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# Non-Invasive and Non-Destructive Techniques in Medicine and Industry [and Discussion]

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# Non-invasive and non-destructive techniques in medicine and industry

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[Plate 1]

The paper deals with the question 'What can industrial users of radiological and ultrasonic non-destructive testing methods learn from medical users of non-invasive diagnostic methods and vice versa?' and similarly, 'What can designers of equipment for the two types of users learn from each other?'

It compares the requirements of each of the two disciplines: in medicine, as complementary to clinical methods; in industry, as a maintenance aid and as a surveillance method to assist design. The basis of the comparison is the purpose of the examination, the significance of the cost factor and the differing definitions of quality and safety.

The paper also deals with the problem of cooperation and of 'interfaces' between the various teams, a problem aggravated by different educational and training backgrounds of the various interdependent teams.

The above comparison is set into a background of the evolution of the methods, and conclusions are attempted for the future.

The question I shall endeavour to examine is: 'What can users and designers of radiological and ultrasonic equipment in engineering learn from their counterparts who are active in the medical field and vice versa?' At first sight they have little in common today due to the development of technology. Figure 1 is a modern example of the task confronting the engineers using non-destructive testing techniques. Their aim is to prove that the thousands of feet of weld on this steel structure, and the materials used, are all sound. The radiographic or ultrasonic technique must be suitable for the material and the geometry, and the equipment has to be mobile, rugged, and, for underwater work, hermetically sealed, often remotely controlled.

Figure 2 is the test object of the medical radiologist: the human body. Although both groups use radiographic and ultrasonic equipment, it is clear that the design of their apparatus is completely different; it has to be adapted to the task.

On reflection, however, we shall find that although the equipment design has attained high sophistication in both directions, users and designers can still learn much from the other discipline, as, in fact, they have in the past.

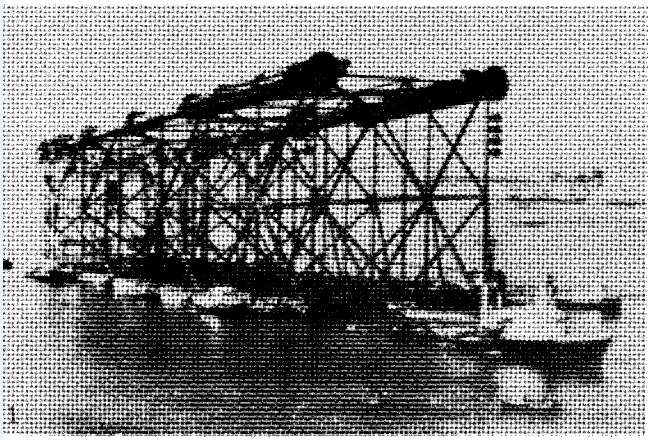
## HISTORY

### (*a*) *X-rays*

(i) *Medical applications*

The idea of using X-rays medically and as a serious diagnostic tool came immediately following their discovery by Röntgen in December 1895. I believe that the speed of the acceptance and the expansion of this diagnostic method around the world still stands without parallel more than eighty years later.

Development in medical X-rays has been continuous. Major milestones were the vacuum (Coolidge) tube in 1913–14, the ray- and shockproof tubes in 1924–8, the rotating anode tube in 1929, the image intensifier in 1953 and the computer-assisted tomograph in 1969–70. Corresponding improvement is seen in high tension generators and particularly in the X-ray controls, films and screens. Apparatus and particularly mechanical handling equipment have equally become more sophisticated and diversified for special applications.



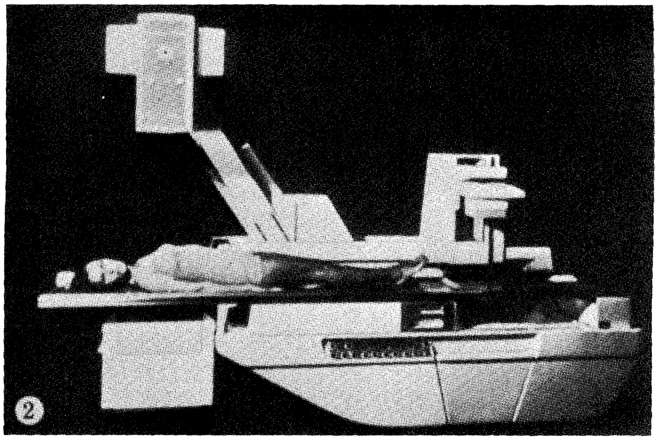


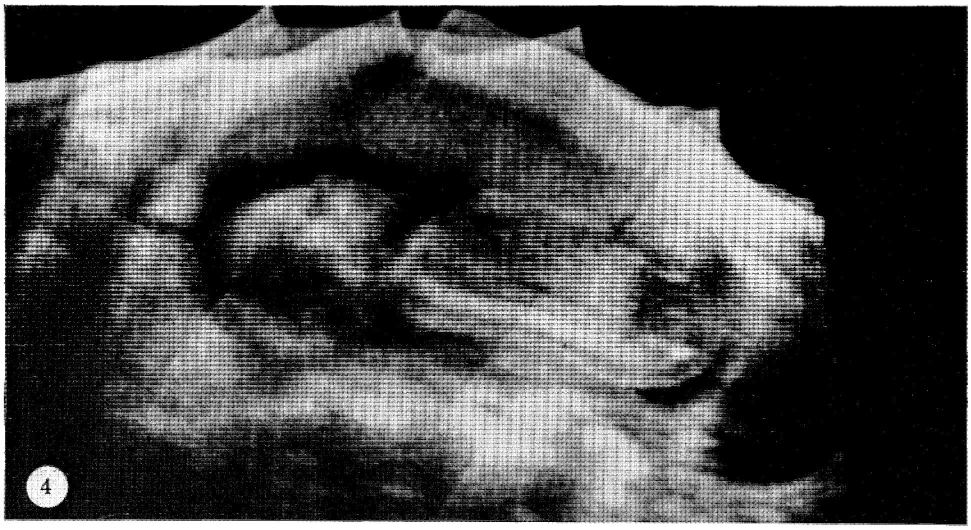
FIGURE 1. North Sea oil platform 'Thistle A' being towed to its final position, containing thousands of welds and spars to be tested and maintained.

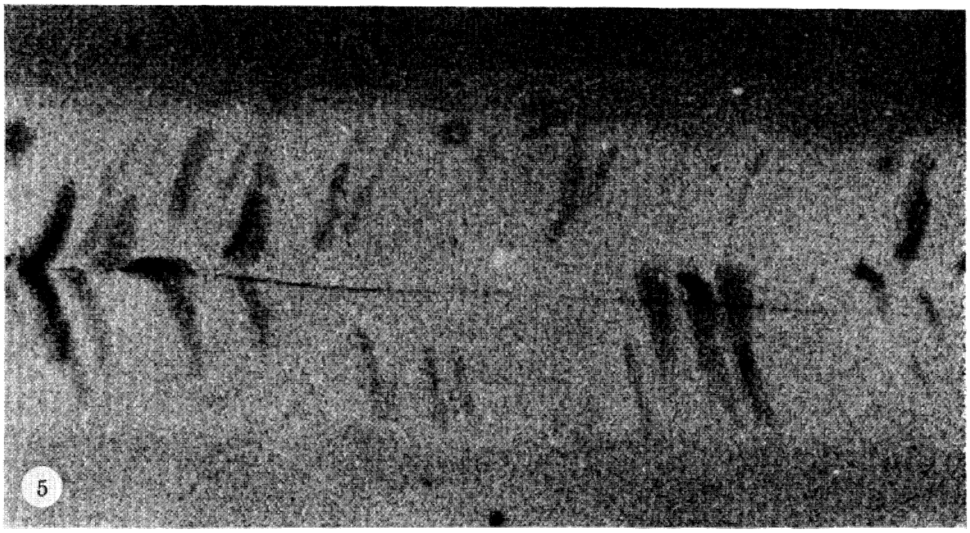
FIGURE 2. The 'test object' of the medical radiologist: the human body.

### (ii) *Industrial applications*

Although ideas for industrial applications of X-rays came also early – Röntgen himself demonstrated his rays on a variety of objects – they were slow and patchy at first. Radiation-shielded and shockproof equipment had first to be developed for the method to establish itself, and it was in the late 1920s before one could call industrial radiography an accepted method of testing. It is interesting to see from the record, however, that the earliest ideas and experiments at the turn of the century already included the testing of welds, armaments and even postal parcels to detect bombs. Serious application of the X-ray technique in engineering began by adaptation of high-energy therapy equipment which was developed for cancer treatment. It was found that X-ray equipment of around 180–200 kV allowed examination of steel sections of up to 5–6 cm thickness with exposure times of about 5 min and a focus film distance of about 80 cm. Since these were therapy tubes having relatively large focal spots, a compromise had to be made between prolonged exposure times and excessive geometrical unsharpness.

Radium, radon and, later, radio-active cobalt and iridium followed, allowing reasonable exposure times on steel sections up to approximately 10 cm thickness. After World War II, linear accelerators and betatrons, invented in the early 1940s, were developed gradually up to 30 MeV to deal with sections up to 40 cm thick. Though the designers aimed at both medical and engineering applications, the main impetus for equipment development still came from the requirements of deep therapy in the hospital.





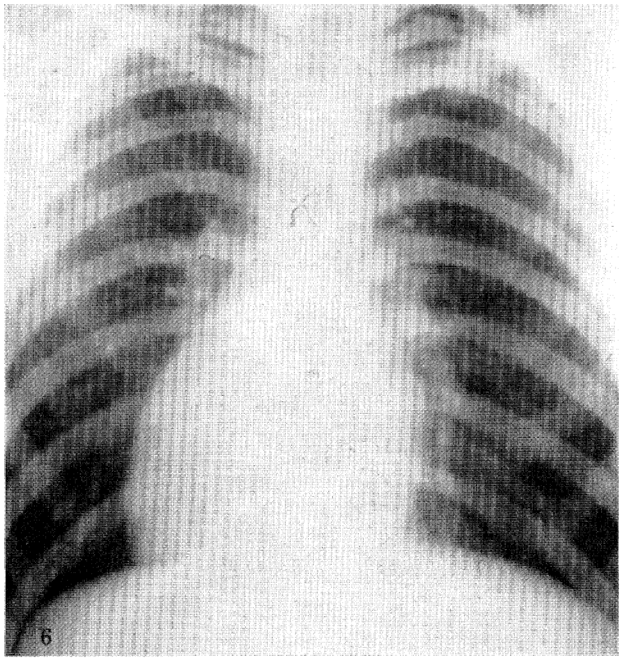


Figure 4. Ultrasonic two dimensional 'grey-scale' image of a late pregnancy. The foetus and placenta are clearly seen.

Figure 5. Typical longitudinal weld radiograph exhibiting high contrast: the image is confined to the area of interest. The radiograph shows 'herringbone' porosity in a weld.

Figure 6. Chest radiograph showing large area and normally low contrast in order to contain wide density range.

### (*b*) *Ultrasound*

*Industrial* use of ultrasound came nearly half a century later than X-rays. Unlike these, ultrasound was not a fundamental discovery in physics and most of its properties were already demonstrated many years before serious application development took place. The last war, of course, gave a powerful impetus to this work; ultrasound seemed to work best where X-rays failed, on heavy steel sections and on hairline crack defects: a fortunate complementary tool, vital for armament construction and shipbuilding. In this country, Desch, Sproule & Dawson (1946) and, simultaneously in America, Firestone (1945) succeeded in developing practical equipment. Basic A-scan echo pulse traces often suffice to answer specific engineering non-destructive testing questions and this technique still predominates in the search for cracks, tears and lack of fusion in welds and rolled material. Figure 3 illustrates a typical application.

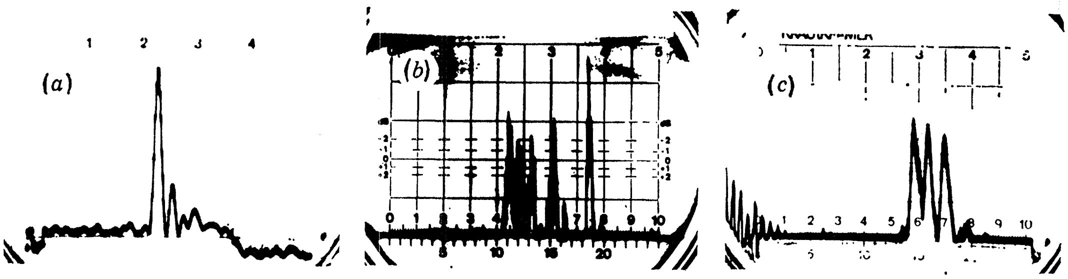


FIGURE 3. Ultrasonic 'A-scan' echo traces of welds, showing lack of fusion (*a*) and porosity (*b*) and (*c*). Numerical classification is applied to both reflected pulse amplitude and to time base.

*Medical* applications of ultrasound, on the other hand, got off to a slow start; they were derived from industrial usage, there was no spectacular advantage to be seen and the image was difficult to interpret. Promising applications were found in cardiology, brain examination and particularly in pregnancy cases.

Development remained slow: the typical A-scan trace tended to be regarded for many years by the medical profession as a research tool. The two-dimensional image made its appearance around 1954 but only much later, when the so-called 'grey scale' – a wide density range – was developed, was medical interest truly aroused. Here at last was an image that the radiologist recognized. Since the early 1970s the two-dimensional grey scale images of the B-scan variety allowed observation of movement in 'real time'. Figure 4, plate 1, shows a typical two-dimensional grey scale illustration of a pregnancy case.

Fired by the doctor's enthusiasm, rapid expansion in equipment development took place. Progress was so fast that, on a visit to a recent exhibition of the British Medical Ultrasonics Group, one obtained the impression that several technical solutions were being offered for the same problem, side by side. One felt that some of these would hardly have the chance to be tested in the field since they appeared to be already surpassed when they made their appearance.

At any rate, owing to this remarkable effort, medical ultrasonics which began hestitatingly have leap-frogged ahead of their industrial counterparts in many respects.†

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† A useful survey of the evolution of non-destructive testing equipment is given by Mullins (1964), and of X-ray equipment for medical applications in the Jubilee number of the *British Journal of Radiology* (1973). A historical review of medical ultrasonics has been made by C. R. Hill (1973).

## PURPOSE AND LIMITATION

Before we can suggest promising fields of mutual benefit, it will be well to assess the purpose and limitations of the examinations in our two fields: medical and industrial. Basically, the purpose is similar in both. Early and accurate diagnosis in medicine allows more effective treatment, in many cases even preventive medicine. In industry, detection of incipient failures by non-destructive techniques makes it possible to avoid accidents and to plan overhaul and repairs at convenient times, thus causing the minimum dislocation of the normal operation of plant and structures.

Where the two disciplines differ is that in industry, non-destructive testing is also a powerful guide to product designers both to achieve a better product and one which can be tested easily and, preferably, in service. In medicine, the Almighty cannot be so influenced but one can perhaps change for the better the patient's living and working conditions, the obvious examples being the fights against pneumoconiosis and cancers of the lung and breast.

TABLE 1. QUALITY AND INTERPRETATION: GENERAL CRITERIA

| *engineering* | *medicine* |
|---|---|
| relatively simple structures | complex tissue |
| comparison with destructive test | no comparison with destructive test |
| comparison with numerical standards frequently possible | no comparison with numerical standards |
| artificial defects can be used | no artificial defects |
| where economic and possible:<br>digital measurements<br>yes–no criteria<br>automation | analogue images<br>no yes–no criteria<br>no automation |
| replacement of human opinion where possible | qualified human opinion essential |

In *medical* diagnostic radiology and nuclear medicine the major difference compared with industrial radiography is the limitation imposed by the harmful effect of radiation on the patient. This has, of course, strongly influenced equipment design and produced important developments such as the X-ray image intensifier and faster screens and films. It also gave indirect extra impetus to medical ultrasonics, particularly in pregnancy monitoring.

There is also the need to keep exposure times short (preferably to a few milliseconds) in order to reduce unsharpness due to movement of the patient and his internal organs or the injected dye. This requirement has led to the development of the rotating anode tube, heavy generators, condenser equipment and accurate exposure control devices.

It is interesting to note that, despite these limitations, X-ray examination is still the predominant diagnostic method in medicine, whereas, paradoxically, in industry, ultrasonic techniques tend to supplant radiation methods. The main reasons for this are the radiation risk to personnel and the higher cost. The two methods, however, are truly complementary and each should be asked the diagnostic questions which it is best able to answer.

## Quality and interpretation

Let us consider the quality requirements and interpretation of the results. Table 1 shows the comparison between the two application fields.

In engineering, the structures are relatively simple (compared with the human body) and destructive testing can frequently be used as a basis of comparison; moreover, artificial defects can be produced. This makes for some differences and relative simplicity compared with diagnostic radiology.

As a result, it is often possible to specify numerical standards of measurements, mainly in ultrasonics but sometimes this can also be applied to industrial radiography. Where possible, automatic digital yes/no acceptance criteria together with digital printout may be applied. Automation is the next logical step. In other words, automatic methods may replace human opinion in suitable cases, leading to increased inspection speed and reduction of cost.

In medicine this is not possible and qualified human judgement is necessary in each examination. For this, in general, analogue images are found most informative, but in some special cases such as heart and brain examination, A-scan traces similar to those shown in figure 3 are used.

## Image contrast in radiography

In *industrial radiography*, the non-destructive testing worker obtains most information from a high-contrast image of just adequate size which shows the critical area. Figure 5, plate 1, shows a weld radiograph to illustrate a typical case. It is essential, of course, that the critical areas should be known and this is the responsibility of the qualified design engineer. He may decide to examine all of these or only a predetermined proportion.

The *hospital radiologist* has the clinical symptoms to guide him. On the other hand, he normally wants to see more than the critical area: he gains essential information by looking at surrounding normal tissue; his trained eyes and brain need to detect pathological conditions. As an example, figure 6, plate 1, shows a chest radiograph. It must be noted that it is not possible to reproduce in print the density range seen on a radiograph or with the aid of a viewing lantern. I remember my own surprise when we proudly presented the radiologist with what we thought was a brilliant chest picture, having worked patiently and successfully on increasing the contrast. To our dismay, he asked for the contrast to be reduced – to obtain a greater density range – and was very pleased when we produced for him what was to us a dull, flat radiograph.

## The influence of cost

Let us now consider the importance of the cost of the examination. In *industry*, non-destructive testing can be regarded as part of the production process and of the maintenance operation. That is to say that the choice of the method and equipment, the demand on time and personnel and indeed whether non-destructive testing – X-ray, ultrasonic or any other – is to be applied at all, can be calculated in terms of market value.

The exception is safety of life and plant. Consideration of possible accidents makes the calculation more complex because it is impossible to evaluate human life in money terms, yet it is necessary for cost calculation to agree on an 'accepted' low probability of the occurrence of the accident. This consideration will, in general, add to the cost of a normal non-destructive testing schedule, based on economic factors alone, in that the schedule will be augmented to make the occurrence improbable. Decisions are not easy because the product must remain marketable. Safety standards of nuclear power plants, for example, would bankrupt many other industries if applied elsewhere.

Figure 7 is a diagram showing the cost and methods of non-destructive examination. Column (*a*) shows the position in industry, assuming an arbitrary non-destructive testing schedule. Assuming that safety considerations apply, this schedule is shown augmented to a higher level in column (*b*), for instance by using additional radiographic or ultrasonic examination or occasionally an additional test method. The important point to note is that in engineering, non-destructive examination is carried out according to a prearranged schedule and that the cost of this can be precalculated.

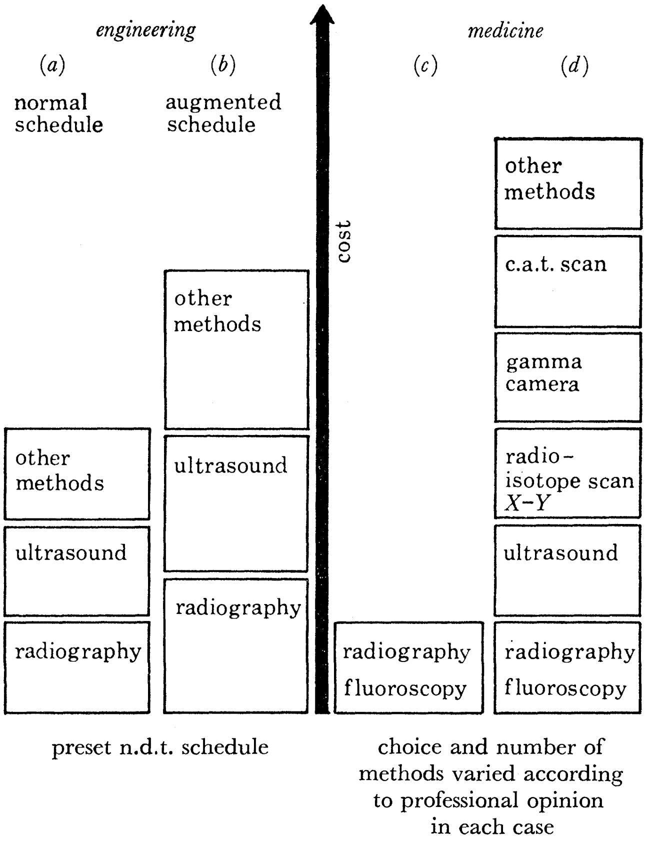

FIGURE 7. Cost and methods.

In *medicine*, value calculations are not possible; theoretically only the best will do, irrespective of the cost of the examination or the time taken. However, we know that reality is different and cost considerations are bound to influence hospital diagnostic routine, though – purely from the medical point of view – they ought not. As an example, referring to figure 7, let us assume that a given radiological programme (column (*c*)) does not lead to adequate diagnosis. In this case, further tests may be ordered for the same patient and – in a well equipped hospital – one or several of a number of different diagnostic methods may be applied (column (*d*)). The conventional X-ray routine may now be replaced or augmented by radio isotope scanning, gamma camera imaging and ultrasonic scanning. Computer assisted X-ray tomography (c.a.t.) has also taken over an important part of conventional radiography. Many other methods may be added. A modern hospital has an array of complex and expensive equipment in which the emphasis is as much on the 'throughput' of patients as on diagnostic sensitivity.

Hospital organization must take account of this and yet remain flexible to allow for further development and increase in the number of methods with the advance of technology. The choice of the methods directly influence, of course, the cost of the examination; moreover, unlike in engineering, the schedule cannot be predetermined. Efficient utilization of existing equipment and a wise purchase programme for the hospital are further difficult and complex targets in which medical practice is strongly influenced by non-medical considerations.

In the problem of cost, therefore, the medical man is unquestionably in a more difficult position than his counterpart in industry. To arrive at an acceptable compromise the answer must be in the study of organization as well as medicine.

## People and training background

We should now consider the people of different training backgrounds who have to work together as interdependent teams, both in industry and in medicine. In *industry*, the design engineer and the metallurgist are usually qualified professionals and – though it is their design which is being tested – they normally delegate all or the greater part of the non-destructive testing process to less qualified personnel, the technicians. Both groups need specialized training in the application, in the methods, and, most importantly, in the interpretation of the results. There are now excellent courses available for all, but a great deal is still to be done in the field of national, and internationally accepted, standards of test methods, equipment and syllabuses. In my view, something can be learned by industry in all these from the established formalized training of medical radiologists and radiographers.

Figure 8 shows the various teams and their interdependence. Diagram *a* represents the groups in a typical engineering enterprise. The professional design engineers and metallurgists are shown in contact with the technicians charged with carrying out the non-destructive examination. Both groups in turn are shown to be in contact with the equipment manufacturers and thus with the equipment designers. These three teams are separated from one another by dividing lines which may be called 'interfaces'. The problem of cooperation between the groups is relatively simple in industry, because the difference is in the level of technical education and training and not in the type. To indicate this, the interfaces are shown as thin lines.

Diagram *b* shows the situation in *medicine*. Again the professionals, here the various medical specialists of the modern hospital, are shown in contact with each other and are separated by thin interface lines to indicate similarity of fundamental training. Such specialists, involved in non-invasive examinations, are radiologists, radiotherapists, surgeons, nuclear medicine specialists, cardiologists, obstetricians, urologists and others. The whole medical group in turn is in contact with the hospital physicists and the radiographers, who again are in contact with each other. To indicate different training background the interface lines are thick.

Good collaboration between all groups is, of course, important but, because of the differing educational background, not easy. It can be said, however, that there has been for a long time excellent collaboration between the radiotherapist and the hospital physicist. Radiation hazard to patient and personnel has extended the role of the physicist. His role has proved particularly useful with the trend of modern diagnostic equipment towards increased complexity and the application of new physical principles.

I also regard good collaboration in the design stage between all user groups and the manufacturer to be essential, as shown in figure 8. Only in this way is it possible for the manufacturer to develop new diagnostic equipment that is practical and easy to operate. It is no coincidence that companies where this collaboration is well established have become leaders in X-ray development.

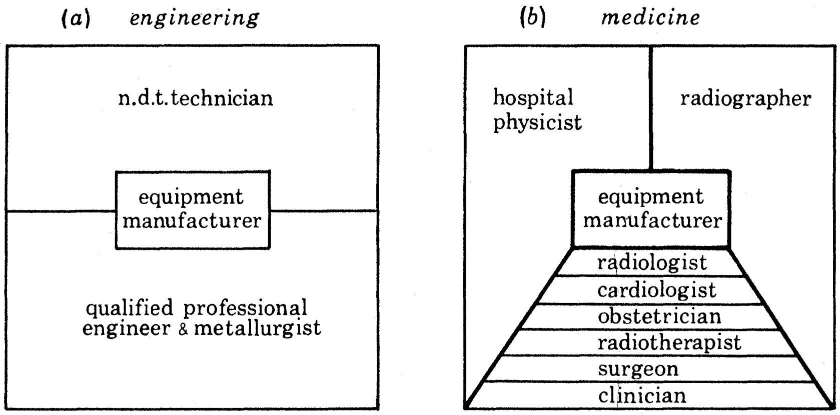

FIGURE 8. The interface problem.

In contrast to industry all (or almost all) interpretation is carried out by professional medical personnel. Because of the pressure on manpower, it is not surprising that voices are heard to the effect that simple cases may be reported on by non-medicals.

These interfaces have arisen because of the ever-increasing specialization and the need today is to shorten the communication chain and to break down the barriers. I believe that there is plenty of room, indeed the need, for including some knowledge of the other group's work and even technical jargon in the educational and training syllabuses of all teams concerned. There are some excellent post-graduate courses available in medical physics. It is my view that there should be even more medical teaching to physicists and I hope that more graduates will avail themselves of them. Equally, I believe that it is desirable to teach more medical physics in medical schools.

To summarize, industrial non-destructive testing course syllabuses could, I feel, learn from the medical radiographers' training and conversely in medicine – because of the interface problem – all concerned should strive for a common language in their syllabuses.

## EQUIPMENT

### (a) *X-ray tubes, generators and controls*

A brief review of the equipment used in industrial and medical radiography and consideration of technology shows that no significant interchange between radiography in engineering and medicine has occurred or is likely to occur in the future.

The reason is that the X-ray requirements are different. Whereas for medical radiography very short exposure times are used with energies up to approx. 150 keV, for industry longer times but much higher energies, up to several million electron volts, are needed to achieve adequate penetration of the test object, usually steel. This leads to very different X-ray tubes, controls and generators.

However, the technology between industrial radiography and X-ray therapy is similar. In the 1930s, cable units around 250 kV were adapted from therapy for industrial uses and the same happened in the 1960s for betatrons and linear accelerators.

The need for access to the test object and for mobility led to specific development of self-contained tube heads and these are now available from 100 to 400 kV. Transportable tube heads are now the major part of industrial X-ray installations.

### (*b*) *Television fluoroscopy and image intensifiers: cineradiography*

In these fields, which were all developed for medical work, the industrial user and equipment designer may well find more applications for special purposes in engineering. Medical film/screen combinations and, of course, film processing units could also be found suitable in industrial applications.

In general, one could state that it is unlikely that the medical worker will be able to make much use of developments in the industrial field whereas the industrial non-destructive testing user and designer may find some of the development of viewing/film equipment suitable for his purpose.

### (*c*) *Handling equipment for X-rays and ultrasonics*

Mechanical handling equipment for medical use is designed to position the human body and the X-ray tube or ultrasonic probe. It can, therefore, be designed to deal with a defined range of sizes and weights. The need for speed and accurate positioning led to a high degree of equipment efficiency and today many specialized constructions are available from most major manufacturers to facilitate application of radiography or ultrasonic equipment in the operating theatre and in specialized medical departments such as cardiology, urology and others.

In contrast, industry presents a much wider range of handling problems and access is often difficult. Where possible, standard units have been developed, e.g. for the internal testing of large bore pipes by so-called ‘crawlers’ or moving rings of ultrasonic probes. In the majority of cases, however, transportable isotope sources, X-ray tube heads or ultrasonic equipment are used. Where the volume of work justifies the expense, purpose-designed systems have been developed. In some cases, the designer for industry will be able to borrow solutions from the medical field and, conversely, the designer for specialized medical applications may be able to adapt some interesting industrial solutions of mechanical handling problems.

### (*d*) *Data handling and electronics*

It is in this field where a closer cooperation of designers for medicine and for engineering would perhaps bring the quickest benefits. Computers, television monitors, measuring and indicating displays, digital printers, line recorders and control circuits are equally suitable for both medical and industrial applications and the differences will be in the presentation, environmental requirements and functional, artistic design.

In ultrasonics the impetus is equally strong in both disciplines. I do not only refer to projects which are still in a rather early stage of development such as flow measurement by Doppler shift or ultrasonic spectroscopy and diffraction. I mean the fertile areas of new types of probe combinations, electronic scanning and improvement in probe–test object or probe–patient interfaces, distance and absorption measurements. Many of these problems involve the use of specialized computers. At a rapid stage of development like the present, so many teams of engineers, physicists and doctors are involved that I am confident that closer contact between the medical and the industrial worlds promises ample reward for both.

## CONCLUSION

I consider that it would also be helpful to see an occasional review of industrial non-destructive testing equipment in specialized medical journals such as *The British Journal of Radiology*, and conversely, of hospital apparatus in periodicals dealing with non-destructive examination.

I have considered the close parallel roads on which the two disciplines, diagnostic medicine and industrial non-destructive examination, travel. They have learnt much from each other in the past and no doubt will do so in the future. It is not easy, in the pressure of everyday work, to keep in contact with the other side but meetings such as our present one will, I am certain, benefit both.

I wish to thank the following organizations for the use of figures in this paper: Taylor Woodrow Construction Ltd (figure 1), CGR Medical Ltd (figure 2), Pantatron Systems Ltd (figure 3), The Welding Institute (figure 5), Kodak Ltd (figure 6), and Dr D. Rose, The Royal Marsden Hospital (figure 4). I also wish to thank friends and colleagues who kindly gave me their comments and criticisms of the draft paper.

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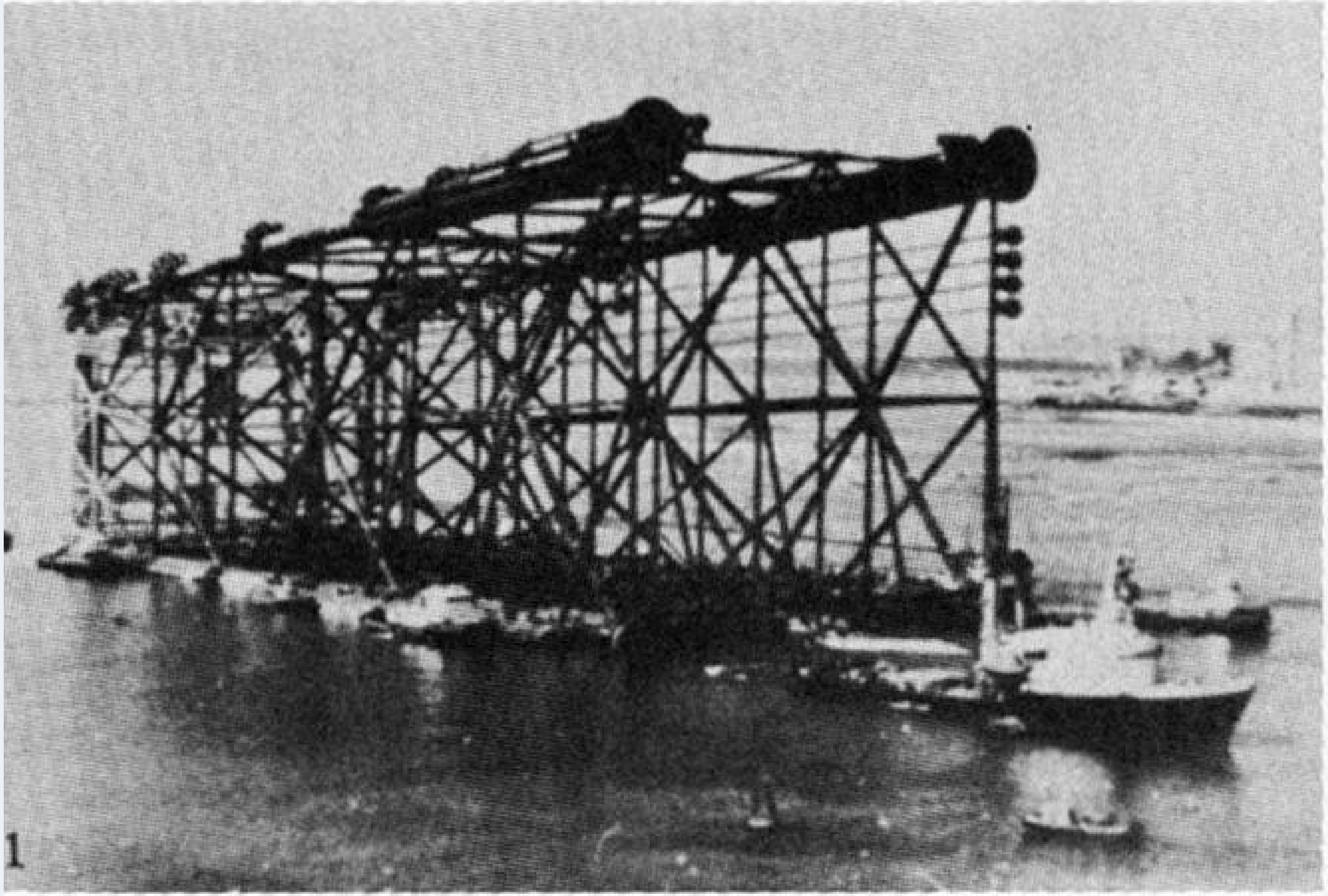
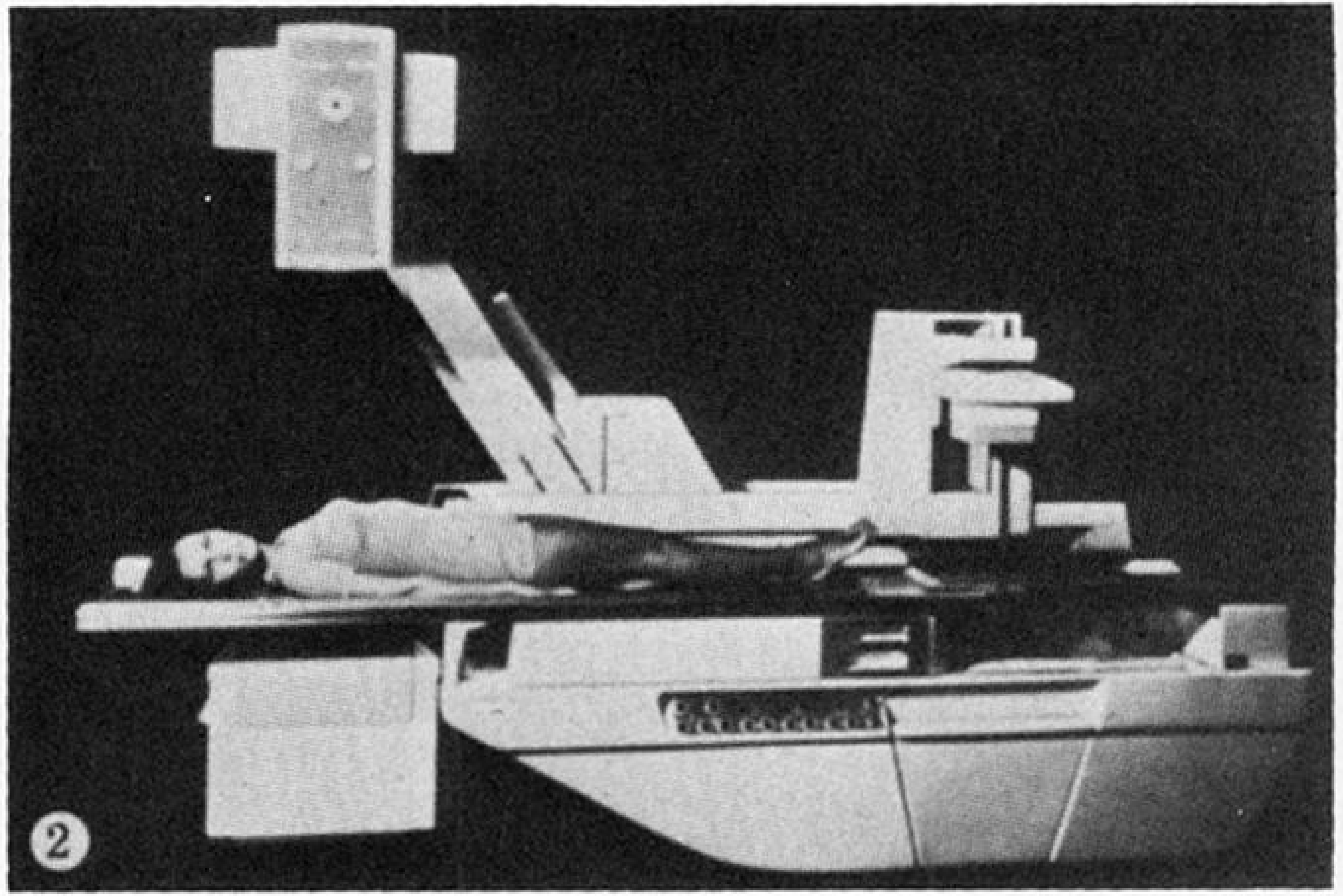
## *Discussion*

D. GORDON (*City University, London, U.K.*). Dr Nemet has referred to the rapidity with which doctors accepted the value of X-rays within a matter of a year. A similar rapid acceptance occurred with the E.M.I. scanner. On the other hand, when in 1954 I showed that ultrasonic echoes could be obtained from the brain, I had to wait 8 years before I was allowed to use it other than on dying patients.

Joyner showed that ultrasound would demonstrate pulmonary embolism nearly 10 years ago and though I have used this technique for 8 years I cannot rouse any interest among chest physicians. I am at present working on the Doppler measurement of the retinal circulation and after 5 years have still far to go.

As acceptance is so random, I can only hope that I live long enough to complete the job.





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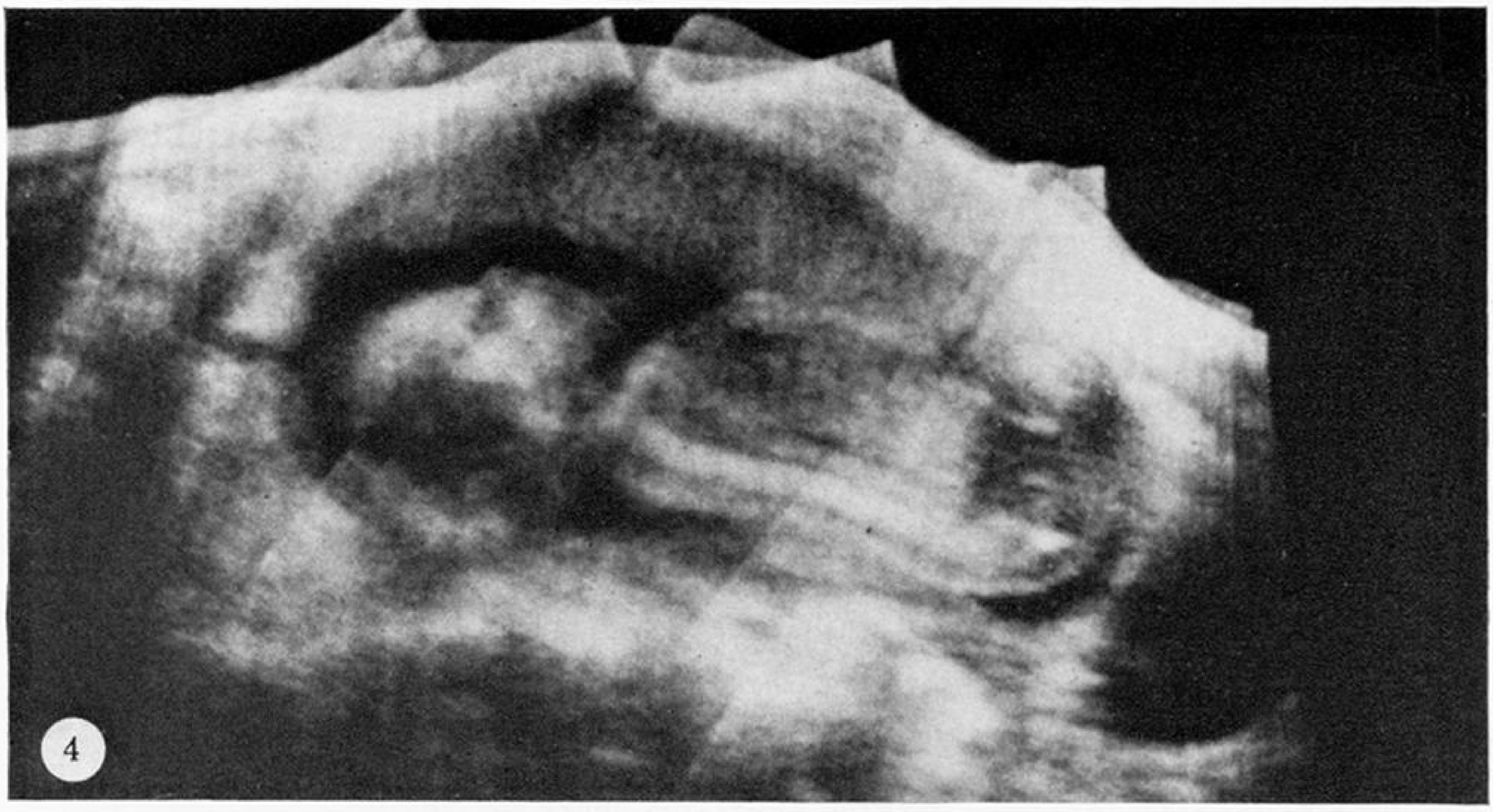

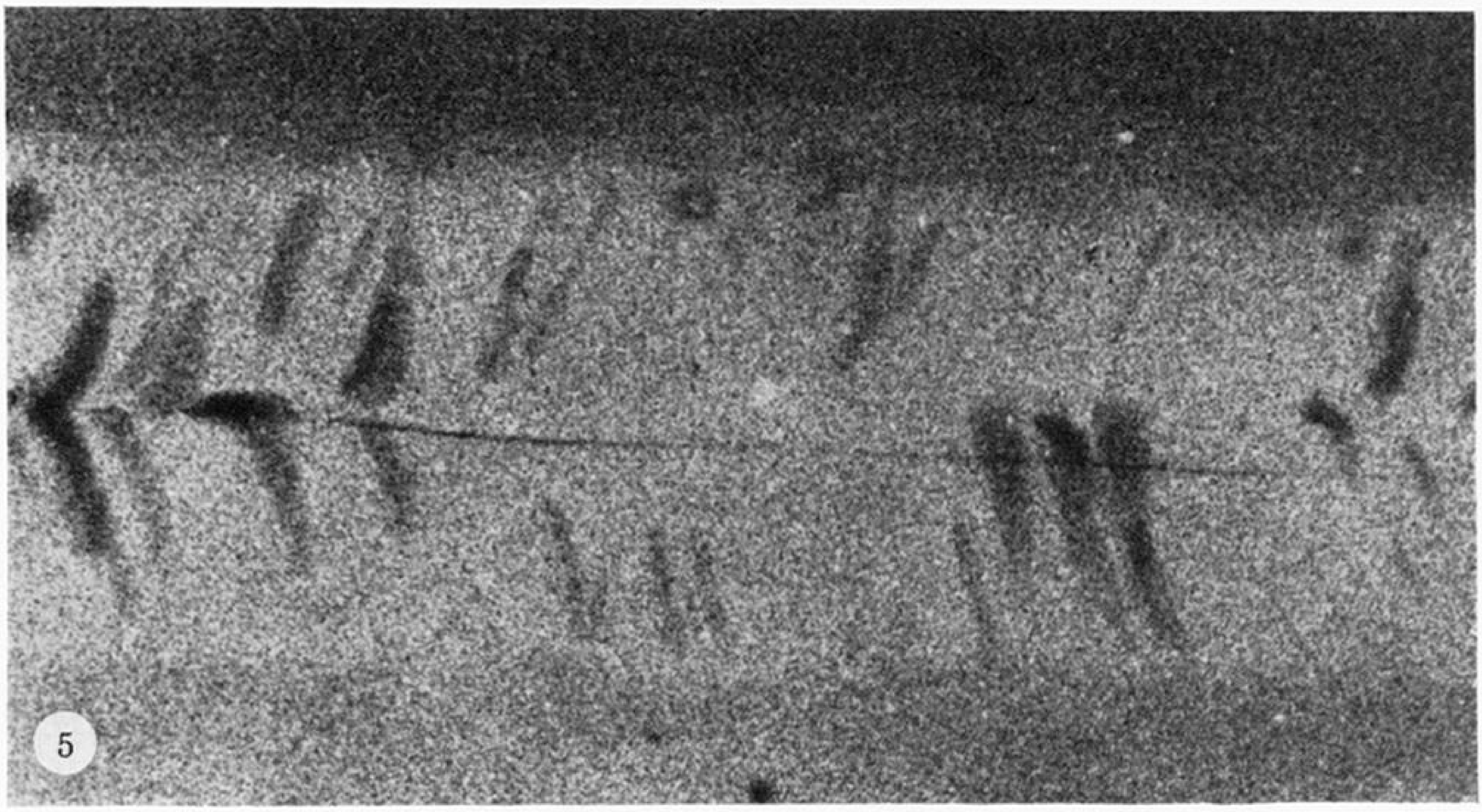

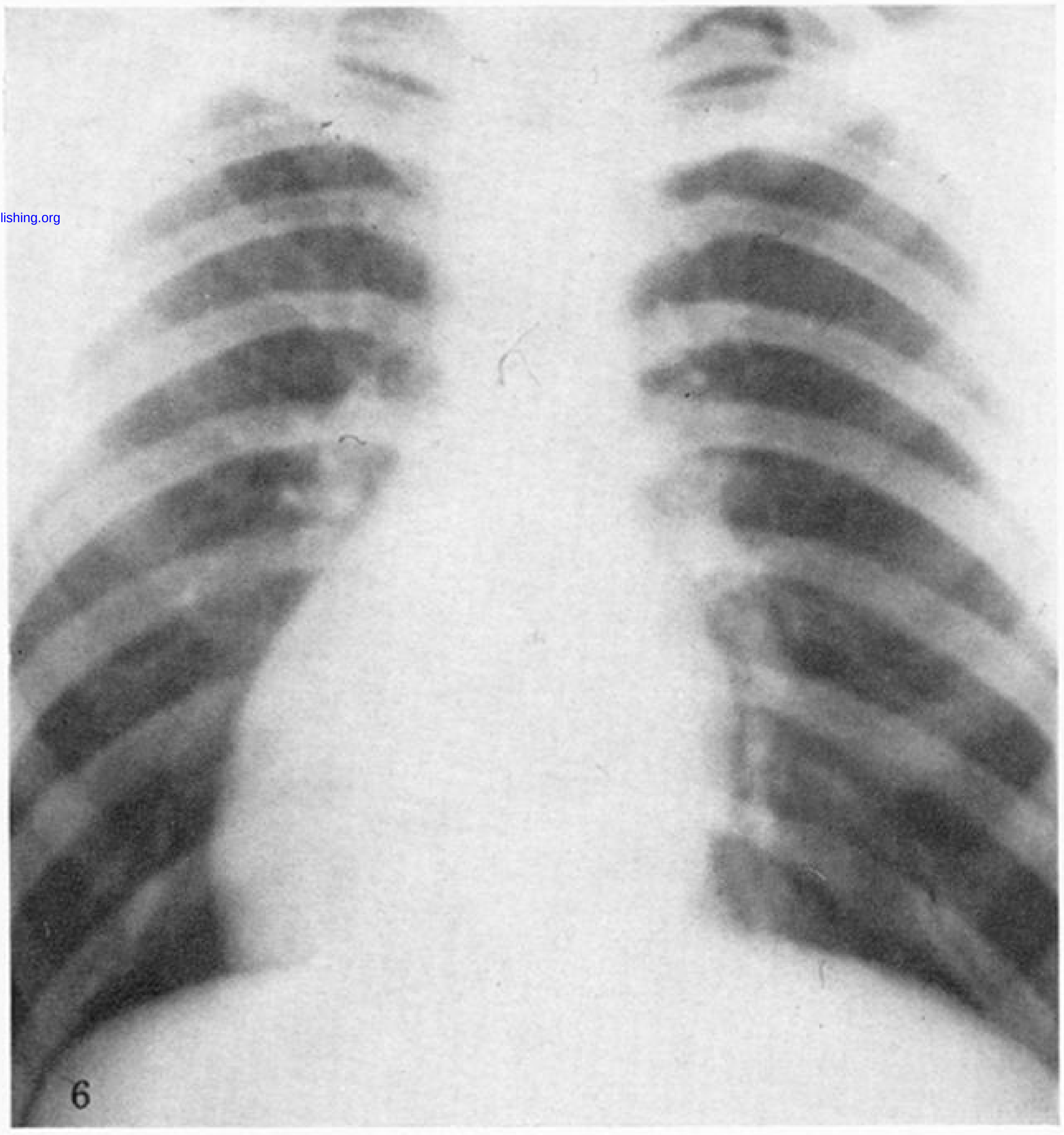

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