Some limitations that impair the picture quality of computed tomography are presented. Picture grain is analyzed in detail and its relationship to different matrix sizes is demonstrated. The choices of matrix size for viewing various parts of the body are defined, and the need for higher resolution in the future is debated. Comparison is made between two scanning systems: the moving fan beam with rotation and the simple rotating fan beam. Possible artifacts in the picture caused by drift and delay in detector response are discussed.

Computed tomography has for some 4 years been used extensively for diagnosing lesions within the head; the technique is now being extended for diagnosis within the body using faster, higher resolution machines.

This system has been operative long enough for most of its capabilities to be appreciated: soft tissue has been rendered visible; the pictures are presented in tomographic form; and a quantitative measurement can be obtained of the x-ray absorption values of the various organs.

The quality of the pictures currently obtained is amply demonstrated in figures 1 and 2. On the whole, the organs appear well defined in outline and tone. However, some imperfections are apparent. It is the purpose of this article to examine some of the major defects in CT pictures, state their causes in simple mathematical terms, and indicate which of these are fundamental to the principles under which the CT system operates. It is important to understand the limitations which govern picture quality before assessing whether the system can be further improved.

Some of the terms used are defined below:

Picture matrix. The picture is made up of a series of absorption values appearing as a grid of equally spaced squares, the number of squares in the vertical and horizontal lines being the matrix size (e.g., 320 x 320).

Spatial resolution. This term defines the clarity of the picture and is determined by the matrix size. It could also be defined as the spatial distance between the squares of the matrix.

Picture accuracy. This is the accuracy to which the absorption value of each picture square can be calculated.

Sensitivity. Sensitivity is a measure of the contrast of the picture (i.e., the width of the range of absorption values or window of values) which reproduces the tones between black and white displayed on the picture.

Limitations Governing Picture Quality

Picture Grain

A major defect that may be apparent on the picture is "picture grain"; this is particularly noticeable in figure 1. While the picture is clear, the clarity of metastasis of the liver (top left) is impaired by a mottled appearance. On the other hand, the kidney in the same picture stands out above the picture grain and appears well defined.

What is the cause of the picture grain? Can anything be done to counteract it? These are important questions since the indistinctness of an image caused by picture grain is a major hindrance to accurate diagnosis.

Basically, picture grain is caused by an insufficiency of photons arriving in the detectors after penetrating the body, and this limits the accuracy to which each picture point can be calculated within the matrix. This random variation of the amplitude of the matrix points is the picture grain, which can be expressed in terms of amplitude and coarseness (fig. 3).

Picture Spatial Resolution

So far, only the inaccuracy of the value of each picture point (grain) has been discussed. Improving picture resolution (gaining clarity) may be more important when variations in the shape of certain organs need to be detected. This obviously involves increasing the number of picture points (i.e., increasing matrix size), which in turn requires scanning with a narrower beam and taking more readings across the body. Unfortunately, the more the matrix size is increased, the greater the grain amplitude of the picture, since the restricted amount of information must now be shared among a greater number of picture points.

The relationship can be expressed as follows: (inaccuracy)$^2 \propto$ (resolution)$^3$ or, in looser terms, (grain)$^2 \propto$ (matrix size)$^3$. Practically speaking, if the matrix size is

![Fig. 1.—Section of abdomen taken through liver and kidneys showing metastasis of liver (top left). Kidney appears much clearer than liver metastasis, which has been impaired by picture grain, due to small variations of tissue density.](image)
doubled from 160×160 picture points to 320×320, the grain will increase in amplitude by a factor of 2.8. However, as indicated in figure 3, the additional grain will be of a finer nature (cf. figs 4A and 4C).

In the strict sense, increasing the matrix size should not be considered as a trade-off between accuracy and resolution, as can be understood if the process is seen in reverse. If accuracy were to be improved by intentionally blurring the picture, it is obvious that extra information is not added. All that happens is that spatial information is removed in the interest of making the picture more intelligible to the eye (which has a limited tone range easily saturated by the presence of excessive grain on the picture).

The presence of grain must be accepted as fundamental to any CT system. Current machines have reached a level of detector efficiency such that grain has been reduced to a level close to the theoretical limit; thus there is little room for improvement unless x-ray dosage to the patient is increased.

**Patient Dosage**

For normal examinations, the dose is usually limited to about 3 R. This is the incident intensity of radiation to the skin and applies to both the head and body. If the slices are taken such that the radiation does not overlap, then the dose to the skin will be the same for one slice as for a series of slices. If dosage exceeds 3 R, the benefits of the examination to the patient must obviously be taken into account.

Picture grain varies according to the relationship \(1/\sqrt{dose}\). Thus with increased dose, picture grain improves. Figure 4B has been taken using four times the x-ray dose used for figure 4A. Consequently, the grain is only half as apparent.

There are obvious factors influencing the amount of x-rays penetrating the patient’s body, such as body width and its mean absorption. These, too, will naturally influence the grain of the picture.

**Choice of Matrix Size**

The differential absorption of the specific organs to be viewed is of fundamental importance in the choice of an appropriate matrix size, since it may be advantageous to show them at the maximum spatial resolution obtainable without impairment by grain. For example, when very accurate readings are required on rather large objects (e.g.,

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Fig. 2.—A. Section through lungs and heart. Window height adjusted to display lung tissue. B. Section approximately 3 cm higher on different patient. Window height adjusted to differentiate fat and tissue of heart. Picture grain of both these pictures considerably improved by reduced absorption of lungs.

Fig. 3.—Plot of frequency spectrum of x-ray photon noise after modification by algorithm for application to picture matrix. Peak amplitude occurs at frequency well below maximum frequency applied to matrix. This lower frequency accounts for coarseness of grain compared to finer detail seen in pictures of certain organs (e.g., kidney, fig. 1), where clarity is result of sum of higher, nonrandom frequencies. The 320×320 curve peaks at twice the frequency, so that a greater amplitude is expected as well as finer grain by factor of two.
scanning for brain tumor or liver metastasis), a coarse matrix is desirable to reduce grain to a minimum. This is illustrated in figure 5 where a picture of a liver is displayed at varying matrix sizes and reduced window widths. The lower matrix sizes show the structure within the liver very clearly. On the other hand, when shape is of paramount importance (e.g., in scanning the vertebrae), a very fine matrix could well be used.

Processing very fine matrices involves at present a lengthy computer operation. This problem is partially overcome by processing only a small area of the picture and magnifying it on a matrix of conventional size. For this reason, in this article matrix size is frequently translated in terms of spatial picture point resolution, assuming that a 320 x 320 picture has a spatial resolution of 1 mm between picture points.
Figure 6 demonstrates the relationship between picture resolution (matrix size) and grain for optimal viewing of various parts of the body.

**Abdomen**

In scanning the abdomen where fat and tissue are well differentiated, a resolution of 1 mm (320 x 320 matrix) is adequate (as can be seen in fig. 1.). However, if finer detail is desired, the matrix size could well be increased, perhaps almost doubled, before the tone range of the picture would be seriously impaired by increased grain. The resolution would then be 0.5 mm, and the image could be displayed using the picture magnification technique as previously described. At the other end of the scale, the spine, owing to its high absorption, could be displayed in fine detail at a higher resolution without serious grain interference (fig. 6).

**Head**

A head scan usually requires discrimination between minute tissue differences for the purpose of tumor location; consequently grain must be reduced to a minimum. Twenty times as many x-rays penetrate the head as do the abdomen, but the resultant reduction of grain is still insufficient for fine discrimination. It is therefore preferable to use a low resolution 160 x 160 matrix rather than a 320 x 320. This is illustrated in figures 4B and 4C where on a 160 x 160 matrix grey and white matter are clearly distinguished, but on a 320 x 320 matrix they are not. (To take advantage of the reduced grain, figure 4B has been displayed at three times the sensitivity.)

However, if one is looking at the bone of the head or at the middle ear, the matrix may be increased to 320 x 320 (1 mm resolution) as in figure 4D and could be taken as high as 0.25 mm before the picture would be seriously affected by grain.

Scanning the inner ear and the eye would benefit from matrices 320 x 320 or a little larger.

**Heart**

Heart scans, where the x-rays also penetrate the lungs, benefit from the low mean absorption path caused by the presence of air in the lungs. The presence of fat in certain parts of the heart can be clearly seen on a 320 x 320 matrix.

If the effects of heart motion can be satisfactorily reduced either by synchronization or by much higher machine speed, conditions for scanning the heart would be similar to those for the head. Since slight differences between tissue and blood would have to be detectable, a low resolution of
between 160 × 160 and 320 × 320 would be preferable.

**Lungs**

Figure 24 shows the lungs on a 320 × 320 matrix. Although this matrix has produced a clear picture at 1 mm resolution, it should be possible to take an even clearer picture at 0.25 mm spatial resolution which would be reasonably grain free. The high absorption differential between air and lung tissue makes this possible. However, if the lung tissue must be measured quantitatively, it would be more practical to use the lower resolution matrix.

**Implications of Maximizing Resolution**

Is there anything to be gained diagnostically by increasing resolution to its highest possible limit? At present CT is performing very well at low and intermediate resolution. It is successful mainly because it is a highly efficient method of isolating similar soft tissue organs which would normally be superimposed in conventional x-ray pictures or which, because of their similarity, would be virtually indistinguishable even if x-ray film were sensitive enough to detect them. In these areas, CT has no competitor in the x-ray field. As seen in figure 6, most of its uses require a resolution of between 160 × 160 and 640 × 640.

If resolution were to be increased to its maximum, the picture grain would accordingly increase and the uses of CT would have to be limited, in general, to the examination of contrast media and bone. It would then be competing with conventional x-ray techniques.

In this situation, CT has the advantage of greater detector efficiency than conventional x-ray film methods: it would compete very favorably, producing pictures of either higher resolution or greater sensitivity. The system's ability to position objects three dimensionally and to measure their absorption values would remain an added bonus.

However, these advantages may well turn out to be of only moderate diagnostic value. Moreover, a high resolution machine would be very complicated and costly under present technology, and it would be difficult to justify these costs unless there were a spectacular breakthrough in machine design, to simplify construction.

**Scanning Systems and Their Artifacts**

Picture grain caused by x-ray photons is unavoidable in any x-ray scanning technique. Whatever system is used, the nature of the grain cannot be improved beyond the extent demonstrated above. A picture may also be deteriorated by artifacts caused by the machine, depending on the scanning system adopted. It is possible to imagine many different scanning techniques which would operate satisfactorily, but the following two are probably the best known. A discussion of their respective merits and the artifacts peculiar to each follows.
**Description of Systems**

**Moving fan beam with rotation.** In this system, the fan beam scans across as well as rotates around the patient (fig. 7A). One advantage of this system is its flexibility. Both the length of the scanning stroke taken across the patient and the spatial interval between readings along each stroke can be changed. The scale of the picture can therefore be varied, magnifying small areas if desired.

The detectors can be calibrated outside the body at the end of each stroke, and their electronic stability is not a serious problem. However, owing to mechanical limitations, the maximum speed at which the system can operate is about 10 sec per picture.

**Rotating fan beam.** This method uses a wider fan beam and has a rotational motion around the body only (fig. 7B). The advantage of this system is that it can operate faster than the one previously described since the fan beam, being wider, can take three times as many readings in a given time. In addition, no time is lost at the end of the stroke in reversing the direction of the traverse (as in system 1).

However, many more expensive detectors are required, and these have to be fixed in pitch to fit the largest patient. Since the detector spacing and beam width are fixed, it is difficult to vary the resolution of the machine. Many detectors could be redundant when small patients are scanned. The system is therefore less flexible for viewing small areas. Maintaining electronic stability and calibration of the detectors are major problems and may be a possible cause of artifacts (see below).

**Artifacts**

In both machines the detectors take readings over a wide range of values, and here technology is stretched to the limit. Any imperfections in the detectors may cause artifacts which take different forms according to the particular scanning system used. The main problem areas are drift of detector sensitivity and delay in detector response.

**Drift of detector sensitivity.** In the moving fan beam system, the picture is affected very little by mismatch of detector gain within the bank of detectors. During each stroke, the detectors scan across the whole body, so that detector error is spread across the entire picture and does not concentrate in any one place. The only effect is a change in overall picture intensity which can easily be calibrated out.

In contrast, the rotating fan beam geometry by no means spreads the detector errors evenly across the picture (fig. 8). Certain areas (particularly at the center of the body) are seen exclusively by specific detectors or groups of detectors. It is therefore necessary to match the gain of these detectors extremely accurately if concentric circles are to be prevented. A mismatch of one part in 5,000 could cause the circles to appear, resulting in a spot at the center.

In pictures of the abdomen, with favorable detector calibration these artifacts may tend to merge into the picture grain. But in the case of the most sensitive pictures of the head, it remains to be seen to what extent these artifacts can be eliminated by machine design.

**Delay in detector response.** The detectors have to take readings over a very wide range of values. When large
Changes occur, such as at the edges of bone, small delays in detector response (lag) can cause artifacts which show up in different ways on the two systems.

Figure 9 illustrates the artifacts on the pictures of the two systems when two dense bones are scanned. In the case of the moving fan beam system, the error is evenly dispersed around the object, whereas for the rotating fan beam, it takes the form of a concentrated tail which could result in a more objectionable artifact of higher intensity.

One is left with the impression that neither system is the final word in CT scanning technique and that, in the future, systems will be devised which incorporate the benefits of both.

Conclusions

In the field of differentiation of soft tissue by x-ray and of viewing the shape of soft tissue organs, CT has no rival. However, its performance is limited by the extent to which photon noise can be tolerated in the picture. This limitation is fundamental to the system, and the clarity and accuracy of the picture are not expected to improve spectacularly in the future.

On the other hand, for viewing objects of greater differential absorption than soft tissue, the machine could be stretched considerably further in resolution and could improve on the performance of conventional x-ray machines. At present it is difficult to say whether the added diagnostic value would warrant the greater complexity of the machine, but it is to be hoped that simpler techniques may eventually be found.

Many different systems for scanning the patient are likely to evolve in the future, and some of these may be faster. Each will have its own advantages and disadvantages, and only time and further experimentation will tell which technique will survive.

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SELECTED REFERENCES