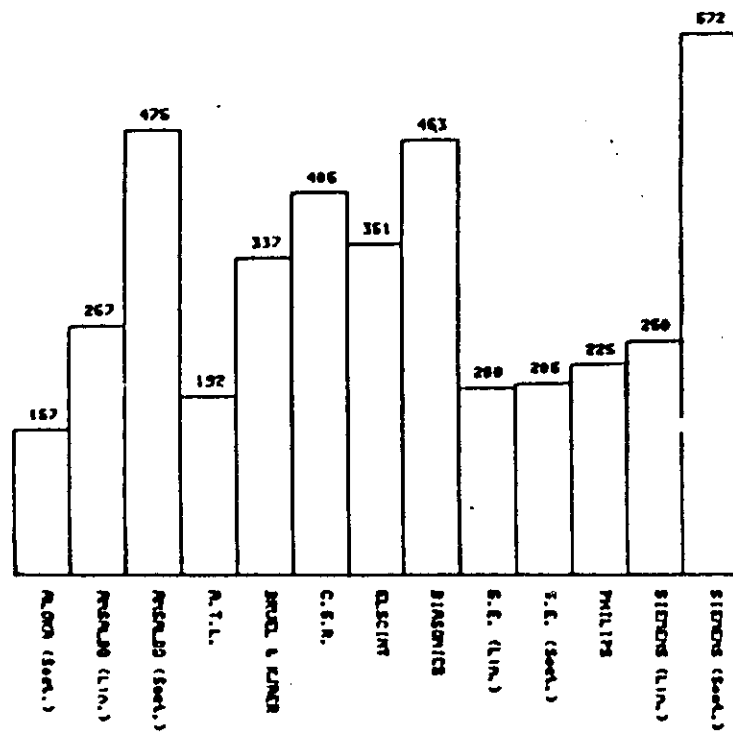
DISTANCE FROM TRANSDUCER : 5 cm



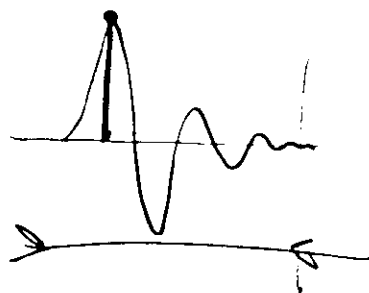
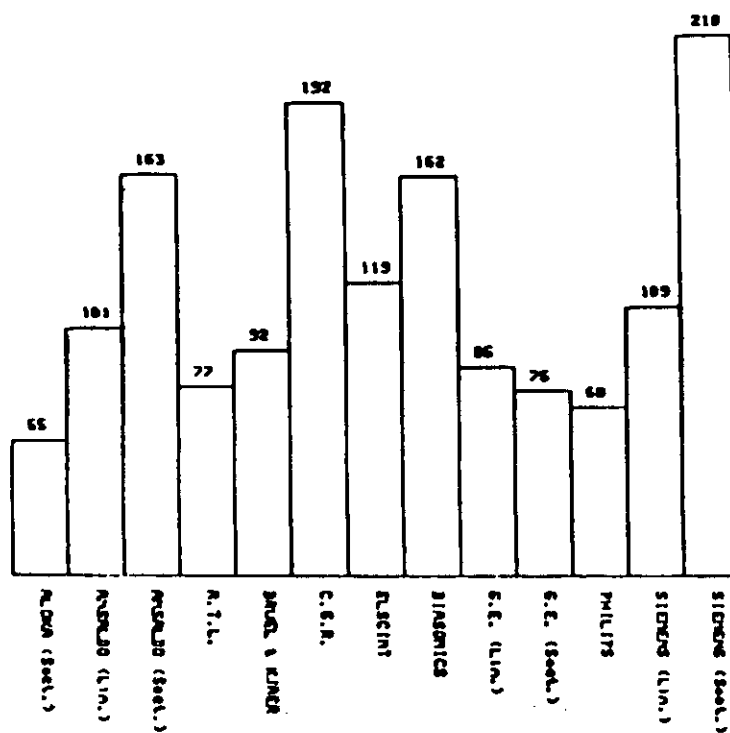
PULSE INTENSITY INTEGRAL
 DISTANCE FROM TRANSDUCER, 5 cm
 LEVELS: 100, 200, 300, 400 of PPK
 SCANNED AREA: 12x12 cm
 BEAM CROSS SECTIONAL AREA: 0.42 cm²

RESULTS OF PERFORMANCE MEASUREMENTS	
Model: ATL MK300C Transducer: 722A 3.0MHz	
1. Isptp (W/cm ²)	192
2. Isppa (W/cm ²)	77
3. Centr. Work. Freq. (MHz)	2.8
4. Bandwidth (MHz)	0.7
5. Duty cycle (%)	0.12-0.34
6. Focal Length (cm)	5
7. Focal Zone (cm)	7
8. Focal Area (mm ²)	8.4
9. Pulse Rep. Freq. (Hz)	2740-7400
10. Scan Frame Rate (Hz)	14-45
11. No. Acoustic Lines	128
12. Image Frame Rate (Hz)	14-45
13. Dead Zone	<8
14. Axial Resolution (mm) at 3cm	<1
8cm	<1
13cm	<1
18cm	<2
15. Lateral Resolution (mm) at 3cm	<3
8cm	<3
13cm	<5
18cm	<5
16. Penetration (cm)	21
17. Geometrical Distortion (%)	<3
18. Imaging of Cysts	GOOD
19. Measurement System Error (%)	<1

Temporal Peak Intensity (I_{ptp}) (W/cm²)



Pulse Average Intensity (I_{ppa}) (W/cm²)



	Isptp	Isppa	Centr. Work. Freq.	Band width	Duty Cycle	Focal Length	Focal Zone	Focal Area	Pulse Rep. Freq.
	W/cm2	W/cm2	MHz	MHz	Z	cm	cm	mm2	kHz
ALOKA	157	55	3.1	0.9	.23-.14	8	8	12.2	2.56-4
ANSALDO sect.	475	163	3.2	1.2	0.19	5	4.5	18.8	<3.78
ANSALDO lin.	267	101	2.9	1.1	.06-.12	5*	4.5*	9.5*	1.4-2.9
A.T.L.	192	77	2.8	0.7	.12-.34	5	7	8.4	2.7-7.4
BRUEL&KJAER	337	92	2.8	0.7	0.13	6	7	13.6	2.7
C.G.R.	406	192	3.0	1.4	[?]	5*	6*	5.9*	[?]
ELSCINT	351	119	3.1	0.9	.04-.43	4.5	5	7.9	1-10
DIASONICS	463	162	2.9	1.2	0.20	7	7	8.9	3.7
GEN. EL. sect.	205	75	3.3	1.0	.17-.21	7*	5.5*	6.4*	3.1-3.9
GEN. EL. lin.	200	85	3.0	1.3	.17-.14	10*	5*	10.5*	3.1-3.9
PHILIPS	225	68	2.9	0.8	0.17	8	10.5	10.5	2.7
SIEMENS sect.	572	218	2.9	1.1	[?]	5.5	7	[?]	[?]
SIEMENS lin.	250	109	3.0	0.5	0.16	8*	8*	12.5*	3.1
(*)=measured at one focus only (see text)									

