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Improved Ultrasonic Measurement Techniques for the Assay of Plutonium and Other Transuranics in the Lung*

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Abstract

At the Lawrence Livermore National Laboratory, we are developing a system that will more accurately measure fat, muscle, and bone content from ultrasonic images of the chest wall. This paper describes a procedure that will allow chest-wall thickness to be determined to within ±1.5 mm (compared with the ± 3–6 mm from current techniques) and may allow absolute errors in chest-wall composition to be reduced to ±4%.

Introduction and Background

Photon attenuation factors for body structures located in the chest wall are needed to correctly assess the content of radioactivity in human lungs. It is standard practice at many whole-body-counting facilities to estimate chest-wall thickness using biometric equations. These equations, such as the one shown in

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work well when measuring and quantifying higher-energy gamma emitters above about 100 keV. However, the uncertainty in chest-wall thickness (about ±6 mm) associated with these equations is unacceptable when measuring and quantifying low-energy x-ray emitters, such as the 17-keV x ray associated with ^{239}Pu. Consequently, more accurate measurements of chest-wall thickness and composition must be obtained when quantifying these low-energy x-ray emitting materials.

Currently at LLNL and other DOE whole-body-counting facilities, chest-wall measurements are done with the aid of ultrasonic imaging units of the type used for routine medical diagnosis. These measurements are more accurate than those obtained from the biometric equations and provide additional information as to the body structures located within the chest wall. Unfortunately, when used alone ultrasound units can lead to judgment errors of up to ±3 mm when determining tissue interfaces. These errors in judgment, when combined with the resolution of the ultrasound unit (typically ±1 mm), lead to even greater measurement errors.*

Each millimeter error in assessing chest-wall thickness causes an average of 10% error in the detector calibration for plutonium for a typical two-detector 5-inch diameter phoswich (or "phosphor sandwich" detector consisting of a sodium-iodide and cesium-iodide crystal) lung counting system. This can be shown by observing the rapid change in counting efficiency vs chest-wall thickness, as in Fig. 2. An error of 3 mm in thickness would produce at least a 30% error in the calibration factor, and hence plutonium content, for a person undergoing a lung count for this material.

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*All errors reported at the 95% confidence level (2 σ).

Figure 3 shows the effect on the calibration factor (detector efficiency) for the same system with various percentages of adipose tissue (fat) in the chest wall. If fat content is not assessed, errors of up to 300% or more can occur in detector calibration, since the human chest wall has been observed to contain as much as 60% fat.[1] Very large errors in the assessment of plutonium content in the lung can occur if the chest-wall thickness and fat content are not measured accurately. Obviously, we would like to reduce these errors as much as possible.

Recent guidance proposed by the American National Standards Institute (ANSI N-13.30) states that maximum acceptable errors due to the calibration of plutonium lung counters (normally done using dosimetry phantoms) be within +50% to –25%.[2] Although accuracy for human measurements is not specifically mentioned in the Standard, it can be implied that this Standard applies to humans as well. Consequently, errors from chest-wall thickness and fat content alone can easily exceed the total attenuation error allowed by the Standard. Other errors, such as those arising from radioactivity distributional effects in the lung, can produce equivalent or even larger errors.

Since errors due to the chest-wall thickness and fat content account for only part of the total error in the determination of lung activity, it is appropriate to restrict these two errors to some value less than the maximum allowed. Other errors (such as varying distribution of radioactivity in the lungs) must also be reduced, but are not addressed in this report. The objective of our study is to limit the errors from chest-wall thickness and fat content to no more than half the maximum of all errors specified by ANSI N-13.30—i.e., to within ±25%. To achieve this level of error in the actual detector efficiency, it will be necessary to reduce the total attenuation error due to chest-wall thickness alone to 15% (1.5 mm accuracy) and errors due to fat content to 20%, or ±4% absolute fat content. We believe this can be achieved through improvement of the existing equipment and techniques currently used to obtain and analyze the measurements. A detailed outline of the rationale for choosing these error values is given in Appendix A of this paper.

This report will discuss work in progress to improve current measurement techniques for chest-wall thickness and fat content to achieve the desired error reductions. A key element in the accomplishment of this task is the improved manner in which ultrasonic scans are now made at LLNL.

Previous Method

The person to be examined for chest-wall thickness and fat content is positioned in a chair with the chest exposed. A small mound of sonolucent gel is placed on the chest surface in the area from which a thickness measurement is desired. The gel acts as a standoff and allows better definition of the chest surface in the image. We obtain the ultrasonic image of the chest wall by placing the probe of the unit (Siemens Sonoline SL ultrasound unit with a 5 MHz linear array small-parts probe) on the mound of gel. The image is frozen using the ultrasound unit and archived with a black-and-white Polaroid photograph. Measurements of chest-wall thickness and fat content are made by using the photograph.

New Method

In our new method, images of the chest wall are obtained using the identical Siemens Sonoline SL ultrasound unit. Analog images are transferred via cable from the video output on the ultrasound unit to an Imaging Technology PC Vision frame grabber board in an AST 286 personal computer. A menu system allows the user to store, retrieve, and analyze images as well as edit the database in which the information is stored. A program named "Vis" is used to digitize and save the images to disk.[3] Image analysis uses both Vis and another program named "Ultra."[4] We use dBase 3 Plus for the database. A person who is trained in sonography and can recognize images of the chest wall along with its associated structures is needed to operate the system.

The following procedure outlines the steps necessary to measure a person's chest wall.

Positioning

The subject to be imaged is placed in a chair with the chest exposed at an angle matching that used for detector placement during the lung count. A thin coating of sonolucent gel is placed on the chest surface. Next, a thin (0.5-mm thick) sheet of "Kiteco" (3M Company) material is placed on the gelled surface. This material is used as a stand-off pad to allow definition of the chest surface. A thin layer of mineral oil covers the Kiteco. Both the gel and oil are commonly used as sonic couplers in diagnostic ultrasound.

We have found that the stand-off pad is a more effective and consistent standoff than using a mound of gel because it provides better definition of the chest surface as well as an image free from artifacts due to air bubbles in the gel. Figure 4 shows the setup.

Imaging

The chest wall is imaged using the 5 MHz linear array small-parts probe. We apply light pressure to prevent distortion of the chest wall (and thus thickness measurements). To master this technique requires practice. See Fig. 5.

When the desired image is acquired, it is frozen as a single frame using the ultrasound unit. The image is transferred to the personal computer, where it is digitized and saved using the Vis program.

Image Analysis and Archiving

Using Vis, the operator outlines interfaces of interest in the images such as fat, muscle, rib, chest surface, and the chest/lung interface using an interactive mouse system. These interfaces appear with higher intensity colors, the highest intensity being the true interface. The true interface is difficult to discern by the human eye since the surrounding colors are so similar (see Fig. 6). Therefore, using the mouse the operator can only approximate where the interface lies. The computer is capable of more accurately determining the true interface in the area of the mouse and places a red dash at the point of highest echo intensity (see Fig. 7).

The image is then scaled so that measurements can be performed. Points are taken along each interface that correspond to an x,y location on the image. This information is then transferred to the Ultra program and appears in graphical form (Fig. 8). In Ultra the areas of fat, muscle, and bone are calculated by integrating each of these tissue areas. In addition the average thickness of fat, muscle, and bone is calculated. This data is stored in a database along with the person's name, social security number, image location, date of examination, and comments. As can be seen from Fig. 6, it is not easy to determine exactly where the interfaces lie. When analyzing an image without the computer and depending on the user's discretion alone, errors of up to ±3 mm in thickness can occur just on the estimate of the interface location. By allowing the user to guide the computer—that is, to show the computer the area to analyze—user error is essentially eliminated from this step because of the computer's ability to locate the interface exactly. Unfortunately, user error cannot be totally eliminated from the process, as imaging errors from distortion of the chest wall can occur if the probe is placed too heavily on the chest surface when the examination is taking place. Errors due to this problem, and other errors involving system resolution and placement of the probe during image acquisition, still remain and are estimated to be about ±1.5 mm.

The measurement accuracy of fat content is improved with this system through more precise thickness measurements of the subcutaneous fat layer. However, this system is limited in that it cannot measure the fat intrusion into and between the muscle layers. The percentage of fat in lean muscle is known to be at least 8%.[5] Our system corrects all images for an 8% fat content in muscle. Additional work in the area of ultrasonic tissue characterization is needed to accurately measure the percentage of fat in muscle for each image.

Conclusions

We have described a method of improving chest-wall thickness and fat measurements in humans. This method offers a substantial reduction in the errors associated with this type of measurement. An estimated attenuation error reduction to ±15% (±1.5 mm) in chest-wall thickness has been achieved. Errors in the measurement of fat content have also been reduced but not quantified as yet. Ongoing research is necessary to more accurately determine the degree of error reduction that can be achieved using these methods.

References

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3. C. F. McMillan, Lawrence Livermore National Laboratory, personal communication, October 24, 1988.

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Appendix A

The Effect of Chest-Wall Thickness and Fat Content on the Phoswich Detector Calibration Factor for ^{239}Pu

We have made the following assumptions for our calculations:

- All subjects are male.
- The average chest-wall thickness = 2.85 cm.
- The average subject fat content in the chest = 30%.
- The phoswich calibration factor for uranium x-rays from high-purity ^{239}Pu in a subject with an assumed 100% muscle chest-wall = 41 cpm/μCi.
- The linear attenuation coefficients for the following materials are:

  u (muscle) = 1.27 cm^{-1}

  u (fat) = 0.57 cm^{-1}

  u (rib) = 4.41 cm^{-1}

As seen from Table 1, the more fat in the chest wall, the larger the calibration factor. Consequently, a calculation for lung act1vity will represent an overestimate in activity if not corrected for fat content. For example, an average subject with 30% fat in the chest-wall would have a 54% higher estimate of ^{239}Pu lung act1vity if fat content were not corrected. This example is not ent1rely realistic since each person's chest-wall is measured for some fat content. The accuracy of measurement for th1s variable however, is ±10% absolute. This means that if a subject with 20% fat in his chest-wall measured to have only 10% fat, a +14% error in the calculation for ^{239}Pu lung activity would be present. On the other hand, 1f a subject with a 60% fat content were measured to have only 50%, the amount of ^{239}Pu activity in the lung would be high by 52%. Hence, the greater the fat content of the individual, the more significant the fat error in the measurement for plutonium becomes.

Table 1. Effect of chest-wall fat content on calibration factor.

Fat (%)	% Change in* Calib Factor	Calib Factor (cpm/μCi)
0	0	41
10	+11	45.5
20	+27	51.9
30	+54	63.1
40	+104	83.6
50	+190	118.9
60	+340	180.4

The range of observable fat content in individuals undergoing lung counts 1s about 10–60% with most individuals falling within the 20–40% range. Thus, errors in the assessment of plutonium due to fat content alone, can vary from approximately 15–50% as discussed above. We want to reduce these errors such that when combined with chest-wall thickness errors, the total error is within ±25%. Assuming the chest-wall thickness error is limited to 15%, the fat error must be reduced from the worst case maximum of about 50% to 20% in order that the total combined error be ±25%, as indicated in Equation (a).

$$\sqrt{(15)^2 + (20)^2} = 25\% \qquad \text{(a)}$$

To reduce the effect of fat errors from 50% to 20% will require a reductlon 1n the absolute measurement of fat from ±10% to ±4%, according to the relationship indicated in (b). This will encompass nearly all body types that are likely to require ultrasonic measurement, except some females and very obese men.

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* See Fig. 3.

$$\frac{X}{10\%} : \frac{20\%}{50\%}$$

$X = \pm 4\%$

If we assume the average true fat content for most individuals is in the 20–40% range, then the maximum error in calibrat1on factor for fat content at absolute ±10% measurement accuracy will be reduced to about 32% in a person containing 40% fat. This requires a reduction in absolute accuracy down to only about ±6% in order to reach a 20% limit in (a), and could be more readily achieved in practice.

Figure Captions

Figure 1. Estimate of chest-wall thickness using biometric equations.

Figure 2. The counting efficiency changes rapidly with varying chest-wall thickness.

Figure 3. The detector efficiency changes with various percentages of fat in the chest wall.

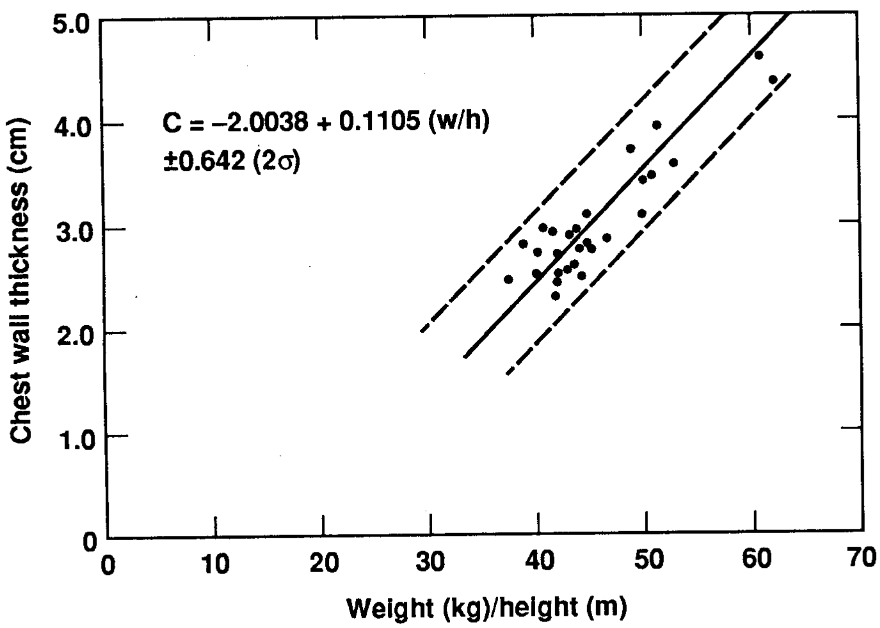
Figure 4. Setup for new ultrasonic imaging method.

Figure 5. Light pressure is applied to prevent distortion of the chest wall.

Figure 6. The chest/lung interface is difficult to discern on the original image.

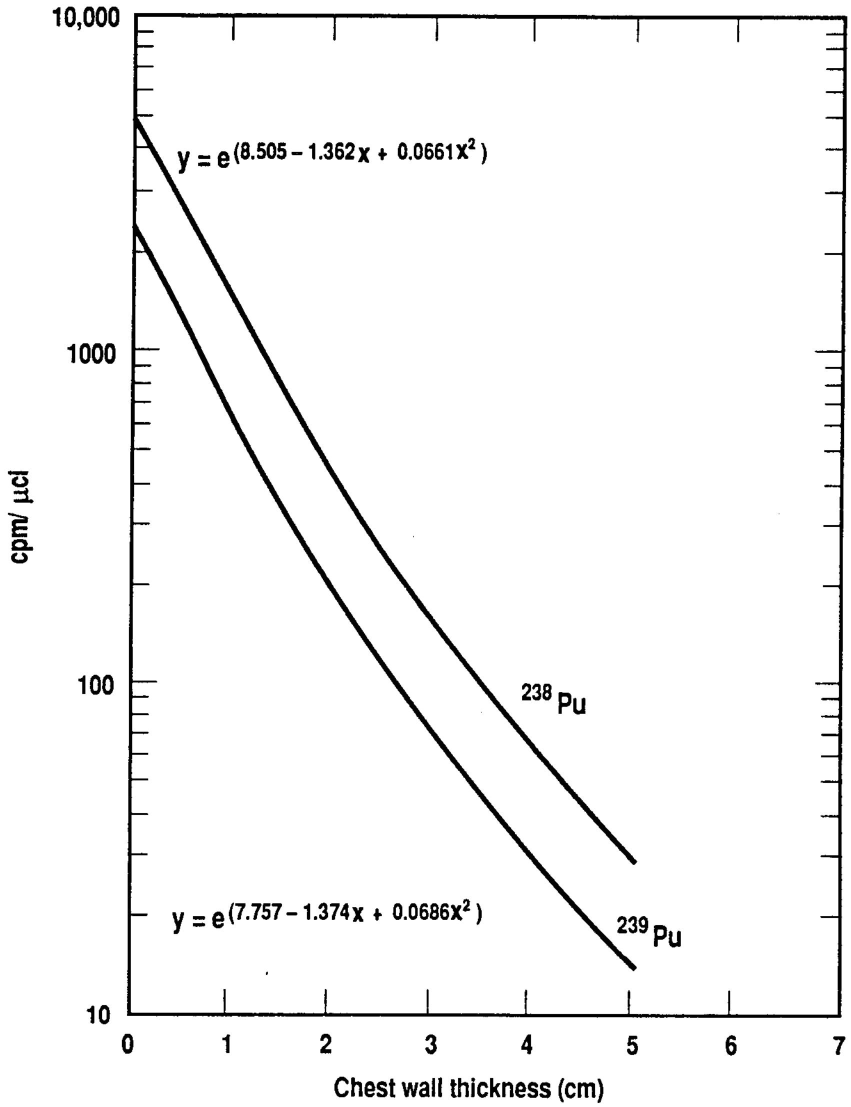
Figure 7. The operator uses a mouse to approximate the interfaces. The computer then more-accurately determines the area of highest echo intensity and places a dash on the screen.

Figure 8. The software can then display the information in graphical form.



5.0
4.0
3.0
2.0
1.0
0
Chest wall thickness (cm)
C = −2.0038 + 0.1105 (w/h)
±0.642 (2σ)
0
10
20
30
40
50
60
70
Weight (kg)/height (m)

Figure 1



10,000
1000
100
10
cpm/ µci
y = e(8.505 – 1.362x + 0.0661x²)
y = e(7.757 – 1.374x + 0.0686x²)
238 Pu
239 Pu
0
1
2
3
4
5
6
7
Chest wall thickness (cm)

Figure 2

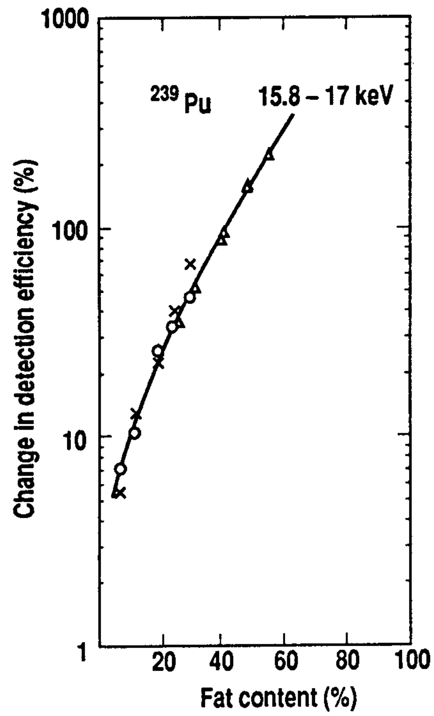

1000
100
10
1
239 Pu
15.8 – 17 keV
Change in detection efficiency (%)
20
40
60
80
100
Fat content (%)

Figure 3

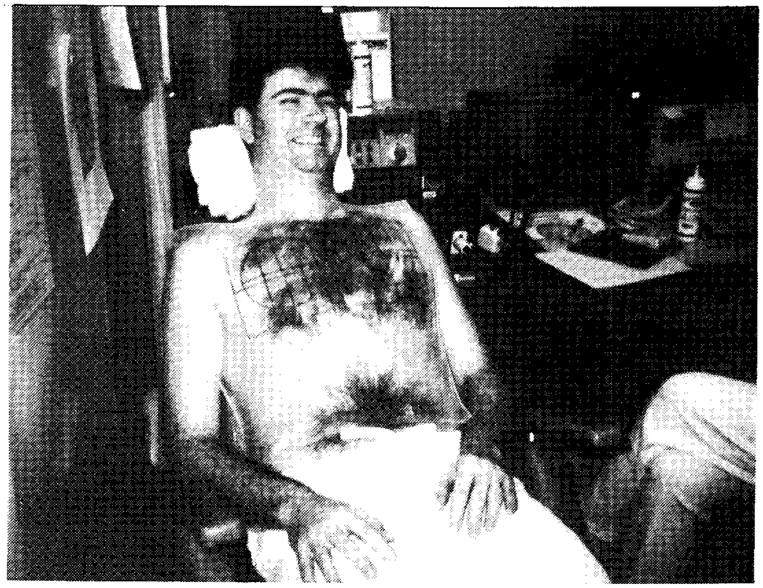


Figure 4

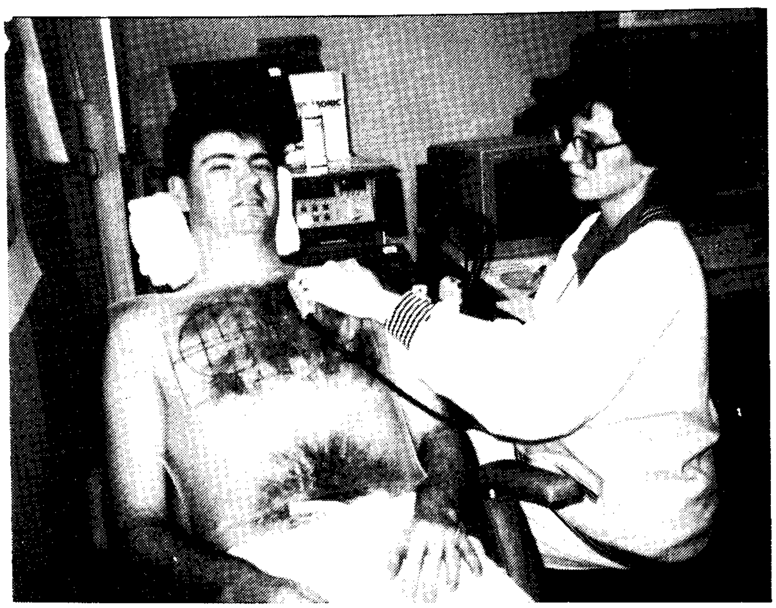


Figure 5

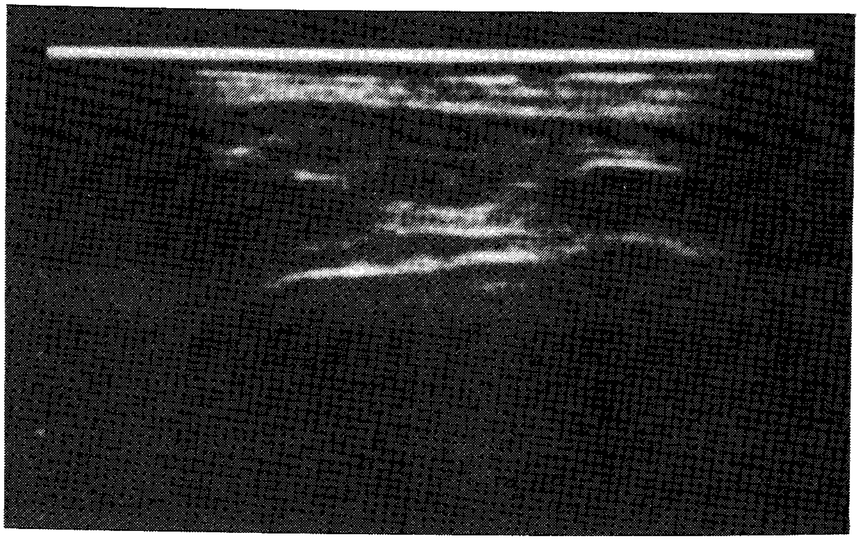


Figure 6

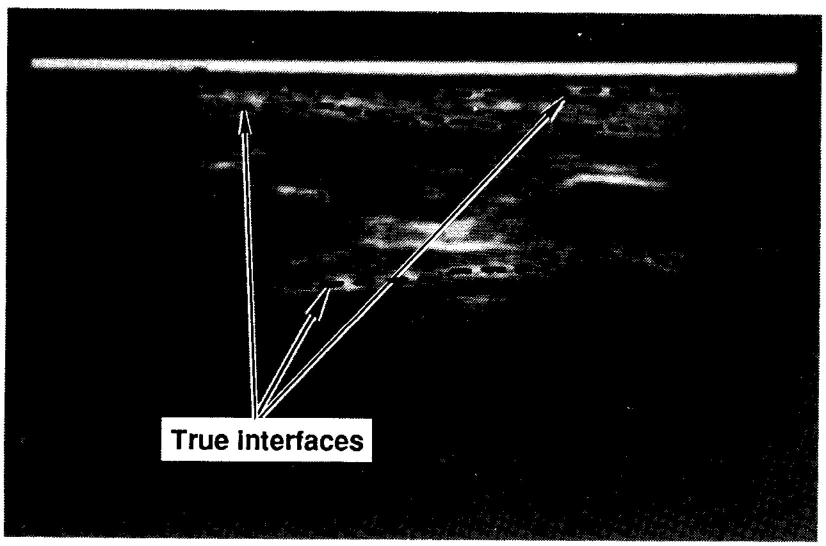


Figure 7

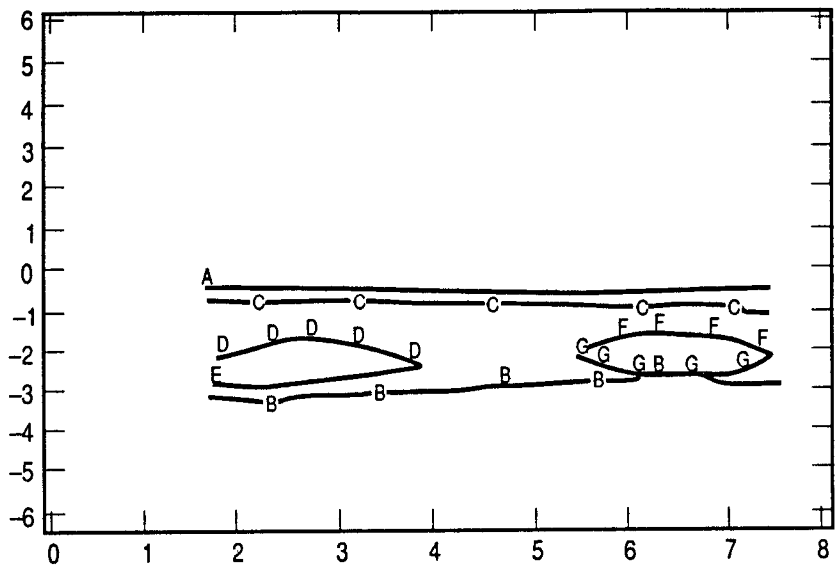


Figure 8

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