

EVALUATION OF CALCIFICATION DETECTABILITY IN FEMALE BREASTS BY ULTRASOUND*

L. FILIPCZYŃSKI, T. KUJAWSKĄ, G. ŁYPACEWICZ

Ultrasonic Department, Institute of Fundamental Technological Research, Polish Academy
of Sciences (00-049 Warsaw, Świętokrzyska 21)

The authors investigated detectability of calcifications by means of shadow and echo methods for 5 MHz frequency. Computing the ultrasonic field distribution around a rigid sphere they determined the shadow range and hence the detectability condition for calcification diameter $\phi \geq 3$ mm. For the echo method former investigations were continued improving the measurement technique and expanding the analysis. To determine the tissue signal background level measurements were performed on 82 breasts of healthy premenopause women. The boundaries of various tissues and inhomogeneities within cause interfering background and its level limits the detectability. The measurement results, confirmed statistically, were used for detectability determination in normal breast tissues (attenuation 1.1 dB/cm·MHz). The calculations show that the minimum diameter of a detectable calcification $\phi = 0.4$ mm for a normal breast. JACKSON et al. [18] and KASUMI [19,20] have demonstrated calcifications 0.1–0.5 mm in dia with frequencies of 4 and 7.5 MHz. These results are in general agreement with our theory if one takes into account the high (SD = 8 dB) scattering of the signal background measurement results. When detecting calcifications in the tumor anechoic area one obtains stressing of fine calcification echoes, thus increasing the detectability when comparing with the case of healthy breast tissues.

Autorzy przeprowadzili badania wykrywalności zwapnień za pomocą metody ultradźwiękowej cienia i echa przy częstotliwości 5 MHz. Na podstawie rozkładu pola ultradźwiękowego wokół sztywnej kuli wyznaczyli długość cienia, a na tej podstawie warunek wykrywalności dla zwapnień o średnicy $\phi = 3$ mm. W przypadku metody echa, kontynuując poprzednie badania, autorzy ulepszyli technikę pomiarową i rozszerzyli analizę. W celu wyznaczenia tła poziomu zakłóceń tkankowych przeprowadzili pomiary na 82 piersiach zdrowych kobiet przed menopauzą. Granice różnych rodzajów tkanek piersi oraz ich wewnętrzne niejednorodności tworzą zakłócające tło, którego poziom ogranicza wykrywalność zwapnień. Wyniki pomiarów, potwierdzone statystycznie, wykorzystano do wyznaczania wykrywalności w normalnych piersiach (współczynnik tłumienia 1.1 dB/cm·MHz). Obliczenia wykazały, że minimalna średnica wykrywalnego metodą echa

* The main thesis of the paper were presented during the VI-th International Congress on the Ultrasonic Examination of the Breast. Paris, 29–30 June 1989 [10].

zwapnienia wynosi $\phi = 0.4$ mm. W przypadku piersi normalnych JACKSON et al. [18] oraz KASUMI [19,20] wykrywali w warunkach klinicznych zwapnienia o średnicach 0.1–0.5 mm przy częstotliwościach 4 i 7.5 MHz. Wyniki te są zasadniczo zgodne z naszą teorią, jeśli uwzględnić duży rozrzut pomiarów tła zakłócającego (odch. stan. 8 dB). Gdy zwapnienia znajdują się w obszarze nowotworu pozbawionym wewnętrznych ech, wtedy zwiększa się wykrywalność drobnych zwapnień w porównaniu do przypadku zdrowych tkanek piersi.

Key words: Breast, ultrasound, calcification, shadow, echo

1. Introduction

The ultrasonic echo method is one of the methods for detecting breast cancer. Even at an early phase of the disease, reactions in tissue cells cause microcalcifications to emerge as it can be seen in a mammogram or an X-ray microframe preparation [22]. They usually occur prior to the infiltration phase and as the disease proceeds, the microcalcifications sometimes reach quite considerable size.

Calcifications contain not only calcium but also phosphorus and many elements such as chlorine, sulfur and various metals. However, probably the particles seen on mammograms, ~ 0.1 mm and larger, contain mainly calcium and perhaps phosphorus. The other particles not containing calcium are too small to be imaged on present state-of-the-art X-ray mammograms [11, 12].

Clinical investigations of breast microcalcifications are based on X-ray mamography. Recently some authors [18–20] successfully detected microcalcifications in some kind of breast tumors by means of ultrasonography. However, diffuse microcalcifications in the breast tissue outside of masses, were not recognized, and if ultrasonography is to be used in the future as a screening modality, visualization of microcalcifications is essential [18].

The purpose of this study was to analyze the detectability of single small calcifications in female breasts and to answer the question as to what are detectability limits if one uses the ultrasonic shadow and echo methods at a typical frequency of 5 MHz. Thus the former, investigations of the present authors [9] were partially revised and continued by improving the measurement technique and expanding the analysis.

2. The shadow method

In this method one observes a shadow which occurs behind the calcification. The authors did not find papers describing comprehensively the shadow behind a spherical body. Computing the ultrasonic field distribution around a rigid sphere assumed as the calcification model it was possible to determine the shadow range $r_{-6\text{dB}}$ as a function of the sphere diameter ϕ and the wavelength [7, 8]

$$r_{-6\text{dB}} = 0.9\phi^2/\lambda \quad (1)$$

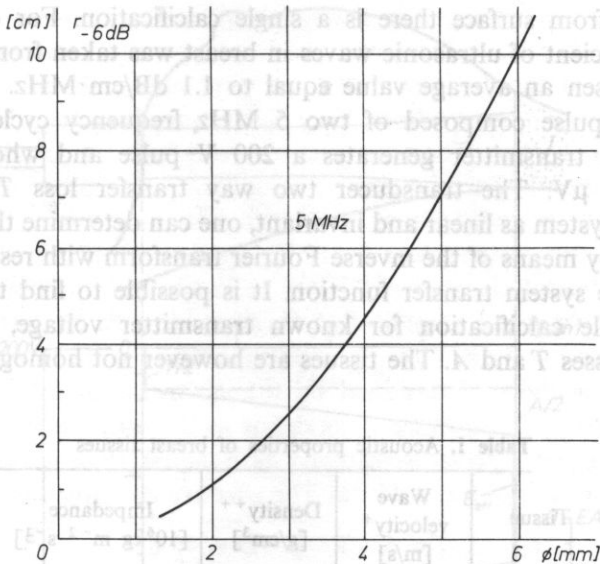


FIG. 1. The shadow range r_{-6dB} as a function of the calcification diameter ϕ calculated for the frequency 5 MHz from the formula 1

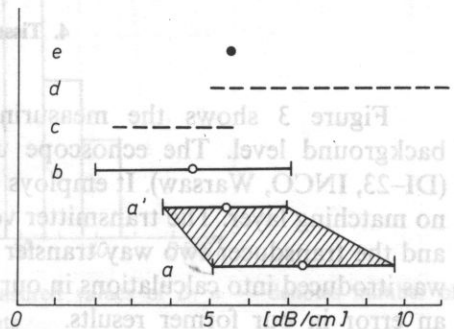
which was found to be valid for continuous wave and for the ka parameter between 12 and 630 ($k = 2\pi/\lambda$, $a = \phi/2$). The 6dB drop in respect to the pressure of the incident plane wave was assumed to correspond to the shadow range. Figure 1 shows the calculated shadow range for the frequency of 5 MHz.

It follows from this Figure that for obtaining a 2.5 cm long shadow the diameter of the calcification should be equal to 3 mm. The obtained result should be considered as the first approximation of the problem.

3. The echo method

For the echo method former investigations [9] were continued improving the measurement technique and expanding the analysis. We assume that inside a breast

FIG. 2. Attenuation coefficients in normal breast measured or assumed by various authors. Points denote mean value, rods — standard deviation, dashed lines — variation range. a, a' — after measurements of D'ASTOUS and FOSTER [4], calculated for various ratios of parenchyma to fat content, b — after measurements of CALDERON et al. [3] extrapolated for 5 MHz, c — after supposition of GREENLEAF and BAHN [13], d — after measurements of BAMBER [1], e — assumed by the authors of this paper



at a distance r' from surface there is a single calcification. For our analysis the attenuation coefficient of ultrasonic waves in breast was taken from literature (Fig. 2). We have chosen an average value equal to 1.1 dB/cm·MHz. We assumed an ultrasonic wave pulse composed of two 5 MHz, frequency cycles, produced by a scanner whose transmitter generates a 200 V pulse and whose receiver has sensitivity of 10 μ V. The transducer two way transfer loss T equals 15 dB. Recognizing the system as linear and invariant, one can determine the pulse reflected from the sphere by means of the inverse Fourier transform with respect to the pulse spectrum and the system transfer function. It is possible to find the radius of the smallest detectable calcification for known transmitter voltage, receiver electric sensitivity and losses T and A . The tissues are however not homogeneous (Table 1).

Table 1. Acoustic properties of breast tissues

Tissue	Wave velocity ⁺ [m/s]	Density ⁺⁺ [g/cm ³]	Impedance [10 ⁶ kg m ⁻² s ⁻¹]
Pectoralis muscle	1545	1.07	1.7
Muscle			
Connective	1545	0.92	1.4
Grandular	1550		
Fat	1470		

⁺ KOSSOFF et al. [21].

⁺⁺ WELLS [26].

and in the case of a breast the boundaries of fat, connective, gland and muscle tissues and inhomogeneities within cause interfering signals to mask echoes from small calcifications. These signals form the interfering background, and it is the level of this background, rather than that of the scanner sensitivity which limits the detectability of small calcifications.

4. Tissue background level

Figure 3 shows the measuring principle for determination of the tissue background level. The echoscope used was once designed for materials testing (DI-23, INCO, Warsaw). It employs a 5 MHz plane 5 mm diameter transducer with no matching layer. The transmitter voltage was 200 V, the receiver sensitivity 10 μ V, and the transducer two way transfer loss was $T = 30$ dB. The value of 15 dB which was introduced into calculations in our older paper [9] was erroneous thus introducing an error in our former results.

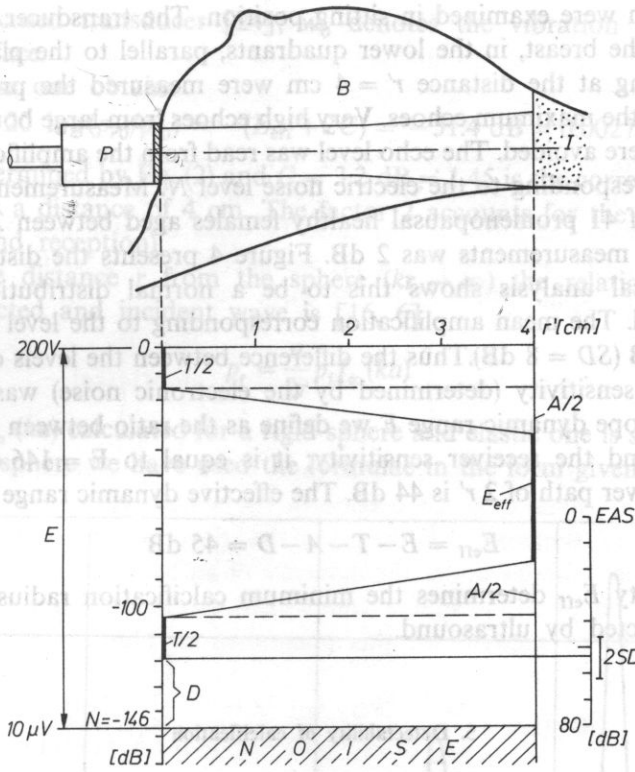


FIG. 3. The principle of determining the level of masking tissue echoes in the breast B showing all signal losses on the way from the probe P to idealized reflectors I and backwards. E — echoscope dynamic range, T — transducer two way transfer loss, A — attenuation loss, N — electric noise level, EAS — echoscope amplifications scale, SD — standard deviation, E_{eff} and D — see the text

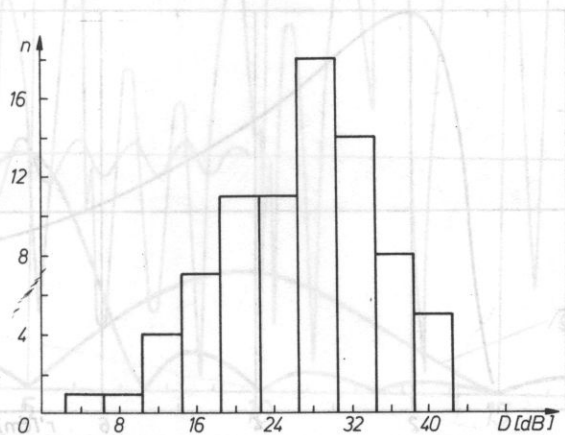


FIG. 4. The histogram showing the distribution of measured values of D . n — denotes number of measurements

The women were examined in sitting position. The transducer was applied at the bottom of the breast, in the lower quadrants, parallel to the plane of the ribs. Echoes occurring at the distance $r' = 4$ cm were measured the probe inclination being to obtain the maximum echoes. Very high echoes from large boundary surfaces of two tissues were avoided. The echo level was read from the amplification scale, the 80 dB level corresponding to the electric noise level N . Measurements were carried on 82 breasts of 41 promenopausal healthy females aged between 20 and 50. The accuracy of the measurements was 2 dB. Figure 4 presents the distribution of the results. Statistical analysis shows this to be a normal distribution at an 0.05 significance level. The mean amplification corresponding to the level of echoes from tissue was 53 dB ($SD = 8$ dB). Thus the difference between the levels of tissue echoes and echoscope sensitivity (determined by the electronic noise) was $D = 27$ dB.

The echoscope dynamic range E we define as the ratio between the transmitter pulse voltage and the receiver sensitivity; it is equal to $E = 146$ dB. The tissue attenuation A over path of $2 r'$ is 44 dB. The effective dynamic range (Fig. 3) is thus

$$E_{\text{eff}} = E - T - A - D = 45 \text{ dB} \quad (2)$$

The quantity E_{eff} determines the minimum calcification radius which can be potentially detected by ultrasound.

5. Detectability of calcification

The value of E_{eff} would correspond to the ratio of the reflected wave to that of the incident one, if the beam were parallel and the reflecting object were plane. In the case of a sphere which is small with respect to the beam diameter, one must consider the relative pressure distribution on the beam axis $p_0(r')/pcw_0$ as shown in Fig. 5 for

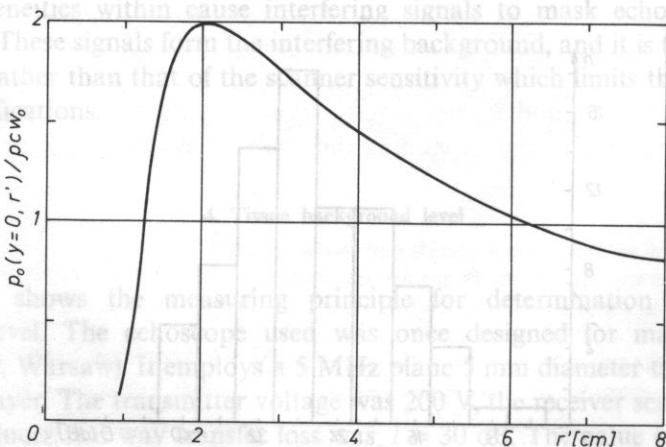


FIG. 5. The relative acoustic pressure amplitude calculated along the beam axis of a plane disc transducer used in measurements

a plane nonfocused transducer [24]; w_0 denotes the vibration velocity on the transducer surface.

In this case one obtains

$$20 \log(p_{r0}/p_{i0}) = -(E_{\text{eff}} + 2C) = -51.4 \text{ dB} \approx 0.0027 \quad (3)$$

where E_{eff} is determined by Eq. (2) and $C = 3.2 \text{ dB} \approx 1.45$ is the correction coefficient from Fig. 9 for a distance of 4 cm. The factor 2 accounts for the double gain (in transmission and reception).

At a large distance r from the sphere ($kr \rightarrow \infty$) the relation between the backward reflected and incident wave is [16, 6]

$$p_r = \frac{a}{2r} p_i f_\infty(ka) \quad (4)$$

The modulus $f_\infty(ka)$ calculated for a rigid sphere and elastic one is shown in Fig. 6. For the elastic sphere we have used the formulae in the form given by HASEGAWA

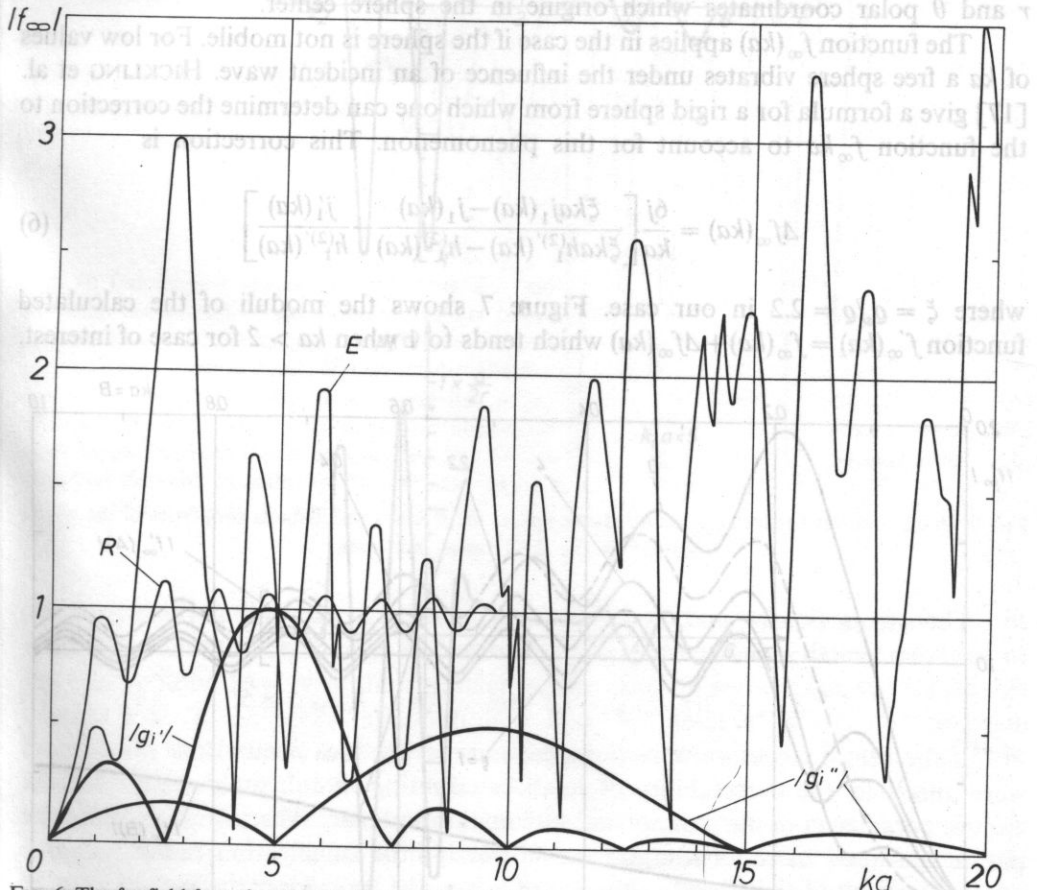


FIG. 6. The far field form function f_∞ for backward reflection from a rigid (R) and an elastic (E) sphere with the Poisson's ratio $\nu = 0.2$; g_i' , g_i'' — spectra of the two-cycle sinusoidal pulse for $ka = 5$ and 10 , respectively

[14] and HASEGAWA et al. [15]. We assumed that the calcification had the mechanical properties of skull with density $\rho_s = 2.2 \text{ g/cm}^3$ and compressional wave velocity $c_1 = 3.2 \text{ km/s}$ [25]. The Poissons' ratio was assumed as most probable to be $\nu = 0.2$.

One can determine the pulse reflected from the sphere by means of the inverse Fourier transform with respect to the spectrum $g_1(ka)$ and the system transfer function. We define the latter as the ratio between the reflected and the incident harmonic waves [5]. From formula (4) we have for $kr \rightarrow \infty$ the pulse backward reflected from the sphere ($\theta = \pi$) in the form

$$p_r(\tau) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{a}{2r} f_\infty(ka) g_i(ka) \exp(jk\alpha\tau) d(ka) \quad (5)$$

where $\tau = (ct - r \cos\theta)/a$ is dimensionless time, c is the wave velocity in breast tissue r and θ polar coordinates which originate in the sphere center.

The function $f_\infty(ka)$ applies in the case if the sphere is not mobile. For low values of ka a free sphere vibrates under the influence of an incident wave. HICKLING et al. [17] give a formula for a rigid sphere from which one can determine the correction to the function $f_\infty ka$ to account for this phenomenon. This correction is

$$\Delta f_\infty(ka) = \frac{6j}{ka} \left[\frac{\xi ka j_1(ka) - j_1(ka)}{\xi ka h_1^{(2)'}(ka) - h_1^{(2)'}(ka)} - \frac{j_1'(ka)}{h_1^{(2)'}(ka)} \right] \quad (6)$$

where $\xi = \rho_s/\rho = 2.2$ in our case. Figure 7 shows the moduli of the calculated function $f'_\infty(ka) = f_\infty(ka) + \Delta f_\infty(ka)$ which tends to 1 when $ka > 2$ for case of interest.

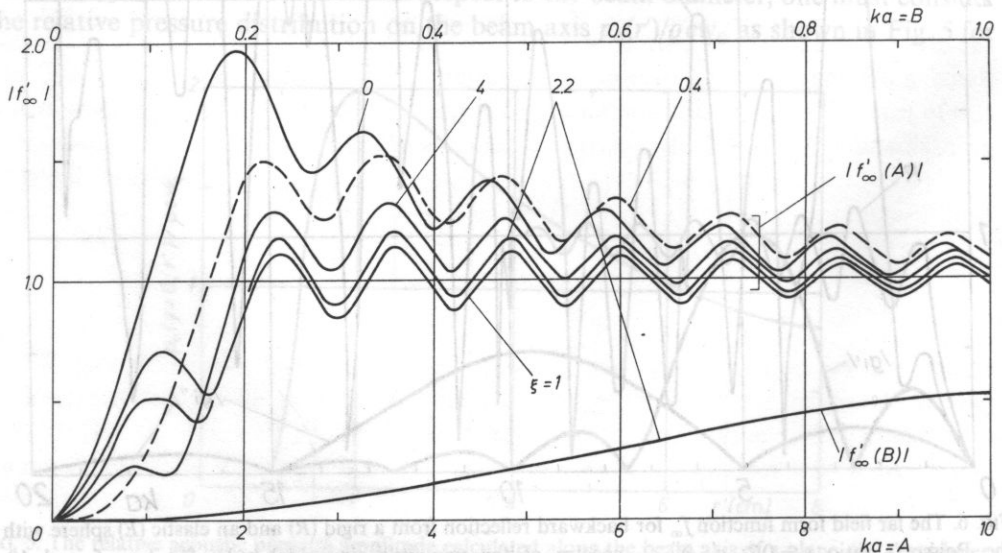


FIG. 7. The function $f_\infty(ka)$ for a movable rigid sphere at various ratios of densities $\xi = \rho_s/\rho$, (ρ_s and ρ denote densities of the sphere and surrounding tissue, respectively)

Figure 8 shows the ultrasonic pulses reflected from a rigid sphere, as given by Eqs. (5), (6). The reflected waveforms resemble the incident pulse and there is negligible difference between the immobile and the free sphere. Because of this, one may assume approximately that elastic spheres do not move either, and one can apply for this case an analogous theory of wave reflection.

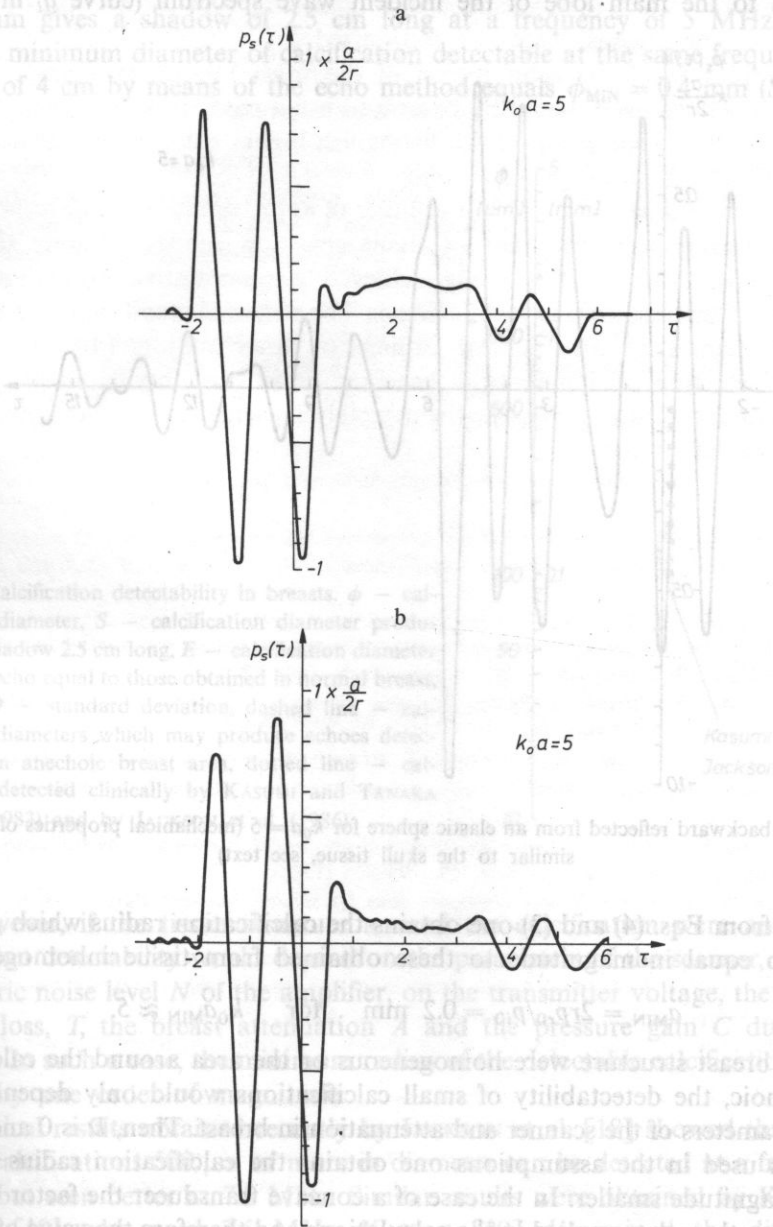


FIG. 8. Pulses backward reflected from rigid spheres for $k_0 a = 5$, a) movable sphere b) immovable sphere. Very small pulses are caused by creeping waves

Figure 9 presents the ultrasonic pulse reflected from an elastic sphere. One can notice much longer duration time of the reflected pulse and some oscillations of its amplitude. For a rigid sphere one can assume $f_{\infty}(ka) = 1$. This condition can be also assumed for an elastic sphere though the approximation is not so good in this case. One should take into consideration those sections of the curves R and E which correspond to the main lobe of the incident wave spectrum (curve g_i in Fig. 6).

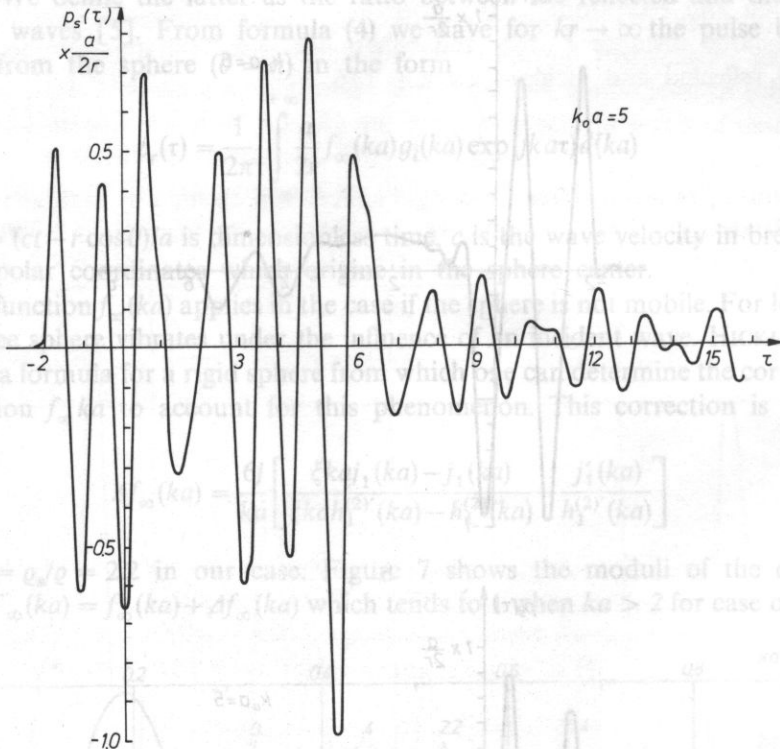


FIG. 9. Pulse backward reflected from an elastic sphere for $k_0 a = 5$ (mechanical properties of the sphere similar to the skull tissue, see text)

Then, from Eqs. (4) and (3) one obtains the calcification radius which gives rise to an echo equal in magnitude to these obtained from tissue inhomogeneities

$$a_{\text{MIN}} = 2rp_{r0}/p_{i0} = 0.2 \text{ mm} \quad \text{for} \quad k_0 a_{\text{MIN}} \approx 5. \tag{7}$$

If the breast structure were homogeneous or the area around the calcification were anechoic, the detectability of small calcifications would only depend on the electric parameters of the scanner and attenuation in breast. Then, D is 0 and, for the parameters used in the assumptions one obtains the calcification radius a_{min} one order of magnitude smaller. In the case of a concave transducer the factor C can be much greater than that applied in the calculations and therefore the value of a_{min} can be even smaller.

6. Discussion and conclusions

The obtained results are presented in Fig. 10.

The calcification detectability of the shadow method is very low when comparing with the echo method. The diameter of the calcification equal to $\phi = 3$ mm gives a shadow of 2.5 cm long at a frequency of 5 MHz.

The minimum diameter of calcification detectable at the same frequency in the distance of 4 cm by means of the echo method equals $\phi_{\text{MIN}} = 0.4$ mm ($SD = 8$ dB)

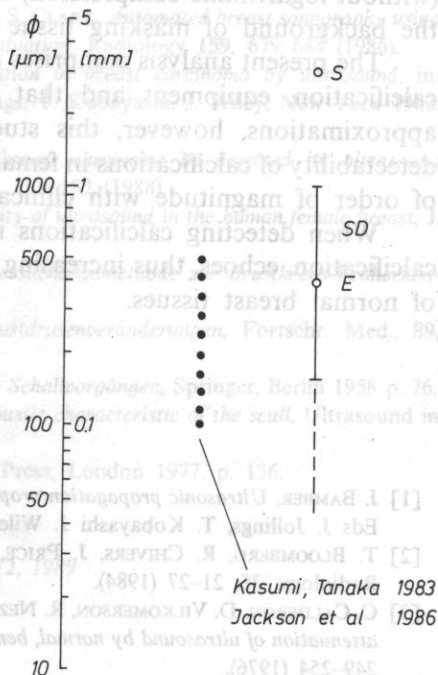


FIG. 10. Calcification detectability in breasts. ϕ — calcification diameter, S — calcification diameter producing the shadow 2.5 cm long, E — calcification diameter giving an echo equal to those obtained in normal breast tissues, SD — standard deviation, dashed line — calcification diameters which may produce echoes detectable in an anechoic breast area, dotted line — calcification detected clinically by KASUMI and TANAKA (1983) and by JACKSON et al. (1986)

However, if the tissue structure around the calcification were anechoic, the calcification detectability would depend on the parameters of the scanner, namely: on the electric noise level N of the amplifier, on the transmitter voltage, the transducer transfer loss, T , the breast attenuation A and the pressure gain C due to beam focusing. In such a case, the minimum radius of the detectable calcification could be smaller by one order of magnitude.

Clinical results obtained recently by JACKSON et al. [18] showed that inside of tumors calcifications 500 μm or more in diameter can be detected at a frequency of 4 MHz but seen better at 7.5 MHz. Similar results were obtained by KASUMI and TANAKA [19] who used 7.5 MHz, KASUMI [20] determined the diameters of detectable calcifications to be between 100 and 500 μm .

The conditions formulated for the size of detectable calcifications are necessary but not sufficient, for there is still the practical problem of distinguishing calcification echoes greater than comparable tissue echoes. KASUMI and TANAKA [19] always detected calcifications in the tumor anechoic area that stresses fine strong calcification echoes. However, they could not identify calcifications in diffuse benign lesions. JACKSON et al. [18] concluded that diffuse microcalcifications in the breast tissue, outside the masses, were not recognized.

The amplitude of the echo is one of the most important characteristics of calcifications. Therefore it would be desired to use a receiver with a linear response (without logarithmic compression) to distinguish higher calcification echoes against the background of masking tissue echo.

The present analysis comprises a number of approximations with respect to the calcification, equipment and that of tissue masking echoes. Despite the many approximations, however, this study achieved a quantitative evaluation of the detectability of calcifications in female breast. The obtained results agree in the range of order of magnitude with clinical findings of other authors [18–20].

When detecting calcifications in anechoic areas one obtains stressing of fine calcification, echoes, thus increasing the detectability when comparing with our case of normal breast tissues.

References

- [1] J. BAMBER, *Ultrasonic propagation properties of the breast*, in: Ultrasonic examination of the breast Eds J. Jollings, T. Kobayashi J. Wiley, New York, 1983 37–44.
- [2] T. BLOOMBERG, R. CHIVERS, J. PRICE, *Real-time ultrasonic characteristics of the breast*, Clinical Radiology, **35**, 21–27 (1984).
- [3] C. CALDERON, D. VILKOMERSON, R. NEZRICH K. ETZOLD, B. KINGSELY, M. HASKIN, *Differences in the attenuation of ultrasound by normal, benign, and malignant breast tissue*, J. of Clinical Ultrasound, **4**, 249–254 (1976).
- [4] F. D'ASTOUS, F. FOSTER, *Frequency dependence of ultrasound attenuation and backscatter in breast tissue*, Ultrasound in Med. and Biol., **12**, 795–808 (1986).
- [5] E. DIELESAINTE, D. ROYER, *Ondes élastiques dans les solides*, Masson, Paris 1974, p. 36.
- [6] L. DRAGONETTE, R. VOGT, L. FLAX, W. NEUBAUER, *Acoustic reflection from elastic spheres and rigid spheres and spheroids. II. Transient analysis*, J. Acoust. Soc. Am., **56**, 1130–1137 (1974).
- [7] L. FILIPCZYŃSKI, T. KUJAWSKA, *Isobar distributions and shadow range of spheres immersed in water*, Proc. VI Symposium on Hydroacoustics, Gdynia AMW 1989, 115–120.
- [8] L. FILIPCZYŃSKI, T. KUJAWSKA, *Acoustical shadow of a sphere immersed in water. II*, Arch. of Acoustics, **14**, 3–4, 183–192, (1989).
- [9] L. FILIPCZYŃSKI, T. KUJAWSKA, G. ŁYPACEWICZ, *Ultrasonic echo method in detection of breast calcification, Transient analysis*. Archives of Acoustics, **11**, 3, 287–298 (1986).
- [10] L. FILIPCZYŃSKI, T. KUJAWSKA, G. ŁYPACEWICZ, *Evaluation of calcification detectability in femal breasts by ultrasound*. VI International Congress on the Ultrasonic Examination of the Breast, Paris June 29–30 1989 Abstracts p. 32.
- [11] B. GALKIN, S. FEIG, A. PATCHEFSKY, J. RUE, J. GAMBLIN, S. GOMEZ, L. MARCHANT, *Ultrastructure and microanalysis of benign and malignant breast calcifications*, Radiology, **124**, 245–249 (1977).

- [12] B. GALKIN, P. FRASCA, A. FEIG, K. HOLDERNESS, *Non-calcified breast particles. A possible new marker of breast cancer*, *Investigative Radiology*, **17**, 119–128 (1982).
- [13] J. GREENLEAF, R. BAHN, *Clinical imaging with transmissive ultrasonic computerized tomography*, *IEEE Transactions on Biomedical Engineering*, **BME-28**, 177–185 (1981).
- [14] T. HASEGAWA, *Comparison of two solutions for acoustic radiation pressure on a sphere*, *J. Acoust. Soc. Am.*, **61**, 6, 1445–1448 (1977).
- [15] T. HASEGAWA, Y. KITAGAWA, Y. WATANABE, *Sound reflection from an absorbing sphere*, *J. Acoust. Soc. Am.*, **62**, 1298–1300 (1977).
- [16] R. HICKLING, *Analysis of echoes from a solid elastic sphere in water*, *J. Acoust. Soc. Am.*, **34**, 1582–1592 (1962).
- [17] R. HICKLING, H. WANG, *Scattering of sound by a rigid movable sphere*, *J. Acoust. Soc. Am.*, **39**, 276–280 (1966).
- [18] V. JACKSON, E. KELLY-FRY, P. TOTSCHILD, R. HOLDEN, S. CLARK, *Automated breast sonography using 7.5 MHz PVDF transducer: Preliminary clinical evaluation*, *Radiology* **159**, 679–684 (1986).
- [19] F. KASUMI, H. TANAKA, *Detection of microcalcification in breast carcinoma by ultrasound*, in: *Ultrasonic examination of the breast*, [Eds.] J. Jellings, T. Kobayashi, J. Wiley, New York 1983, 89–96 (1983).
- [20] F. KASUMI, *Can microcalcifications located within breast carcinoma be detected by ultrasound imaging?*, *Ultrasound in Med. and Biol.* **14**, Sup. 1, 175–182 (1988).
- [21] G. KOSOFF, E. KELLY-FRY, J. JELLINS, *Averaged velocity of ultrasound in the human female breast*, *J. Acoust. Soc. Am.*, **53**, 1730–1736 (1973).
- [22] V. MENAGES, *Mammographie, die zurverlässigste Untersuchungsmethode zur Brustkrebs-Fruherkennung*, *Elektromedica*, **2**, 42–49 (1979).
- [23] K. PRECHTEL, *Mastopathie und altersabhängige Brustdrüsenveränderungen*, *Fortschr. Med.*, **89**, 1312–1315 (1971).
- [24] H. STENZEL, O. BROSZE, *Leitfaden zur Berechnung von Schallvorgängen*, Springer, Berlin 1958 p. 76.
- [25] D. N. WHITE, G. R. CURRY, R. J. STEVENSON, *The acoustic characteristic of the skull*, *Ultrasound in Med. and Biol.*, **4**, 225–252 (1978).
- [26] P. N. T. WELLS, *Biomedical Ultrasonics*, Academic Press, London 1977, p. 136.

Received on August 12, 1989

The surface acoustic wave (SAW) incident upon the interdigital transducer is submitted to the reflection as result of:

the acoustics impedance variation in the transducer domain (the mechanical type reflection),

the regeneration by the electrically loaded transducer (the electrical type reflection).

In the case of a pair of two transducers in SAW filters the wave reflection generates multiple echoes, respectively high level of which can caused considerable distortions in amplitude and phase characteristics of filters. The phenomenon of wave reflection from the structure of interdigital transducer can be applied for constructing some SAW devices, for example resonators. On the other hand, by using the exact description of this phenomenon, the effect can be precisely eliminated in the undesirable cases. In this paper the above mentioned aspects of transducers are considered on the strength of its equivalent scheme.