Diagnostic Ultrasound

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COVER ILLUSTRATION. Stop-action cross-section of the left ventricle, demonstrating mitral stenosis. The cross-section was made through the long axis of the ventricle during diastole. The fused anterior and posterior mitral leaflets are seen ballooning into the left ventricle. Thickened posterior chordae tendineae are shown connecting the posterior leaflet to the posterior papillary muscle. (From Radiology **103**:387, 1972.)

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Preface

Diagnostic ultrasound has emerged in the past decade as a highly effective and practical tool of great clinical value. Applied by a variety of techniques in different medical disciplines, it often provides diagnostic information not otherwise available without risk or discomfort to the patient. As a consequence ultrasound has become a permanent part of the diagnostic armamentarium and an essential ingredient of high-quality medical care.

This text is based on a series of lectures given at the College of Physicians and Surgeons, Columbia University, in the spring of 1973. Its purpose is to provide a comprehensive survey of the field of diagnostic ultrasound. It is part of a continuing effort by the individuals concerned to inform the medical community of the principles and applications of diagnostic ultrasound and to encourage its appropriate use. It not only reviews accepted, routine applications of diagnostic ultrasound in detail, but also presents several chapters on new or emerging techniques and applications. Hopefully, therefore, it will be useful to individuals already active in the field as well as those just beginning, or seeking an overview.

Lectures and texts cannot provide the student with an exceedingly important aspect of diagnostic ultrasound. They can only hope to impart an awareness of it. That aspect is the high degree of skillful operator interaction required for successful performance of ultrasound examinations. Ultrasound examinations require a "closed-loop" type of evaluation. Performance of an examination must be constantly modified and adapted to the patient and his problem on the basis of information gained during the examination.

Generally, ultrasonic information is not optimally recorded unless it is anticipated, actively elicited, and deliberately depicted. These examinations are not easy to perform and their clinical value is almost completely dependent upon the skill of the examiner. Those beginning in ultrasound are therefore urged not only to learn the appropriate body of knowledge but also to acquire an adequate amount of supervised experience developing the art of diagnostic ultrasound.

Donald L. King

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1 Diagnostic ultrasound: historical perspective

JOSEPH H. HOLMES, M.D.

In contrast to the early acceptance and rapid application of x-rays to medical diagnosis, the development of diagnostic ultrasound has been comparatively slow and beset with technologic difficulties. Progress has depended upon the development of efficient ultrasound transducers, powerful amplifiers, and complex electronic display devices, in a sense paralleling the development of modern electronic technology. Early investigators using ultrasound for diagnostic purposes depended heavily upon equipment and techniques previously developed for industrial or military purposes. Almost uniformly these proved inadequate for medical application. Only after the design of equipment specifically for medical diagnosis was progress rapid and the clinical value of diagnostic ultrasound proved. At present, ultrasonic techniques have assumed in many instances a preferred role in medical diagnosis and have become an essential ingredient of quality medical care.[1]

The first attempts at locating submerged objects with ultrasound probably came after the sinking of the Titanic in 1912. During World War I Langevin and associates[2] sought to utilize ultrasound for the detection of submarines. Improved technology led to the development and widespread military and civilian use of sonar (*so*und *n*avigation *a*nd *r*anging). Simultaneously, the industrial materials flaw detector[3-5] was developed. During the same period of time, just prior to World War II, Dussik[6] attempted the first application of ultrasound to medical diagnosis. He sought to visualize the cerebral ventricles by measuring attenuation of an ultrasound beam transmitted through the head. Unfortunately, variations in attenuation caused by the skull proved to be more significant than variations caused by the ventricular system, and the technique was abandoned.

Diagnostic ultrasound received its greatest stimulus from the World War II development of sonar and radar. The combination of advanced radar circuitry with sonar technology greatly improved ultrasonic instrument performance. Utilizing available industrial and war surplus equipment, several investigators began simultaneously to explore the medical applications of reflected ultrasound and to design and develop ultrasound instruments specifically for medical diagnosis. Among the earliest and most prominent of these were Douglass Howry and John Wild, the pioneering developers of ultrasonic imaging beginning in the late 1940's. In the early 1950's Leksell and Edler discovered and developed, respectively, the techniques of echoencephalography and echocardiography. Subsequently, many others undertook the investigation of ultrasonic techniques for medical application. Outstanding among them were Baum, who developed two-dimensional imaging of the eye, and Donald, who developed the first contact compound scanner and pioneered its application in the field of obstetrics and gynecology.

Douglass Howry is credited with being one of the truly far-seeing pioneers of diagnostic ultrasound. He was awarded a Certificate of Recognition of the American Institute of Ultrasound in Medicine in 1956, the Gold Medal Award for Outstanding Research of the American Medical Association in 1957, the Medal of Honor of the Radiological Society of North America in 1957, as well as the University of Colorado Recognition Award for Outstanding Research.[7] Howry (Fig. 1-1) began his efforts at ultrasonic visualization of soft tissues in 1947, while an intern at the Denver General Hospital, shortly after graduation from the University of Colorado School of Medicine.[8] During 1948 and 1949 he collaborated with Dr. W. Roderic Bliss, an engineer, in the construction of a successful pulse-echo

Fig. 1-1. Dr. Douglass H. Howry (1920-1969). Dr. Howry pioneered the compound scanning concept for ultrasonic imaging of the soft tissues. (Courtesy Mrs. Douglass Howry.)

system. The system utilized surplus Navy sonar equipment, a radar amplifier, a Heathkit oscilloscope, and a high-fidelity recorder power supply. During the fall of 1950, while a resident in radiology at the Denver Veterans Administration Hospital, he and Dr. Bliss produced their first cross-sectional ultrasonic images. During 1951 Howry developed the principle of compound scanning—the combination of circular, angular, or linear scanning patterns—to improve image quality. The scans were made with the transducer immersed in water, the latter transmitting the sound waves to the object being examined. Initially a laundry tub was used for this purpose. Later they used a metal cattle watering trough with the transducer running along hardwood rails attached to the side of the tank. At this time significant improvement in image quality was also achieved by the use of a lithium sulfate monohydrate transducer, grown in a tank specially con-

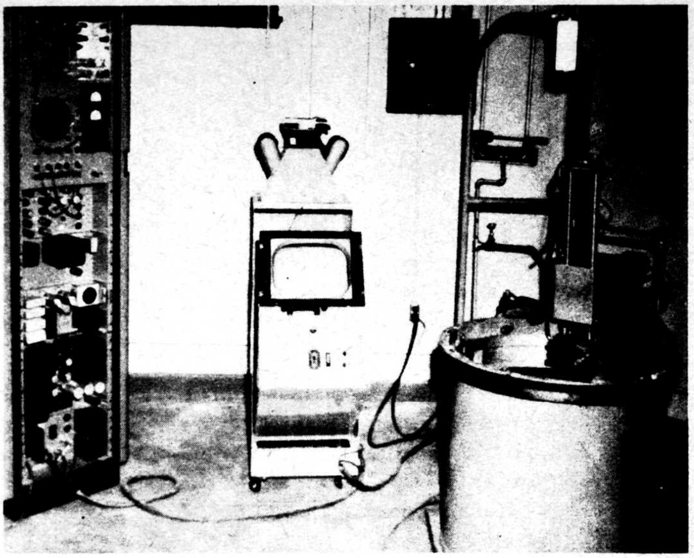

Fig. 1-2. Circular water-path scanner developed by Dr. Howry at the University of Colorado. On the right is the scanning tank. The display system with Polaroid camera is shown in the center. The electronic circuits are mounted in the rack to the left. (From Howry, D. H.: Radiol. Clin. North Am. 3:433-452, 1965.)

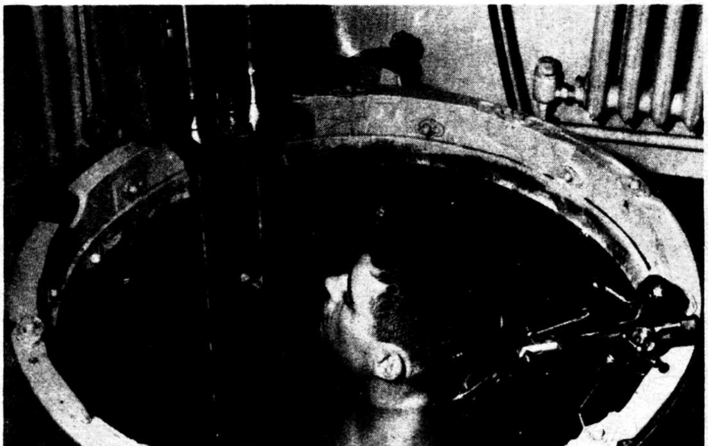

Fig. 1-3. Scanning position for transverse cross-section of the neck. The 2½-inch focused transducer is seen just below the water level. The transducer carriage travels around the tank on the outside track.

structed for this purpose. In 1952 the first publication by Howry and Bliss appeared in the *Journal of Laboratory and Clinical Medicine.*[9]

By 1954 the third generation of Howry's "Somascope" (Fig. 1-2) was constructed under the supervision of Drs. Howry and Holmes.[10,11] The scanning tank (right) was originally a B-29 gun turret. The transducer carriage was mounted on a metal ring, immersed in water, and rotated 360 degrees around the tank. During rotation of the carriage around the tank the 2½-inch focused transducer moved back and forth across the carriage in a 4-inch linear scan. The combined linear and circular motions produced a compound scan in a plane of cross-section parallel to the surface of the water. The patient under examination sat in the tank holding lead weights to maintain his position (Fig. 1-3). The echoes received were displayed as intensity-modulated dots in their appropriate orientation on the large screen and photographed by the camera mounted above it. A long persistence phosphor screen was used and provided a form of gray scale to record variations in echo intensity. One of the most successful images made with this apparatus,[12] a cross-section of the neck, is shown in Fig. 1-4. In this illustration can be seen the outlines of the neck muscles, the carotid arteries and jugular veins, the larynx, and the vocal cords.

Additional examples of the outstanding performance obtained with this apparatus, in many instances yet to be surpassed, are presented in Howry's review article.[8]

By the 1960's a series of studies on animals was also carried out to verify the anatomic accuracy of the ultrasonic pictures.[13] The animals were scanned in the water tank, overdosed with anesthesia, the bodies then frozen, and comparable anatomic cross-sections obtained. Fig. 1-5 shows a transverse cross-section of a dog urinary bladder. The echo pattern of the spine and lumbodorsal muscle groups is seen at the top. The circular structure (center) is the distended urinary bladder, while the flank folds and penis are at the bottom. The group of echoes within the bladder arises from the intravesicle catheter. Upon release of the catheter and drainage of the bladder, the circular outline of the bladder collapses. Fig. 1-6 shows a transverse cross-section of a cat liver in which an abscess was produced by injection of a suspension of *Escherichia coli* and turpentine. The spine and dorsal muscle groups are outlined at the top. The circular ring of echoes to the right arises from the stomach. Left of this, within the otherwise echo-free liver, are multiple irregular echoes produced by the hepatic abscess (arrow). The location of these echoes corresponded to the site of the abscess at autopsy.

Although excellent results were obtained with the circular water-path scanner, seri-

Fig. 1-4. Transverse scan of the neck. The black central area represents the cervical vertebra. Posteriorly (at bottom) can be seen the outlines of the various muscle groups. Anterolaterally on either side are two small circular structures, the carotid artery and jugular vein. Anteriorly (top) are echoes representing the larynx and vocal cords. (From Howry, D. H.: Radiol. Clin. North Am. **3**:433-452, 1965.)

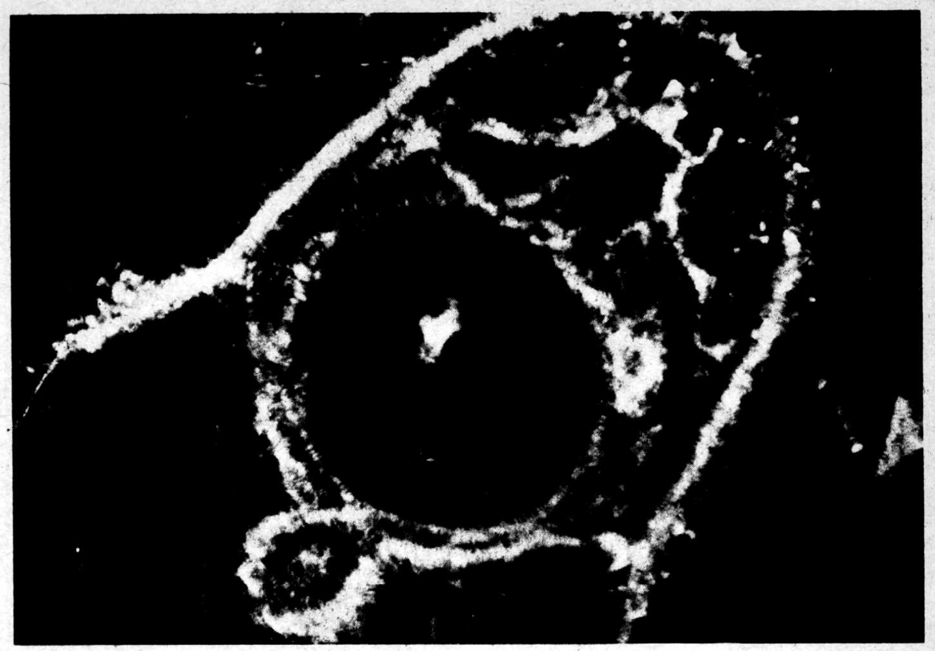

Fig. 1-5. Transverse cross-section of dog urinary bladder. (From Holmes, J. H.: Am. J. Dig. Dis. **8**:12, 1963.)

Fig. 1-6. Transverse cross-section of cat liver following creation of hepatic abscess (arrow). (From Holmes, J. H., and Howry, D. H.: Am. J. Dig. Dis. **8**:12-32, 1963.)

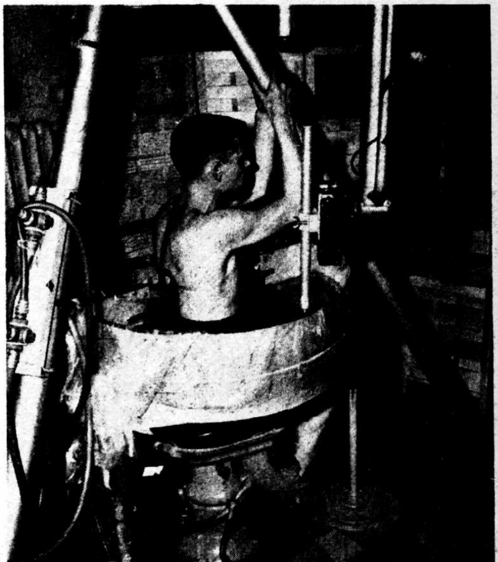

Fig. 1-7. Semicircular water-path scanner. (From Holmes, J. H., and Howry, D. H.: Am. J. Dig. Dis. **8**:12-32, 1963.)

ously ill patients could not be examined with it, and the technique was too cumbersome for routine clinical use. These difficulties were partly circumvented by construction of a modified water-path scanner (Fig. 1-7), using a semicircular tank with a rectangular window cut into its flat surface. The tank was lined with heavy plastic and the patient positioned against the plastic in a sitting position. A modified dental chair was used that could be easily raised or lowered to obtain serial cross-sections at multiple levels. The transducer carriage was suspended from an overhead tripod and rotated through a 140-degree path. Excellent images could be obtained with this system (Fig. 1-8); however it also was cumbersome for use on very sick patients and pregnant women. Therefore, in 1960 design of a contact scanner was begun.[14]

The instrument, completed in 1962, is shown in Fig. 1-9. The scanning carriage was suspended from an overhead framework. The vertical, horizontal, and angular movements of the carriage were hand-controlled. The motor-driven transducer inside the carriage moved in a sector scan 30 degrees to each side of perpendicular. A plastic shoe in contact with the skin prevented the transducer from digging into the patient. A typical cross-section obtained with this instrument is shown in Fig. 1-10. Utilizing this scanner, extensive obstetric and gynecologic studies were initiated by Thompson[15] and Gottesfeld.[16] Subsequently, a completely hand-operated con-

Fig. 1-8. Transverse cross-section of the kidney obtained with the semicircular water-path scanner. Skin surface is at the top. The renal cortex appears echo-free. Centrally are echoes from the vessels and collecting system.

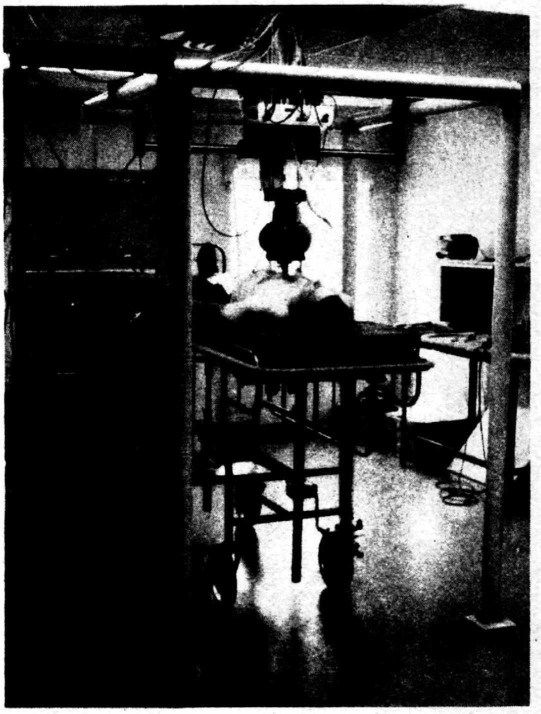

Fig. 1-9. Compound contact scanner developed at the University of Colorado, 1960-1962. The electronics and display oscilloscopes are in the rack at the left.

Fig. 1-10. Transverse cross-section of the liver made by the compound contact scanner, viewed looking toward the feet. Note echoes from the porta hepatis *(PH)* and falciform ligament *(FL)*. *LL*, Left lobe; *RL*, right lobe; *RT*; right; *LT*, left.

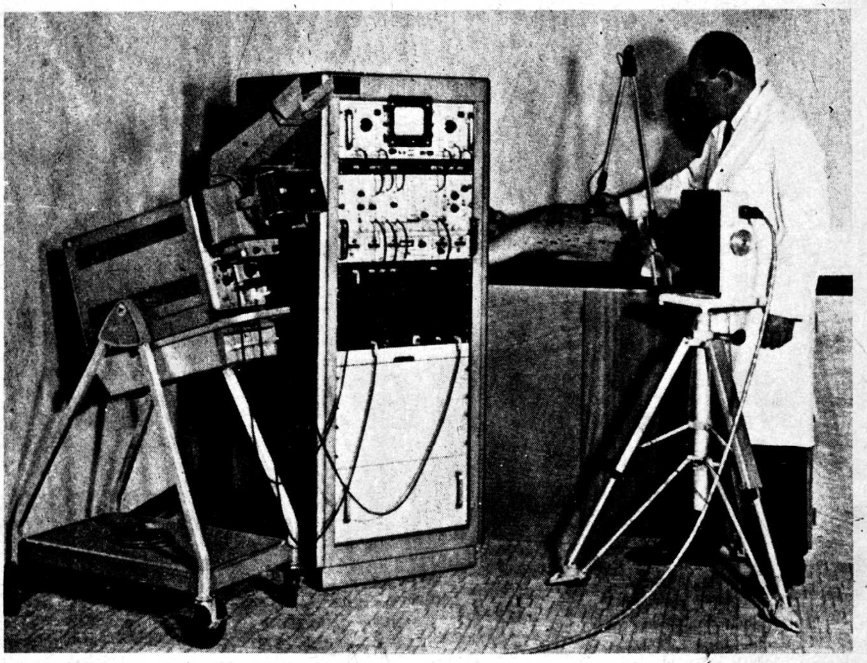

Fig. 1-11. First commercial ultrasonic scanner manufactured in the United States of America. The pivot-arm scanner is mounted on a tripod at the right. The electronics and display oscilloscope are in the rack and cart at the left. The three-jointed arm scanner remains a widely utilized design concept. (Courtesy Picker Corp.)

tact scanner (Fig. 1-11) was designed by William L. Wright, an engineer working with the University of Colorado research group. It became the first commercial scanner marketed in the United States. The design concepts incorporated in this scanner remain in widespread use today.

John J. Wild (Fig. 1-12) was also one of the earliest pioneers in the development of diagnostic ultrasound. He is credited with demonstrating that ultrasound could detect differences between normal tissues, benign tumors, and malignant cancers.[17] He began his investigations in 1949 with the cooperation of the Naval Air Station, Wold-Chamberlain Field, Minneapolis, Minnesota. He and his co-workers utilized equipment modified from a naval ultrasonic trainer. His first tissue studies were done on pieces of intestine and showed that different echo patterns could be obtained from each of the different layers of the specimen.[18] Other studies revealed the ability of ultrasonic echo pattern to differentiate cerebral neoplasms from surrounding normal brain tissue.[19]

At this time Dr. John Reid, an engineer, began work with Dr. Wild on the development of a two-dimensional scanning system.[20,21] Fig. 1-13 is their first published example of an ultrasonographic cross-section of the breast.[22,23] The one-dimensional A-mode records of the normal breast and breast with tumor are shown in *A*, while in *B* are the corresponding two-dimensional cross-sections.

Fig. 1-14 shows a close-up view of the transducer designed by Dr. Wild for scanning the breasts. A sloping plastic chamber

Fig. 1-12. Dr. John J. Wild. Dr. Wild's early investigations demonstrated the ability of ultrasound to differentiate different types of tissue. (Courtesy Dr. John J. Wild).

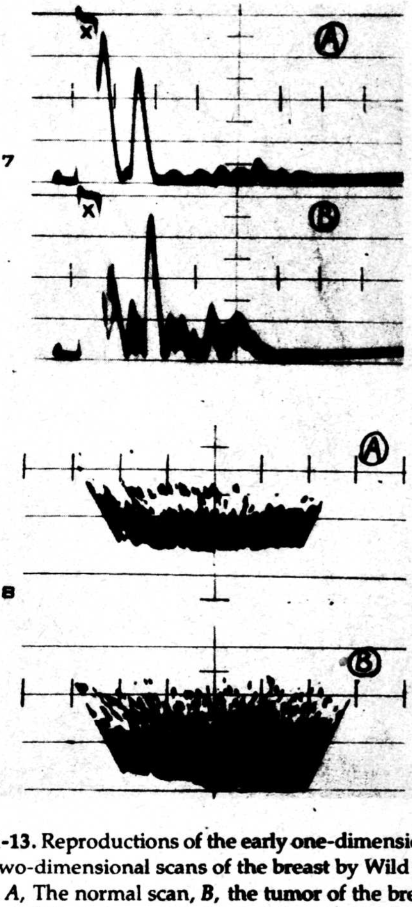

Fig. 1-13. Reproductions of the early one-dimensional and two-dimensional scans of the breast by Wild and Reid. *A*, The normal scan, *B*, the tumor of the breast. (From Wild, J. J., and Reid, J. M.: Am. J. Pathol. 28:839-861, 1952.)

with its smaller end covered with a rubber diaphragm is applied directly over the breast and sonic contact achieved by use of aqueous jelly. The transducer moves back and forth within the plastic chamber to provide the scanning motion. By 1956, after studying a series of seventy-seven patients with suspected breast abnormalities, Wild and Reid reported a 90% accuracy in the diagnosis of benign versus malignant lesions.[24] While his success at diagnosis of breast cancer awaits confirmation, Wild's greatest contribution, the demonstration that ultrasound could differentiate between normal and malignant tissue, has served as a constant stimulus for the improvement of ultrasonic techniques and instrumentation.

Ian Donald is largely responsible for the development of the contact scanning concept and for pioneering the extensive application of ultrasonic imaging in obstetrics and gynecology. In 1954, while in London, he met Dr. Wild and learned of his early work in diagnostic ultrasound. Donald began his own investigations with ultrasound shortly thereafter in Glasgow. His initial experiments utilized an ultrasonic metal flaw detector. With this he examined excised uterine fibromyomata and ovarian tumors and found that the echo patterns reflected from the specimens demonstrated distinct differences. With this encouragement he began clinical evaluation of patients.* The ultrasonic flaw detector available to him at that time could only operate successfully through a water-filled tank at some distance from the patient's skin. The tank used was a flexible latex rubber bucket. The difficulties presented by this arrangement led to his consideration of various alternatives and ultimately to the development of the contact scanner.

In 1955, Mr. Tom Brown, an engineer at the Research and Development Department, Kelvin and Hughes, Ltd., began his long association with Professor Donald. During the next 2 years they designed and constructed a prototype hand-operated, two-dimensional contact scanner.[25] The principle of contact scanning is now almost universally used clinically for ultrasonic imaging of the pelvis and abdomen. The primary advantage of contact scanning

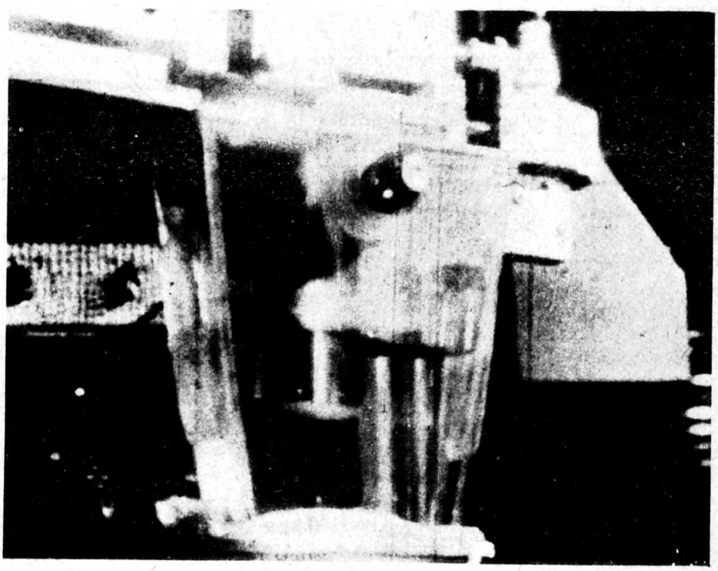

Fig. 1-14. Close-up photograph of Wild and Reid's early breast scanner.