

Lecture 14: Acoustic Imaging

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- ◆ Acoustic Waves
- ◆ Sonar
- ◆ Ultrasound Imaging

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Acoustic Waves (1)

Acoustic Waves

Nature of Acoustic Waves

- ◆ Compression waves in matter.
- ◆ Frequency ranges
 - **Sound:** (16... 20,000) Hz (perceived by human auditive system),
 - **Infrasound:** < 16 Hz,
 - **Ultrasound:** > 20,000 Hz.
- ◆ Mechanical processes.
 - Elongation is a change of pressure, i.e. a *scalar* mechanical quantity.
 - Underlying mechanical movement takes place *in propagation direction* – **longitudinal wave** – no polarisation.

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Acoustic Waves (2)



- ◆ Propagate at different speeds in gases, liquid and solid materials.
 - Speed of sound in air: 343 m/s (at 20 °C, dry air)
 - Speed of sound in water: 1482 m/s (at 20 °C)
 - Speed of sound in steel: approx. 5900 m/s (depending on composition)

Other gaseous, liquid and solid materials range around these values.
In (solid) beryllium, 12,900 m/s are reached.

- ◆ no propagation in vacuum (unlike electromagnetic waves)

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Acoustic Waves (3)



Mutual Interaction of Acoustic Waves

- ◆ For small elongations, acoustic waves in lossless homogeneous media obey the wave equation

$$\Delta p = \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2}$$

where p is local pressure, and c_0 speed of sound.

- ◆ Since the wave equation is linear in p , different acoustic waves superpose linearly.
- ◆ Consequentially, they do not perturb each other.
- ◆ Interference phenomena and Huygens' principle hold for acoustic waves, too.

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Acoustic Waves (4)



Interaction of Acoustic Waves with Matter

◆ **Reflection (Spiegelung)** occurs at surfaces where materials of different acoustic properties bound to each other.

◆ **Refraction (Brechung)** according to Snell's Law (cf. Lecture 3).
Total reflection can occur at separating surfaces.

Note that the speed of sound in air is smaller than in water, and in water smaller than in solid materials. Total reflection therefore typically occurs where sound waves coming from air reach a water surface.

◆ **Absorption**

◆ **Scatter (Streuung)** occurs due to inhomogeneities of the material.
Important for imaging is *back-scatter*.

◆ Attenuation of sound waves in water increases proportionally to the frequency.

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Sonar (1)



Sonar

Active Sonar

◆ Method to detect objects (e.g. ships, submarines, seaground, fish) in water by sound reflection

◆ A short pulse of sound is emitted ("ping"); reflected signals are detected.

◆ Distance measurement is based on the time-of-flight.

◆ Direction (*bearing*) is detected by using differences in arrival time at several hydrophones.

◆ 2-D and 3-D images are obtained in polar coordinates similarly like in radar.

◆ Typical frequencies for active sonar are in the audible spectrum (often between 1 and 5 kHz, occasionally lower).

◆ The higher the frequency, the more energy is absorbed in water.

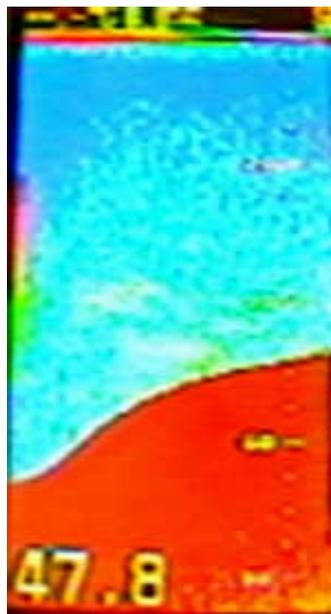
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Sonar (2)

- ◆ When sonar is applied in deep water, refraction has to be accounted for: Deeper layers of water are denser, thus bending sound away.
- ◆ The **thermocline** is a boundary layer in ocean water (depth between 30 and 100 m) which separates warmer surface water from colder deep sea water.
- ◆ Density differences in deep ocean water cause sounds to be bent in large arcs back to the surface. By reflection, the same sound signal can describe further arcs. It returns to the surface every approx. 60 km, constituting concentric circular **convergence zones**.
- ◆ **Echosounding** is sonar measuring of distance to the sea floor.

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Sonar (3)



Sonar image taken by a remotely operated vehicle released from a research ship in Lake Michigan. Red: Sea floor segments, white and green: swarms of fish.

(J. Hanssen 2002, http://www.uwm.edu/Dept/GLWI/people/jjanssen/research_1.htm)

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Sonar (4)



Sonar and Fauna

- ◆ Marine animals, e.g. whales including dolphins, use echolocation which works like sonar.
- ◆ Bats use echolocation with ultrasound in air.
- ◆ Sonar signals can interfere with animal echolocation, inducing loss of orientation.
- ◆ High intensity sonar signals cause injuries and deaths of marine animals.
- ◆ Low intensity sonar signals are reported to help marine animals to keep distance to ships.

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Sonar (5)



Passive Sonar

- ◆ Systems that use existing sound sources, without sending pulses.
- ◆ Spatial resolution is achieved by using chains of hydrophones and the recorded time differences.
- ◆ Main purpose: Detecting objects without attracting attention to the observer – mostly military use, lack of publicly available detail information

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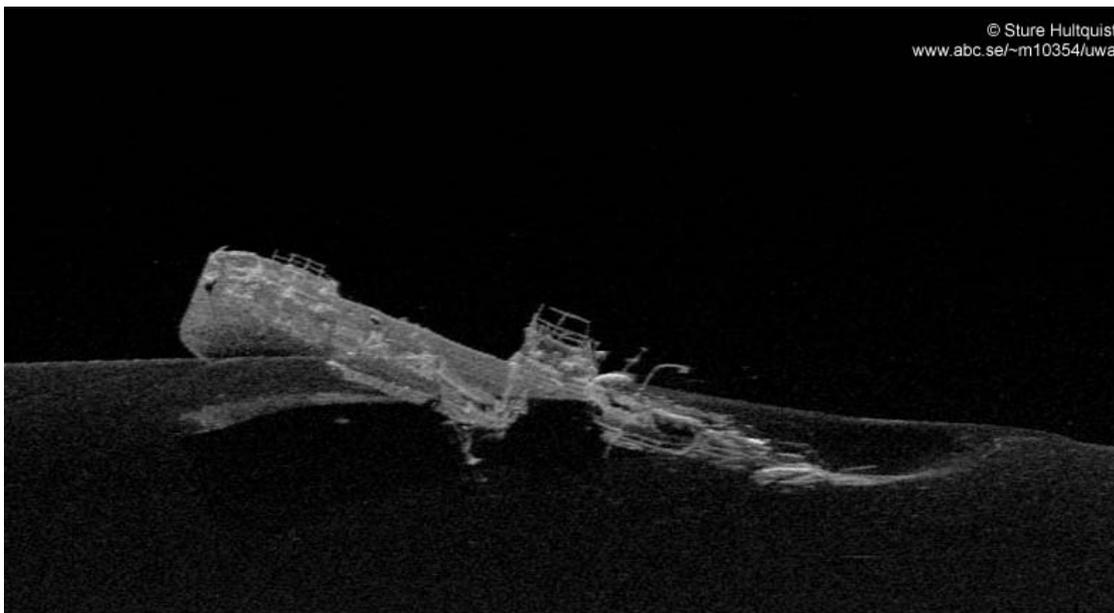
Sonar (6)

Side-Scan Sonar

- ◆ Technique to scan large areas of the sea floor.
- ◆ The sonar device is moved by a ship through the water.
- ◆ Sonar pulses are swept through a wide fan across the trajectory of the ship.
- ◆ Echoes are recorded continuously.
- ◆ Typically, high frequencies are used (100 to 500 kHz).
- ◆ Objects can be depicted in fine detail.

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Sonar (7)



Side-scan sonar image of the ship "Hertha", which sank near the Swedish coast in 1922, lying at a depth of 65 m. (S. Hultquist, <http://www.abc.se/~pa/mar/sidescan.htm>)

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Ultrasound Imaging

Back-Scatter of Ultrasound Beams

- Remember the wave equation in a homogeneous lossless medium:

$$\Delta p = \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2},$$

p local pressure, c_0 speed of sound.

- Wave equation in an inhomogeneous medium:

$$\Delta p - \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2} = \frac{\kappa(x) - \kappa_0}{\kappa_0 c_0^2} \frac{\partial^2 p}{\partial t^2} + \text{div} \left(\frac{\rho(x) - \rho_0}{\rho(x)} \nabla p \right),$$

κ compressibility, ρ density, varying around κ_0, ρ_0 .

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- For small $\frac{\kappa - \kappa_0}{\kappa_0}$ and $\frac{\rho - \rho_0}{\rho_0}$, scatter is weak, leading to the approximations

$$p_0(x, y, z, t) = A(R + z - c_0 t) B(x, y)$$

$$p_{BS}(R, t) = \frac{1}{4\pi R} \int A(2R + 2z - c_0 t) H(z) dz$$

$$H(z) = \frac{1}{4} \frac{\partial^2}{\partial z^2} \int \left(\frac{\rho(x, y, z)}{\rho_0} - \frac{\kappa(x, y, z)}{\kappa_0} \right) B(x, y) dx dy,$$

- $p_0(x, y, z, t)$ incident wave at time t within a region at distance R from transducer,
- $p_{BS}(R, t)$ back-scattered wave from that region encountered at transducer,
- $A(z)$ axial pulse shape (pulse emitted at time $t = 0$),
- $B(x, y)$ beam cross section.

$H(z)$ can be rewritten as

$$H(z) = \frac{1}{4} \frac{d^2}{dz^2} Z_{\text{eff}}(z)$$

with the *acoustic impedance* Z_{eff} (averaged across the beam).

Caution: The quantity imaged is not the acoustic impedance itself, but its second derivative.

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Ultrasound Imaging (3)



- ◆ Note that the back-scattered wave

$$p_{\text{BS}}(R, t) = \frac{1}{4\pi R} \int A(2R + 2z - c_0 t) H(z) dz$$

is a convolution of the (time-reversed and rescaled) pulse with the function H .

- ◆ Since convolution becomes a multiplication in the Fourier domain, we have a 1-D deconvolution problem.

- ◆ Ideally the function H could be obtained in the Fourier domain by dividing the Fourier transform of the received pulse by that of the emitted pulse.

As usual, this cannot be done straightforward; regularisations, e.g. by Wiener filtering, are required.

- ◆ **Attenuation compensation:** In medical application, ultrasound attenuation in tissue cannot be neglected. Formally, this means that instead of $H(z)$ the function $\tilde{H}(z) = H(z)\alpha(z)$ with a known attenuation function $\alpha(z)$ enters the preceding equations.

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Ultrasound Imaging (4)

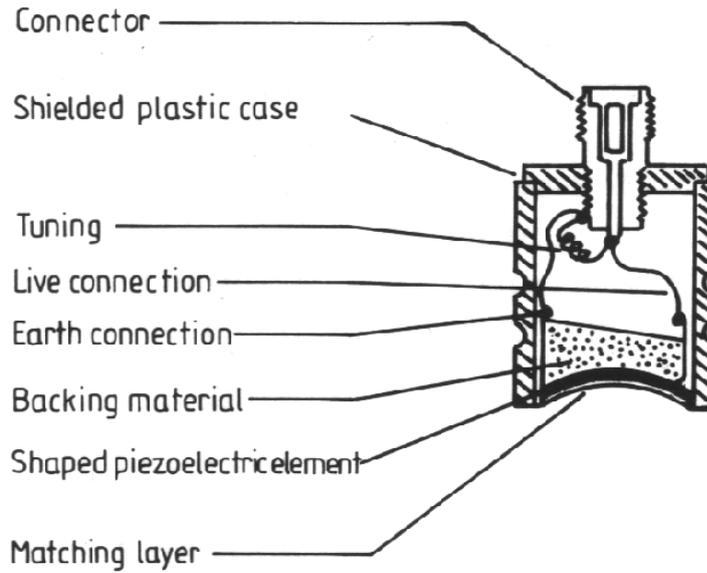


Transducer Technology

- ◆ Piezoelectric elements are used to generate the acoustic pulses and to measure the reflected signal.
- ◆ A single stationary piezoelectric element can be used for directed ultrasound emission and measurement of the back-scatter. Lenses of ceramic or other materials can be used to focus the beam.
- ◆ Transducers for fast directed emission and direction-sensitive measurement are designed to allow fast sweeping of beams.
 - Mechanical rotation of the crystal allows higher frequencies (up to 50 MHz).
 - Electronically controlled transducers contain a large number (50...500) of piezoelements along a straight line or arc. These are electronically activated to steer the beam direction. Frequencies up to 10 MHz can be used. Simultaneous activation of more than one crystal allows focussing by wave interference.

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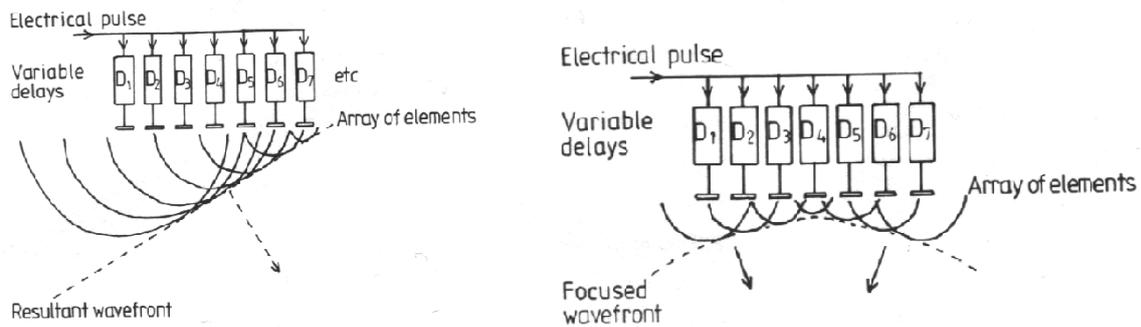
Ultrasound Imaging (5)



Single element ultrasonic transducer. (Webb 1988)

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Ultrasound Imaging (6)



Beam forming in an array transducer. (a) Left: Formation of a wavefront. (b) Left: Formation of a focused wavefront. (Webb, 1988)

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Ultrasound Imaging (7)

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Quantitative Parameters of Medical Ultrasound

- ◆ In medical imaging, the imaged parts of the body have acoustic properties varying around that of water.
- ◆ Frequencies in the range (2...7) MHz are used.
It is consented that these frequencies, with the intensities used, are harmless. Volunteers can therefore be examined.
- ◆ Attenuation limits the scanning depth from centimetres to a few decimetres.

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Ultrasound Imaging (8)

MI
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Qualitative Properties of Medical Ultrasound

Boundaries between water/soft tissue and bones and between water/soft tissue and air lead to reflections.

- ◆ Bone surfaces give strong echoes.
- ◆ At air/water transitions, ultrasound is mostly reflected back into air. Consequentially, gaseous cavities cannot be imaged.
- ◆ It must be ensured that no air is between the transducer and the patient's body – a gel is used.

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Ultrasound Imaging (9)

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Ultrasound image of a 4-months-old human fetus. (CDC/J. Gathany, copied from Wikipedia)

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Ultrasound Imaging (10)

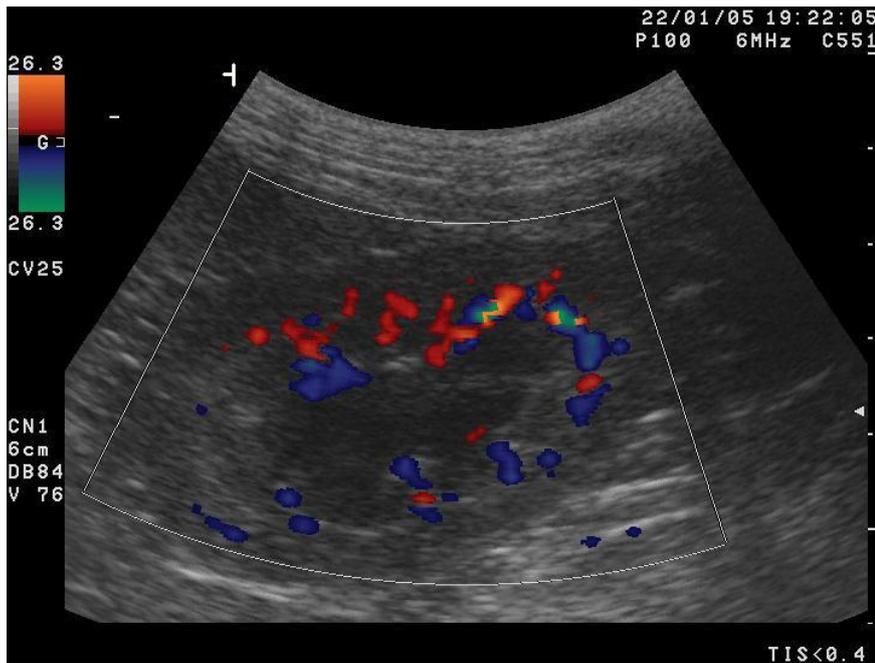
MI
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Doppler Ultrasound Imaging

- ◆ According to the Doppler effect, signal portions reflected by moving objects (blood) are subject to a frequency shift. This allows to image velocity components along the A-scan beam directions.
- ◆ Often pseudocolour representations are used where
 - **red** encodes movement towards the transducer,
 - **blue** encodes movement away from the transducer,
 - **green** encodes turbulent movement (diverging speed).

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Ultrasound Imaging (11)



Doppler sonogram of a human kidney. Colour coding indicates speed (of blood) towards or away from the scanning head. (Kalumet 2005, copied from Wikipedia)

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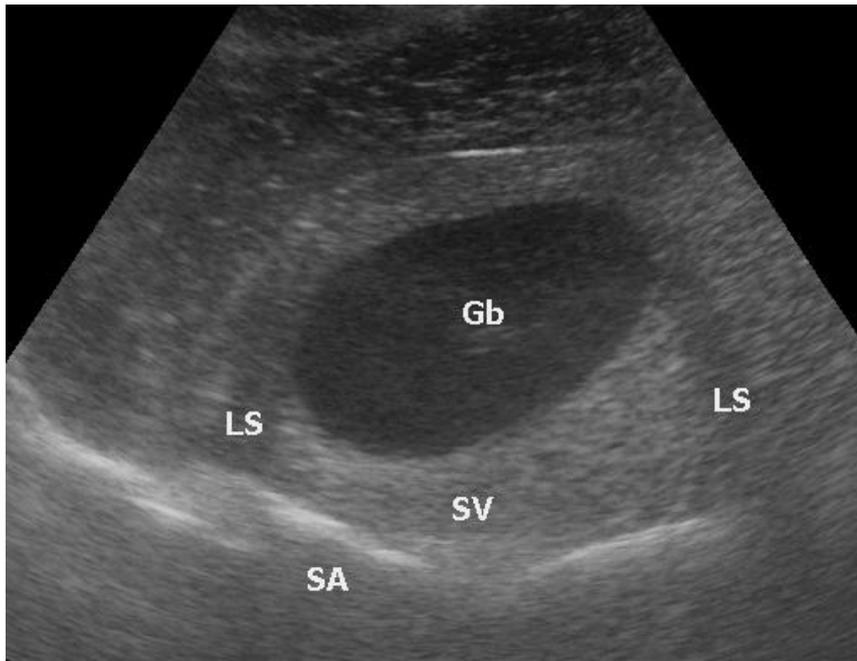
Ultrasound Imaging (12)

Noise and Artifacts in Ultrasound Images

- ◆ **Speckle noise.** Phase shifts and resulting interference phenomena lead to granular textures in the order of magnitude of the employed ultrasound wavelength ($\lambda \approx (0.3 \dots 0.7) \text{ mm}$). This is the main perturbation.
- ◆ **Distal sound extinction.** Dark shadows appear behind strongly reflecting boundaries. In particular, behind air-filled cavities practically no signal is available.
- ◆ **Distal amplification.** Bright shadows appear behind weakly reflecting boundaries of high-impedance regions.
- ◆ **Lateral shadowing.** Where beams are nearly tangent to boundaries, they are weakened by reflections, leaving dark shadows behind these structures.
- ◆ **Multiple reflections.** Particularly, parallel contours induce further, artifactual parallel lines.

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Ultrasound Imaging (13)



Sonogram of a human gall bladder illustrating characteristic artifacts in sonography. **Gb** gall bladder, **SV** distal sound amplification, **SA** distal sound extinction, **LS** lateral shadowing. (Kalumet 2005, copied from Wikipedia)

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Ultrasound Imaging (14)

Ultrasound Imaging Extensions

- ◆ **3-D Ultrasound Imaging.** Scan beams are swept in two directions, resulting in volume data.
- ◆ **4-D Ultrasound Imaging.** Volume data as in 3-D imaging are obtained in short time intervals resulting in a 4-D data array.
- ◆ **Ultrasound Tomography.** Not very frequently used yet. For small objects, it is also possible to measure attenuation integrals along beams by transmitted ultrasound.

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3-D reconstruction from ultrasound imaging of a 32-week old human fetus (*University hospital of Würzburg, <http://www.frauenklinik.uni-wuerzburg.de/>*).

Note that images have to be intensively preprocessed before such an excellent reconstruction is possible. You can learn more about this in image processing lectures.

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Summary

Summary

- ◆ Acoustic waves are compression waves in matter. Their propagation speed depends strongly on the matter. They can superpose each other and show interactions with matter (reflection, refraction, absorption, scatter).
- ◆ Active sonar detects objects in water by sound reflection.
- ◆ Ultrasound imaging is based on backscatter. It suffers from speckle artifacts.
- ◆ Doppler ultrasound imaging allows to measure blood flow.
- ◆ Extensions of ultrasound imaging to 3D and 4D exist.

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References

- ◆ S. Webb, *The Physics of Medical Imaging*. Institute of Physics Publishing, Bristol 1988.
- ◆ B. Jähne, H. Haußecker, P. Geißler, editors, *Handbook of Computer Vision and Its Applications. Volume 1: Sensors and Imaging*. Academic Press, San Diego 1999.

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