A REVIEW OF ULTRASOUND APPLICATIONS

by

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ABSTRACT

A brief history of early applications of ultrasound is given together with an overview of the diverse applications of ultrasound today. Ultrasound is defined and its properties are compared with those of sound.

1. Background

In 1883 Galton[1] designed a whistle for the production of sounds near or above the upper limits of human hearing. However, the first practical and for many years the only application of ultrasound was in sonar for the detection of submarines. The device, first produced by Paul Langevin in 1917[2], used a quartz crystal vibrating at 50 kHz to produce an ultrasound beam which was propagated into water and the reflected beam detected. During World War II the same principle was used for an ultrasound detecting device. The device was mounted on the sides of torpedoes and the sound from ships or submarines caused the torpedoes to be directed towards them. The first industrial application of ulrasound was an ultrasonic flaw detection system, later known as an "inspectoscope". This was developed between 1939 and 1945[3,4]. This system was used for locating flaws in materials and for measuring the thickness of materials for which only one face was available.

World War II was the catalyst for the rapid development of pulse techniques in radar and sonar, and this in turn led to the preference of pulse techniques over continuous waves in the detection of material defects. Ultrasonic non-destructive testing has steadily increased in efficiency and become more sophisticated. Improved ultrasonic non-destructive testing techniques have influenced the applications of ultrasonics to medicine.

One of the early technological advances aiding the development of ultrasound was the introduction in 1945 of ferroelectrics (materials with a natural polarization), that could be obtained in ceramic form. Up to that time the principle transducer materials were quartz crystals, ADP crystals, and magnetostrictive materials.

2. What is Ultrasound?

Ultrasound is a form of mechanical energy having frequencies above the normal hearing range (> 20 kHz). As a form of acoustic radiation, ultrasound obeys the basic principles of sound propagation. In addition, ultrasound's high frequency (and thus short wavelength), results in it conforming more closely than sound to the basic principles of light propagation.

The differences between ultrasound and sound terminology are due to the following major factors. Since ultrasound frequencies do not act upon the ear in such a way as to produce the sensation of sound, the reference level of minimum audible intensity adopted in the definition of sound pressure level (dB), has little meaning. The ultrasound quantity used instead is ultrasound intensity. As in sound, ultrasound intensity is defined as the rate of flow of ultrasound energy through a unit of area, and is measured in watts per square centimetre. Airborne ultrasound is the only form of ultrasound commonly measured in terms of decibels. This is mainly due to airborne ultrasound frequencies being in the range of 20-40 kHz, immediately above the upper sound frequencies. Although these frequencies are inaudible, it has not been confirmed that they have no effect on the hearing mechanism. In addition some airborne ultrasound applications generate audible subharmonics. The majority of applications of ultrasound are, however, based on its propagation in liquids or solids. This results in a corresponding change in basic constants such as the speed of sound with respect to sound and other airborne acoustic radiation. Finally, since many applications of ultrasound are based on the emission of a signal (such as a short pulse) and the reception of its echo, factors such as beam width and pulse duration are important, as are the spatial and temporal, peak and average, intensities of the ultrasound pulse. For more detailed information on ultrasound terminology, the American Institute of Ultrasound in Medicine has produced an interim standard, is shortly to be published in their magazine "Reflections".

3. Medical Applications

Ultrasound has a variety of medical applications, the most common being as an aid to healing in therapy treatments. The most rapidly expanding medical use is as a diagnostic tool, partly due to the commonly held belief that there is no risk from ultrasound. It does appear to provide much less risk than X-radiation as a diagnostic tool. In addition ultrasound has surgical, dental and other applications.

3.1 Diagnosis

Ultrasound was introduced to diagnostic medicine in the mid 1950s and ever since has been growing at such a rate that it has been stated[5] that "with expanding services in ultrasound diagnosis, the frequency of human exposure is increasing with the potential that essentially the entire population may be exposed." The Bureau of Radiological Health (U.S. Department of Health, Education and Welfare) estimates that by the early 1980s, every pregnant woman will undergo at least one ultrasound examination of the fetus. Certainly the sales of diagnostic ultrasound devices have been increasing rapidly over the last 10 years, and are projected to double between 1980 and 1983[6]. In addition, new techniques continue to be developed. Ultrasonic spectroscopy, time delay spectrometry and holographic techniques all offer new potential for this already expanding imaging modality.

Most diagnostic ultrasound equipment uses the pulse-echo measurement technique. The transmitter is an electronic circuit that produces a very short electrical pulse. A characteristic number of pulses per second cause the piezoelectric crystal to vibrate at its resonant frequency and thus to generate pulses of ultrasound. The returning echo is received by the transducer (usually the same piezoelectric crystal as was used to produce the transmitted ultrasound pulse), the ultrasound wave energy causing a mechanical distortion in the crystal and generating an electrical impulse or signal. This electrical signal is processed by another electronic circuit, called the receiver, which amplifies, rectifies and demodulates the electrical echo signal. The resultant signal is then displayed on the A-mode display (oscilloscope).

The A-mode (amplitude modulation), is the oldest and simplest method of displaying pulse-echo information. The horizontal axis on the display represents time or depth into the patient, the vertical axis represents the logarithm of the echo amplitude. A-mode displays are used mainly for echo-encephalography, soft-tissue biopsy and some ophthalmologic examinations.

All other pulse-echo displays are based on the B-Mode (Brightness modulation). In B-mode a small cross-section of the patient is displayed on the screen, the brightness, or shade of gray, representing the amplitude of the echoes. This is modified in the M-mode (time-motion mode), by a constant velocity sweep of the display to enable the motion of moving reflectors in the body to be measured. In the B-scan an articulated arm is attached to the transducer enabling position and angulation to be constantly monitored. As the transducer scans the patient, the B-mode and position information enable a 2-dimensional image to be generated. This is the most frequently used display today. However more sophisticated displays have been developed. One of these relies heavily on television and scan converter technology to produce a Grey-Scale, which, as the name indicates, gives images where the echo amplitude strengths are displayed in shades of grey. Another is the Real-Time Display, which displays images (generally grey-scale) at rates up to 30 frames a second. Real-Time displays are invaluable in cardiac and fetal monitoring studies.

In addition to pulse-echo techniques there are many applications for continuous-wave (cw) beams of sound in diagnosis. For example cw techniques are useful for measuring the change in frequency of the echo from that of the transmitted beam. By use of the Doppler shift principle the velocity of the reflectors may be ascertained. The transducer for Doppler studies is made up of two crystals, a transmitter and a receiver. The echo received is modulated by leakage from the transmitting crystal in the transducer. The beat frequency of these two signals is the Doppler frequency. The Doppler (beat) frequency is detected (by filters), amplified, and usually made into an audible sound. The higher the velocity of the reflector, the higher the pitch (frequency) of the audible sound produced.

The significance, or clinical usefulness, of diagnostic applications of ultrasound has been summarized by Lyons[7] as shown in Table 1. He has graded the significance of clinical usefulness of diagnostic ultrasound procedures as shown below:

<u>Clinical Significance</u>

- * Limited significance
- ** Useful ancillary investigation
- *** Most efficacious, non-invasive examination
- **** Sole investigative tool.

Table 1. Diagnostic Ultrasound Examinations and their Clinical Significance with respect to Other Imaging Modalities (adapted from Lyons[7]).

Body Part	Organ	Examination	Clinical Significance
Head	Brain	Midline determination	*
		Ventricular size (newborn)	**
	Eyes	Eyeball - axial length	**
		- foreign body	*
		- retinal detachment	***
		- mass evaluation	**
		Orbit - proptosis	*
Neck	Thyroid	Mass evaluation	**
		Carotid artery	*
		Potency evaluation	*
Chest	Heart	Pericardial effusion	***
		Valve investigation	***
		Wall evaluation (motion thickness)	***
		Chamber size, function	***
		Tumour detection	***
	Pleural space	Effusion localization	*
	Breast	Mass evaluation	*
Abdomen	Liver)	Evaluation size,	***
	Kidneys)	parenchyma and	***
	Pancreas)	associated masses	***
	Spleen)		***
	Biliary Tract	Gallbladder stone detection	***
		Duct size	**
	Aorta	Aneurysmal dilation	***
	Lymph Nodes	Evaluation	**
	Perito-neal space	Ascites and abscess detection	***
Pelvis	Uterus (pregnant)	Evaluation - fetus	****
		- placenta	****
		- amniotic cavity	****
	Uterus (non-preg-nant)	Mass size determination	**
	Fallopian	Mass evaluation	***
	Ovaries	Mass evaluation	***
	Bladder	Tumour assessment	*
	Prostate) Scrotum)	Tumour detection	*
Extremities	Arteries and veins	Potency evaluation	*

3.2 Therapy

Ultrasound therapy has been used for over 40 years in physiotherapy. It usually involves the application of a hand-held ultrasound transducer to the injured area of a patient, and treating using either a continuous or pulsed beam. The transducer head is generally moved over the area of injury to obtain as uniform a treatment distribution as possible. Coupling the transducer to the treatment area may be achieved by[8]:

(i) treating within a waterbath,
(ii) holding the transducer in contact with the skin using a coupling medium (film of mineral oil, glycerine or aqueous gel) to exclude the air, or
(iii) application through a water-filled rubber or plastic balloon containing water.

The choice of coupling media appears to be important since the energy transmitted by coupling agents in common use appears to vary[9], although Warren et al[10] claim that the difference in transmissivity is only about ±10%.

The objective of ultrasound therapy appears to be to stimulate the blood flow within the injured region, which it appears to do effectively[11], and to provide deep heating to muscles and other tissues. Summer and Patrick[8] claim that the efficacy of ultrasonic therapy is achieved by four specific effects:

(i) Thermal - a temperature rise within the tissue which is proportional to the input power and exposure time. Ultrasound seems to have the advantage that it is absorbed more in muscle than fatty tissue.
(ii) Micromassage - caused by the mechanical reactions of the ultrasound in tissue, such as compressions and dilations.
(iii) Volume reduction - as the ultrasound wave passes through the tissue it produces instantaneous small reductions in volume which are independent of frequency but proportional to the intensity.
(iv) Motion and amplitude - pressure waves set up stress patterns in tissue, producing reciprocal movement of cells.

Lehmann et al[12,13] point out that the main therapeutic value of ultrasound is related to its selectivity of absorption - in soft tissue this absorption is directly related to the protein content of the tissue[14]. Lehmann et al claim that the benefit of ultrasound as a therapeutic agent is that it heats selectively the areas that one requires to be heated, including such areas as superficial bone, scar tissue within soft tissue, tendons and tendon sheaths, etc. Further, that the ultrasound may accelerate the diffusion process across biologic membranes, implying an increased rate of healing.

Although the biological mechanisms of ultrasound therapy have not received systematic investigation, it seems likely that its value lies in the unique heating distribution it provides. There also appears to be some evidence for low-intensity ultrasound induced non-thermal effects which may be important in certain physiotherapeutic applications as the breakdown of fibrous adhesions at the site of an operative incision[15,16].

It is, however, very difficult to assess the benefit of ultrasound therapy, as Roman[17] found. 100 patients were treated or sham irradiated for lower back pain, bursitis of the shoulder and myalgia. Sixty percent of the patients receiving ultrasound were categorized as good or normal, but 72.1% of the unirradiated were in the same category.

Therapy devices have recently been the subject of extensive investigations, both in the United States and Canada[18]. A common conclusion of these surveys has been that most ultrasound therapy devices were not delivering the "dose" prescribed for the patients, errors in measured/indicated acoustic output were found up to ±200%. This has led to federal regulations for ultrasound therapy devices being proposed.

3.3 Surgery

Although ultrasound applications in surgery are highly specialized, they cover a wide range of uses, including the following: the production of lesions in neurosurgery to alter the tissue function at a site in the brain without the disruption of intervening tissue[19], an ultrasonic drill for cleaning blood vessels[20]; the destruction and removal of blood clots[21], gallstones[22] and kidney stones[23]; a vibrating scalpel for cutting biological tissues; as an aid in bone welding[24] and acupuncture[25]. A highly specialized technique, which has become routine in North America for ocular surgery is the phaco-emulsification and aspiration technique for the removal of cataracts[26]. Basically the ultrasound is applied through a hollow titanium needle, the ultrasound breaks up the cataract and the broken pieces are sucked up through the needle.

However, probably the most successful surgical application of ultrasound has been in vestibular surgery for Menière's disease. This disease is due to a disorder of the vestibular end organ which results in attacks of vertigo of varying duration and severity. Treatment involves surgically exposing the lateral semicircular canal and directly applying 3 MHz ultrasound for about 20 minutes. The ultrasound probe tip is placed in contact with the bone over the canal while normal saline flows continuously to provide good coupling. Clinical results indicate that vertigo is abolished in 75%-85% of patients[27].

3.4 Dental

The ultrasonic drill was developed in the early 1960s but never really gained acceptance in dentistry due to the introduction of the high speed rotary drill. However, a number of other applications of ultrasound in dentistry have been steadily growing[28]. These include: cleaning and calculus removal, gingivectomy, root canal reaming, orthodontic filing, amalgam packing and gold foil manipulation. Conventional techniques for these tasks are fairly satisfactory, but there is no doubt that the silence and ease of the ultrasonic method relieves the patient of the stress associated with dental treatment. Frost[29], in 1977, estimated that there may be as many as 100,000 ultrasonic units used in U.S. dental offices for scaling of teeth and periodontal care. However, the cost of this equipment and the general lack of knowledge and training concerning its use, have been responsible for the scarcity of ultrasonic dental instruments in most other parts of the world.

The cavitation effect of ultrasound is used in dentistry for its cleaning power which goes to work on the gums and teeth and their many interproximal crevices. Additionally, ultrasonic massage of gingival tissue assists penetration of antiseptics and other medicines.

3.5 Other Medical Applications

These include ultrasound atomizers[30] (aerosols, nebulizers), where high intensity ultrasound is beamed through a liquid towards an air interface producing a fine dense fog, and gas bubble detection[31] using Doppler ultrasound techniques.

4. Domestic Applications

There are an ever increasing number of consumer-oriented devices being manufactured using ultrasound. Examples of these are quartz clocks, garage door openers, T.V. channel selectors, remote controls, burglar alarms, dog whistles, bird and rodent scarers and traffic control devices. A recent application is use of ultrasound for range-finding on Polaroid cameras. In general, these applications employ low intensities and frequencies at the lower end of the ultrasound range (20-100 kHz). Ultrasound, for these applications, is usually propagated in the air, so that the beam is rapidly attenuated over short distances.

5. Industrial and Commercial Applications

Industrial and commercial applications of ultrasound have been reviewed in a number of reports[32, 33, 34]. Generally these applications can be divided into two categories, high and low power, depending on the power or intensity levels involved. Applications employing higher powers generally rely on compound vibration-induced phenomena occurring in the object or material irradiated. These phenomena include: cavitation and microstreaming in liquids, heating and fatiguing in solids, and the induction of surface instability at liquid-liquid and liquid-gas interfaces. Some of the more common applications of high power ultrasound are shown in Table 2. This table also provides a description of the application and the ultrasound frequency and power or intensity range used, where these parameters are known. One notes that the most practical frequency range for these applications is 20-60 kHz. Most industrial ultrasound is produced using electrostrictive or magnetostrictive transducers[33], where the elements change their physical dimensions in response to an applied electric or magnetic field.

Probably the oldest industrial application is cleaning via cavitation and microstreaming mechanisms. Most cleaning tanks operate at intensities up to 10 W/cm^2, although 2 W/cm^2 is more commonly used. Frequencies are usually between 20-50 kHz. Substantial noise levels are produced by this application due to the violently cavitating liquid.

Plastic welding has become popular in the last 10-15 years, where ultrasound is used in the assembly of toys, appliances, thermoplastic parts. High frequency (above 20 kHz) vibrations at intensities of greater than 20 W/cm^2 produce sufficient heat to melt the plastics at the required locations. The principle advantages of this method are speed, cleanliness, ease of automation, and welds can be accomplished in normally inaccessible places. An interesting recent application is the ultrasonic sewing machine. Here woven or non-woven fibres can be "sewn" together without thread.

Table 2. Low Power Applications of Ultrasound in Industry. Adapted from Lynnworth (32).

Application	Principle	Frequency
Flowmetry	Determining flow rates for gases, liquids and solids - Doppler technique	1 - 10 MHz
Elastic Properties	Relating speed of sound to modes of polerization	25 - 150 kHz
Thermometry	Response to temperature dependence of sound speed or attenuation	Up to 30 MHz
Thickness	Timing round trip interval of beam	2 - 10 MHz
Density, Porosity	Resonant and non-resonant probe transmission	-
Grain size of metals	Ultrasound attenuation	few MHz
Pressure	Frequency of quartz crystal resonator changes with applied pressure	0.5 - 1 MHz
Gas leaks	Detection of ultrasonic "noise"	36 - 44 kHz
Level	Attenuation of ultrasound beam - pulse-echo technique	around 100 kHz
Counting	Beam interruptions counted	40 kHz
Flaw detection	Observe discontinuities in reflected beam	25 kHz to 25 MHz (mW powers)
Delay lines	Transform electric signal into ultrasound and back again after ultrasound has travelled a well-defined path.	-
Burglar Alarms	Ultrasound beamed into room and a certain level of re- flected beam is monitored. If this level changes (with intruder) alarm sounds	18 - 50 kHz (mW powers)
Pest Control	Frequency and intensity of ultrasound bothersome to pests - inaudible to humans	18 - 50 kHz (mW powers)
Sonar	Doppler method determines velocity of object	5 - 50 kHz
Acoustic Microscope	Observe phase shift and at- tenuation of ultrasound beam by the specimen.	Hundreds of MHz

Table 3. Industrial Applications of High Power Ultrasound.

Application	Description	Frequency kHz	Power or Intensity Range
Cleaning and degreasing	Cavitated cleaning solution scrubs parts	18 - 100	Usually below 10 W/cm^2 but up to 100W power
Soldering and braising	Displacement of oxide film to acomplish bonding without flux	Around 30	2 - 200 W/cm^2
Plastic welding	Welding soft and rigid plastic	20-60	Usually 20 - 30 W/cm^2 but power below 1000W output
Metal welding	Welding similar/ dissimilar metals	10-60	Up to 10,000 W/cm^2
Machining	Rotary machining, impact grinding using abrasive slurry, vibration assisted drilling	Usually 20	-
Extraction	Extracting perfume, juices, chemicals from flowers, fruits, plants	Around 20	About 500 W/cm^2
Atomization	Fuel atomization to improve combustion efficiency and reduce pollution; also dispersion of molten metals	20 - 30 000	Up to 800W
Emulsification, dispersion, and homogenization	Mixing and homogenizing of liquids, slurries, creams	-	-
Defoaming and degassing	Separation of foam and gas from liquid, reducing gas and foam content	-	-
Foaming of beverages	Displacing air by foam in bottles or containers prior to capping		
Electroplating	Increases plating rates and produces denser, more uniform deposit	Around 27	30W
Erosion	Cavitation erosion testing, deburring, stripping	-	-
Drying	Drying heat sensitive powders, food-stuff, pharmaceuticals	-	-
Cutting	Cutting small holes in ceramics, glass and semi-conductors	Around 20	About 150W

Metal welding was introduced commercially in the late 1950s in the semi-conductor industry for welding or microbonding miniature conductors. The process involves relatively low temperatures, usually below the melting point of the metal. The welding depends on ultrasonic cleaning. The ultrasound causes mutual abrasion of the two surfaces so that exposed plasticized or metal surfaces can be joined under pressure to form a "solid-state" bond. For this process, very high power densities are needed at the welding tip - of the order of 2000 W/cm^2 at a frequency between 40-60 kHz.

Ultrasound soldering, without fluxes, has also been carried out since the early 1950s. Cavitation in molten solder erodes the surface of metal oxides and exposes the clean metal to the solder so that simultaneous cleaning and tinning of the metal can be effected. The ultrasonic intensities used are up to 100 W/cm^2 at frequencies between 20-50 kHz.

Machining of metals can be carried out using an abrasive slurry between the vibrating tool and the workpiece. Using a rotary machine and an axial ultrasonic vibration, one can machine using diamond impregnated core bits.

Ultrasonic cavitation provides a more rapid cutting action for water cooled core bits. Typically these devices operate at 20 kHz.

In high power applications, the materials being worked are physically changed. This is in contrast to low power applications where the ultrasound is used to examine rather than alter materials. In many cases, these low power applications involve frequencies in the megahertz range as shown in Table 3. Applications not shown in this table include the determination of viscosity transport properties, position phase, thickness, composition, anisotropy and texture from size, stress and strain elastic properties, bubbles, particle and leak detection, non-destructive testing, acoustic emission, imaging and holography, and counting via beam disruption. Much of the equipment used in these applications has intrusive ultrasonic probes, but non-invasive, externally mounted transducers are also used involving both pulsed and resonance techniques.

6. Summary

Ultrasound devices are now used in many fields. In recent years, with the great technological advances that have occurred, there has been significant growth in the number and diversity of ultrasound applications. Figure 1 summarizes the variety of ultrasound devices and applications in use today, an impressive list when considering that the earliest recorded ultrasound source was invented less than 100 years ago. Today the fastest growing ultrasound application is that of diagnostic medicine, although ultrasound applications continue to increase in numbers and usefulness in many areas of industry and medicine.

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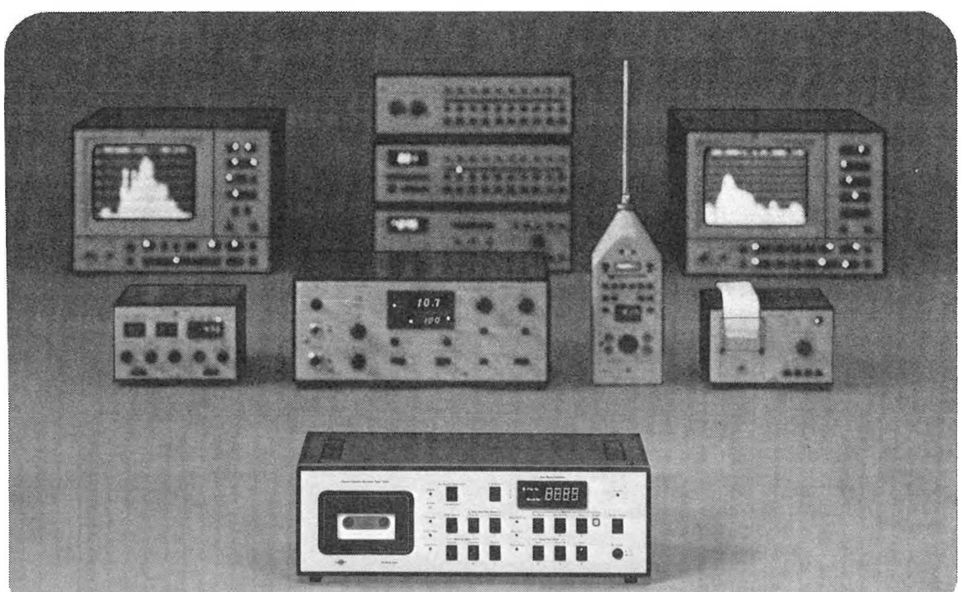

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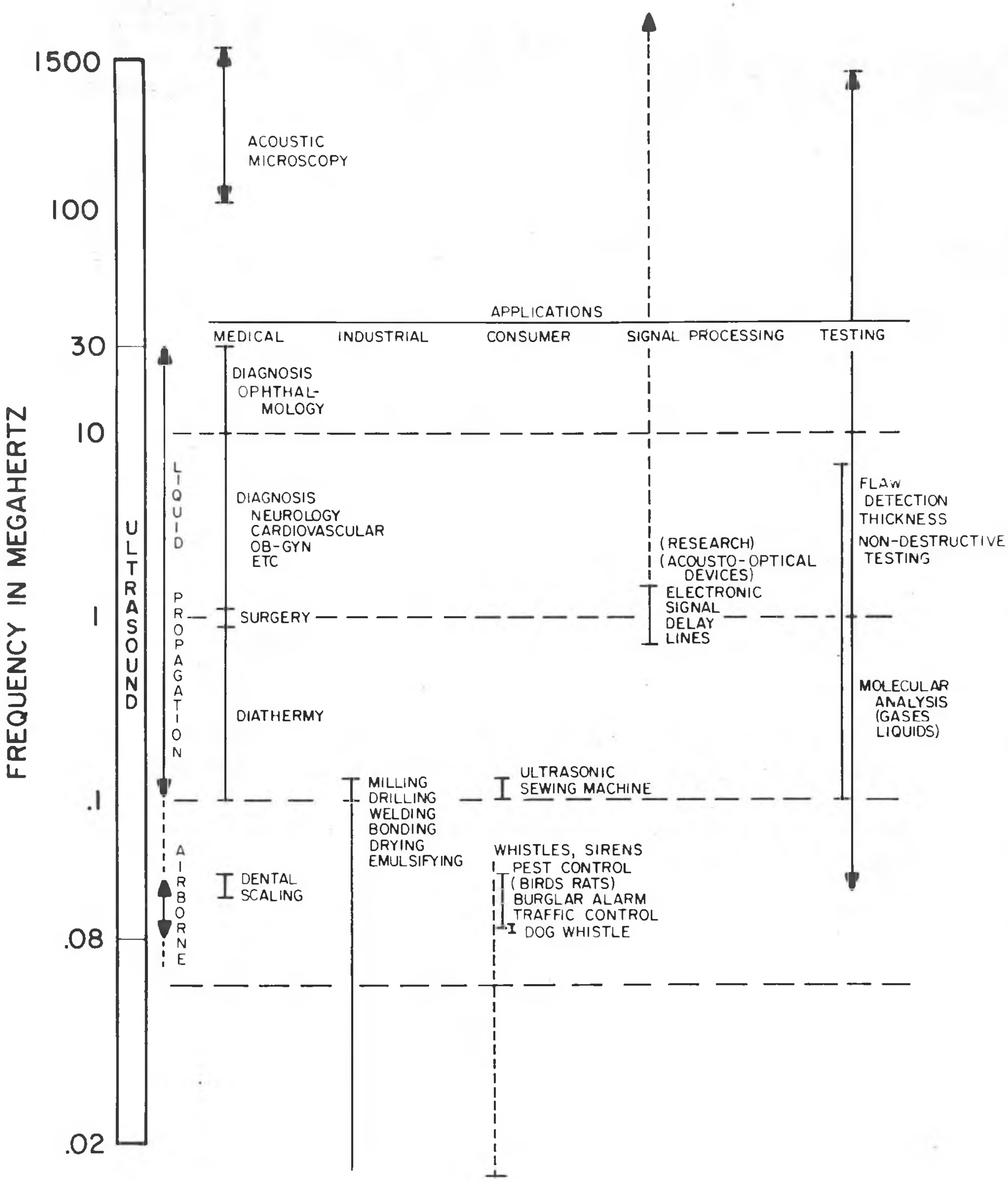
Figure 1. Ultrasound Applications (adapted from Reference 5).



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