Ultrasound/Diagnostic applications of ultrasound

Ultrasound can be used diagnostically in a number of applications. Because it is a method burdened with only minimal risk and a method easily available, it is a relatively widespread technique falling into a number of fields. These are in particular:

- **Ultrasound imaging** - acquisition of tomographic sections based on different acoustic parameters of tissues
- **Doppler imaging** - the use of the Doppler effect to measure and visualize motion or flow
- **Doppler flowmeter** - measurement of blood flow
- **Ultrasound elastography** - visualization of elasticity (stiffness) of tissues
- **Ultrasound bone densitometry** - less suitable than X-ray measurements
- **Acoustic microscopy** - more or less experimental imaging with very high frequency

Ultrasound is also indirectly related to diagnostics as a laboratory tool. In laboratories, ultrasound is used, for example, in the following activities:

- cleaning tools
- homogenization and dispersion of substances
- dispersion of cells into suspension

Ultrasound imaging

Physical principle

Piezoelectric phenomenon

Ultrasound generation using the piezoelectric effect is usually used for diagnostic purposes. To understand the piezoelectric phenomenon, it is necessary to know that in crystals, electric charges can be freely mobile, they are called **free charge carriers** , and they can be tightly bound in the crystal lattice, they are called **bound charges**. If the elastic deformation of the crystal occurs, the crystal structure changes and thus also the relative position of the bound charge carriers. By mutual displacement of the charges, the "centers of gravity" of the positive and negative charges can move away from each other, and a non-zero electric field appears in the crystal. This can then be measured on the surface of the crystal as an electrical voltage. The process can also take place in the opposite way, i.e. if a crystal made of a suitable material is placed in a sufficiently intense electric field, its measurable deformation will occur. This phenomenon is sometimes called inverse piezoelectric effect or electrostrictive effect. If the external electric field is time-varying, the crystal changes its shape with the same period and thus becomes a source of mechanical waves. In addition to some crystals, the piezoelectric phenomenon can also occur in some ceramic materials.

Signal generation and propagation in tissue

A single piezoelectric element called an **ultrasonic transducer** can be both a source and a detector of ultrasonic waves. In conventional ultrasound devices, the arrangement is such that the transducer generates ultrasound waves with a frequency usually in the range of 3 to 10 MHz for a few milliseconds, after which it becomes a detector and captures the reflected waves.

The acoustic waves themselves, which are transmitted to the tissues, propagate as longitudinal waves. At the interface of two environments with different acoustic impedance , it is partly reflected back to the source and partly transmitted. The reflected signal, the so-called echo, is captured by the transducer and converted into an electrical signal, which is usually called a radio frequency signal due to its high frequency.

Because the time elapsed between sending the acoustic signal into the tissue is known, it can be determined at what depth the reflection occurred. To do this, however, it is necessary to know the speed with which ultrasound propagates in the tissues. This speed is around 1540 ms^{-1} in soft tissues.

The frequency of the ultrasound is a very important factor. As the frequency increases, the wavelength of the ultrasound decreases, so in principle, even larger details can be seen and a higher quality image can be obtained. On the other hand, energy dissipation also increases with frequency, so using too high frequencies to examine deep-seated organs would result in disproportionate heating of the skin and surface-seated organs. For that reason, frequencies in units of MHz are used to examine organs located, for example, in the abdominal cavity, and frequencies around 10 MHz are used to examine the thyroid gland and superficially located lymph nodes and vessels. Ultrasound examination with a higher frequency is not quite a routine procedure, e.g. in dermatology (up to several tens of MHz - acoustic microscope).

Speckle

Speckles represent a phenomenon that is characteristic of ultrasonography. The ultrasound wave actually penetrates the tissue in a rather complex way, because the tiny tissue structures have dimensions comparable to the wavelength of the penetrating ultrasound. Thus, a non-negligible dispersion of the waves occurs. Since it is a monochromatic wave, the scattered waves interfere both with each other and with the useful wave. The resulting signal is thus "disturbed" by interference patterns.

The approach to speckles is not entirely straightforward. On the one hand, they reduce the clarity of the tissue section for the untrained eye, on the other hand, they carry at least part of the information about the tissue structure. In the professional literature, one can therefore find both works that try to suppress the speckle eliminator so that the modified image has the character of an "anatomical" section, and works that try to use speckle for computer support of diagnostics.

Ultrasonic probes

Usually it is not enough to have only one converter on the probe, therefore a larger number of converters are placed on the probe. Depending on the shape of the probe and arrangement, we distinguish several types of probes. Basic probes are linear, convex and sector probes, for special applications e.g. pencil, circular or array type probes are used.

Linear probe

In a linear probe, the converters are arranged in one row, the basis is a line segment. The resulting image has the shape of a rectangle. Linear probes are typically used to examine surface organs, so they are usually designed for higher frequencies.

Convex probe

In the convex probe, the converters are again in a row, but their base is slightly convex. The resulting image has the shape of a section of an annulus with a relatively small apex angle. It is the most common type of probe used to examine the organs of the abdominal cavity.

Sector probe

The sector probe is adapted to display a relatively wide section of tissue through a relatively small window (contact of the probe with the patient's body). Technically this can be solved in two ways:

1. **The rotary transducer probe** is an older solution. The transducer rotates rapidly and thus the ultrasonic wave is sent from a relatively small point in a wide direction.
2. **The probe with electronic deflection** is a modern solution. There are a few converters on the probe, the deviation is ensured by a precisely defined phase shift of the waves generated by them, which leads to constructive interference in the desired direction

The image from the sector probe looks similar to the image from the convex probe, but has a much larger apex angle. Sector probes are mainly used in echocardiography and gynecology.

Pencil probe

The pencil probe contains a single transducer. It is typically used as part of a portable ultrasonic flowmeter. The result of the measurement is of course not an image but a curve or an acoustic signal.

Circular probe

In the circular probe, the transducers are arranged in such a way that a very wide to circular tissue section is taken in a plane perpendicular to the axis of the probe. It is mainly used for transrectal examinations of the prostate, but it can be so small that intravascular ultrasound examinations of, for example, atheroma plaques can also be performed.

Array type probe

An array probe is one of the ways to obtain a 3D image. The converters are arranged in a matrix (array) and by their cooperation data are obtained for the entire volume under the probe.

Display modes

A mode

A mode (***A**mplitude*) is a one-dimensional display, typically a signal from only one converter. Individual reflections registered by the ultrasound probe are displayed on the monitor as impulses on the timeline. The amplitude of the pulses corresponds to the intensity of the reflected ultrasound waves. In order not to have a disturbingly significant depth-dependent attenuation, the radio frequency signal is also amplified by a so-called TGC amplifier (***Time Gain** Control) , whose* amplification increases with the time that has passed since the echo was sent.

And the mode currently has only limited use, e.g. in eye biometrics. A mode is, however, the starting point for all other methods, because they can be imagined as individual "rays" in A mode, whose graph values are converted to grayscale.

B mode

B mode (***B** rightness*) is the basis of tomographic imaging. Basically, there are two types of display - static and dynamic.

- **Static display**

Static display is historically older, technically easier and has been abandoned for a long time due to the availability of electronics and computer technology enabling routine dynamic display. The measurement was performed using one transducer that was moved along the patient's body. An image was obtained by successive summation of individual measurements.

- **Dynamic display**

In dynamic imaging, there are a number of converters in one probe that work together and whose echoes are evaluated in such a way that we see the resulting image as an image taken in real time. Today, this is clearly the most common way of display.

M mode

M mode (**M***otion*) is used to examine the movement of anatomical structures, especially the heart. In principle, it is nothing more than the fact that a one-dimensional record is taken at regular time intervals. The measured echoes are then encoded into grayscale and displayed below each other by time.

3D display

In principle, a three-dimensional image can be obtained in two ways, with a three-dimensional probe and reconstruction.

- **Three-dimensional probes**

In principle, a three-dimensional probe does not differ from a normal two-dimensional probe, only the converters are not arranged in a row but in a matrix. Such a probe then makes it possible to capture data from the entire volume in a relatively short time, so real-time imaging is even possible, sometimes referred to as 4D imaging. The disadvantage is that the probes are relatively clumsy, it is necessary to guarantee good contact of the patient's body with a relatively large area.

- **Reconstruction approaches**

A three-dimensional image can also be obtained by mathematical processing of images taken with a probe. The first attempts consisted in the fact that the probe was attached to the frame with controlled displacement and all the processing consisted only in the synchronization of the displacement and the recording of the images in the memory. The system of sensors sensing the position of the probe in space was more flexible. The values of individual voxels were then calculated on the basis of a series of slices supplemented with information about the position of the probe. Modern devices are even more sophisticated, the examining doctor only freely "passes" the probe over the area of interest and their position is determined mathematically from the sections obtained, and then a three-dimensional image is reconstructed.

Blood flow velocity display methods - Doppler methods

Doppler methods are based on the frequency change relationship. The aim of these methods is to measure the speed of moving structures.

Continuous Doppler imaging - flowmeters

In this measurement, we have to use a separate transmitter and receiver of ultrasonic waves. A transmitter with a single converter continuously generates an acoustic signal and therefore cannot be switched to receiver mode. Flowmeters have an acoustic output, as the change in frequency is in the audible range for the speed of blood flow in the human body. Flow meters display the speed of blood flow as a function of time. The disadvantage of this method is that the arrangement and location of the monitored vessels cannot be visualized. Therefore, in the case of two overlapping vessels, we do not know in which of them we are measuring the blood velocity.

Pulsed Doppler methods

We use these methods in combination with reflection methods (B). We use probes that can work in different modes, we are talking about duplex measurement. We monitor the time and frequency shift of the reflected wave. On the monitor, we can see what speed we are measuring and where we are measuring it.

- **The duplex method** is a combination of two-dimensional dynamic imaging and the pulsed Doppler speed measurement method. Two-dimensional dynamic imaging provides us with information about the morphology of the monitored area (and the morphology of vessels). Pulsed Doppler measurement provides a recording of the speed spectrum of blood flow in a vessel.
- **Color duplex ultrasonography** − The image is composed of a color and black-and-white part. The black-and-white part provides morphological information about reflectivity, the color part provides information about movement in the monitored section (blood flow movement). Blood flow from the probe is shown in blue, flow to the probe in red. The brightness of the color then indicates the speed of the flow. The time to acquire a color image is greater than the time required to acquire a black and white image. Therefore, the frame rate of color images is smaller than the frame rate of a black and white image.

Links

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- Doppler echocardiography