Total Digital Radiology Department: Spatial Resolution Requirements

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The minimum spatial resolution required for a total digital radiology department has yet to be defined. A pilot study designed to provide this information was performed. Abnormal and normal radiographic images of children were digitized and redisplayed on film at spatial resolutions of 5.0, 2.5, 1.25, and 0.625 lp/mm. These resolutions are comparable to a digital display of a 14 × 14 in. chest image having pixel elements of 4096 × 4096, 2048 × 2048, 1024 × 1024, and 512 × 512, respectively. Contrast resolution was maintained at 12 bits or 4096 gray levels. The three phases of data acquisition were (1) the standard analysis of receiver operating characteristics, (2) a checklist evaluation of the "seeability" of important structures, and (3) a comparison of all resolutions and a discernment of usability. Fifteen radiologists participated in the study. On the basis of the pediatric cases used, the results showed that the needed spatial resolution for a total digital radiology department may be around 2.5 lp/mm (2048 × 2048). Checklist data on seeability of structures and comparisons of all resolutions give information on specific changes that are occurring as the resolution is decreased, and, when included with the receiver-operating-characteristic data, they become a major component in developing a resolution standard. The finding that 2.5 lp/mm is the required spatial resolution makes construction of a total digital radiology department possible with present state-of-the-art technology.

The total electronic or digital radiology department becomes more possible every year because of the electronic revolution and the consequent increase in computer power and capabilities [1–3]. One major requirement is that performance proficiency must be equal to or better than that permitted by the existing film-based system. Therefore, establishing the spatial- and contrast-resolution needs for such a department is imperative.

Contrast resolution has the greatest effect on general diagnostic accuracy. However, in terms of engineering design requirements for a total digital radiology department, spatial resolution has the greatest impact on design costs, transmission-speed requirements, and storage needs. For example, assume that a 1024 × 1024 pixel spatial resolution with a 10-bit gray-scale contrast resolution is not sufficient to give the radiologist equivalent diagnostic information on a digital display as compared to a 14 × 14 in. (35.6 × 35.6 cm) chest film. Doubling the spatial resolution will increase the amount of information to be manipulated in each image by 300%, whereas doubling the contrast resolution from 10 bits to 11 bits will increase the amount of information to be manipulated by only 10%.

This pilot study used clinical images to investigate spatial-resolution requirements for a total digital radiology department.

Materials and Methods

Original clinical film images were digitized and written back to film at spatial resolutions of 5.0, 2.5, 1.25, and 0.625 lp/mm. These resolutions are comparable to a digital display of a 14 × 14 in. chest image having pixel elements of 4096 × 4096, 2048 × 2048, 1024 × 1024,

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and 512 × 512, respectively. Contrast resolution was maintained at 12 bits. For this study, the display medium was always film.

Eight pediatric cases (four with interstitial lung disease and four normals) were selected. The abnormal radiographic findings accepted as correct for the four disease cases were (1) diffuse interstitial infiltrates, especially in the right and lower lung—possible pulmonary edema; (2) bilateral rib notching, diminished pulmonary vascularity, increased interstitial markings, and diminished bilateral pulmonary vascularity associated with abnormal cardiac configuration; (3) peribronchial thickening, increased interstitial markings, and possible cystic fibrosis or asthma; and (4) diffuse bilateral infiltrates and wet lung/edema. Truth of diagnosis was based on follow-up radiographs. For the normal cases, subsequent normal radiographs were required.

Normal cases were matched to the disease cases for film type, density range, age, and sex. Each case was digitized by using a 100-μm aperture on a Boller and Chivans flatbed microdensitometer (Applied Science Division, Perkin-Elmer, Garden Grove, CA). The number of points per line and the number of lines were set to 2048 × 2048 and covered an area of approximately 8 × 8 in. (20.3 × 20.3 cm) which was sufficient to include all the necessary information. This sampling procedure gave a resolution of 5 lp/mm without concern that we were introducing sampling error. The resulting digital images were then stored in a VAX 11/780 computer (Digital Equipment Corp., Maynard, MA), and a Gaussian blur function was applied to the original images. For creation of different spatial resolutions, the Gaussian blur's full width at half maximum was increased, thereby increasing the diameter of the blurring function so that it averaged more of the data as the resolution was decreased. The values used were 2, 4, and 8 for 2.5 lp/mm, 1.25 lp/mm, and 0.625 lp/mm, respectively. Tests were run on the blurred images to ensure that any changes introduced would be within acceptable tolerances. The mean and standard deviation of the pixels were calculated for the original and all the blurred images. If the blurred images were being produced properly, the means should have been the same and the standard deviations should have decreased as blur increased. This was the case for all images.

The flatbed microdensitometer was then used to write the four sets of 2048 × 2048 image matrices (differing only in their spatial resolution) on Kodak OM-1 film (Eastman Kodak Co., Rochester, NY). Each image took 4 hr to write. The total time for digitization and writing was 160 hr. A look-up table was incorporated to increase or decrease the light in the light-emitting diode in order to achieve the same contrast levels as those measured in the original images. The look-up table was created by digitizing a conventional radiograph of a step wedge, writing it back to film, developing the film, and then comparing the resulting densities measured with a densitometer to the original step wedge. A corrective look-up table was then incorporated to adjust the light-emitting diode's intensity as it wrote back to film. The process was continued until the difference between the original and the copy deviated by no more than 2%. This same step wedge was written to film many times and was used to standardize the radiographic film developer. Each time a batch of films was ready to be processed, the step wedges were put through the processor first, and adjustments were made until the densities measured were the same as those of the original step wedge. Once that was accomplished, the films were processed. This pilot study used not only the four sets of digital images written to film but also the original analog images. The original images provided a basis of comparison for the digitized images.

Three phases of data acquisition were used in this study. In the first phase, each of the 15 participating radiologists was shown images from only one resolution level. Because there were five sets of resolution images (four digital and one analog), the results discussed in the following sections represent the answers from three radiologists per resolution level. To counter any bias due to this experimental design, the radiologists in all groups were matched on background, experience, and familiarity with pediatric chest images. The observers were a mix of fourth-year residents and junior and senior staff members. During each session, four types of data were acquired. First, the images were shown one at a time in random order to the participating radiologists. Their task was to decide whether the findings were abnormal. They used a six-point certainty scale as described in Seeley et al. [4] when giving their diagnoses so that an analysis of standard receiver operating characteristics could be performed [5–7]. If the finding was abnormal, the radiologist was required to state the type of abnormality and location of the disease. In the second phase, the case images were displayed again one at a time, but this time the radiologists were asked to rate the "seeability" of different structures. The checklist used for the thorax images and most of the scale used to define the perceptibility of the structures are described fully in Seeley and Newell [8]. The third type of data acquired was the subjective evaluation of each radiologist concerning the usability of different levels of spatial resolution. In this phase, all the resolutions for selected cases were put on the light box, and the radiologist assessed each spatial resolution level. Finally, eight radiologists were given images of the same case in random order and had to place the images in order of highest to lowest resolution. These eight radiologists fully represented the cross section of observers used in the study. Only eight were used because of time constraints.

Results

Analysis of Receiver Operating Characteristics

Figure 1 shows the receiver-operating-characteristic curves and the areas under the curves for all of the five resolutions studied. In general, the results were very clear. The 0.625 lp/mm spatial resolution was not acceptable. The information

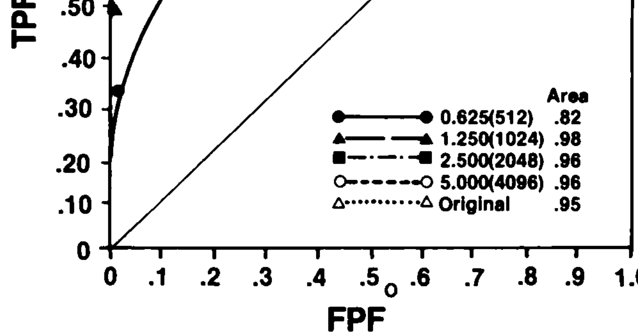

Fig. 1.—Receiver-operating-characteristic curves and areas under the curves for the five resolutions studied. TPF = true positive fraction; FPF = false positive fraction.

content from the 1.25 lp/mm resolution was virtually equivalent to that of the original films. A detailed analysis of the responses showed that the radiologists viewing the 0.625 lp/mm resolution reported 70% false-positives, therefore overcalling these images. This result was also verified anecdotally in conversation with the radiologists.

Checklist Analysis

The findings in the receiver-operating-characteristic analysis were further substantiated by the results of the data analysis of the seeability checklist. Table 1 shows the type of structures that disappeared. The ratio X/Y means that at the lowest resolution, the structure was seen only X times out of the Y total for all resolutions (i.e., Y maximum = 75, 15 radiologists at 5 resolutions). Frequently, structures were not imaged at all at the low-resolution. What disappeared was the fine detail or the sharpness of the edge resolution.

Comparison of Resolutions

The next set of data was consistent with the previous two. When the radiologists viewed all the different resolution levels at one time, they unanimously agreed that (1) they would not want to work with the 0.625 lp/mm resolution; (2) although they could see everything necessary on the 1.25 lp/mm resolution images, they did not feel comfortable with these images; and (3) they would be satisfied to work with the 2.5 lp/mm images and did not think that the 5.0 lp/mm level was necessary. This last point was supported by the data from the eight radiologists who were asked to put the images in order of resolution from low to high. All eight correctly ordered the 0.625 and the 1.25 lp/mm images. However, in comparing the 2.5 and the 5.0 lp/mm images, two of the radiologists were unable to differentiate between the two.

TABLE 1: Type of Structures That Disappeared in the Lowest Resolution

Structure	Ratio of Structure Seen (X/Y)
Peripheral structures	
Interstitial structures	4/55
Pulmonary vascular structures	7/62
Edge resolution	
Hilar bronchial structures	2/55
Hilar vasculature	7/62
Osseous erosions	
Ribs	0/41
Clavicles	0/30
Cortical structures	
Ribs	5/64
Clavicles	6/56
Trabecular structures	
Ribs	0/35
Clavicles	0/27

Note.—Ratio X/Y: the structure was seen X times at the 0.625 lp/mm resolution out of Y total sightings at all five resolutions. In many cases the structure was not seen at all at the lowest resolution.

Discussion

Experiments dealing with the evaluation of clinical images must be carefully controlled. Several choices and solutions went into the planning and implementation of this experiment.

For the experimental phase, we needed to ensure that the images and experimental situation were as close as possible to the radiologists' accustomed clinical conditions. Film was selected as the display medium for this study because (1) film is what the radiologist is used to, and it has been shown that introducing a new system can greatly affect the sensitivity of the radiologist [4]; and (2) no other type of medium can display all of the different resolution levels. Once it was decided to use film, Kodak OM-1 film was chosen because it had the same type of blue background that the radiologist was expecting (we would not be introducing bias due to an unfamiliar background), and it was one of the few films sufficiently sensitive to the light-emitting diode that we were using.

The upper limit of 5 lp/mm was chosen because this is the point for standard film-screen systems at which the modulation-transfer function levels off, and it is the standard spatial resolution in clinical practice. Because this study was concerned with spatial resolution only, contrast resolution was taken at 12 bits to ensure that any effects due to contrast or contrast-spatial resolution interactions would be virtually eliminated. We used a Gaussian blur function to reduce resolution. It best simulated what would occur with imaging systems of different spatial-resolution acquisition capabilities, and it allowed us to maintain the same number of scan lines in each of the resolution levels, thus avoiding problems or bias due to the images not being equal in every aspect except spatial resolution (i.e., artifact introduction through the reduction of the number of lines and pixels in each line whether through averaging or subsampling). The objective was to ensure that the resultant images would be truly representative of images from acquisition systems of different spatial capabilities.

Figure 2 shows all four resolutions for one of the cases used in the study. Fine-detail resolution is degraded as resolution decreases. To show how much information was lost at the different resolution levels, a 512 × 512 section was taken from the 2048 × 2048 digital matrix and displayed on the monitor. Figure 3 is a composite of these images. Each part is the upper left-hand corner of the corresponding image in Figure 2. Once the 512 × 512 sections were extracted, the 2.5, 1.25, and 0.625 lp/mm resolutions were subtracted from the 5 lp/mm section. Figure 4 shows the type and amount of information that are lost as the spatial resolution decreases. As can be seen from the increase in fine detail, when lower and lower resolutions are subtracted from the 5 lp/mm image, there is a definite loss of high-frequency information as spatial resolution decreases. Thus, there is a marked decrease in information content for the radiologist to use for diagnosis. However, smaller losses in high-frequency information seem to give acceptable diagnostic accuracy as was described for the analysis of receiver operating characteristics.

The results of the study show that, on the basis of the pediatric cases used, the needed spatial resolution for a total

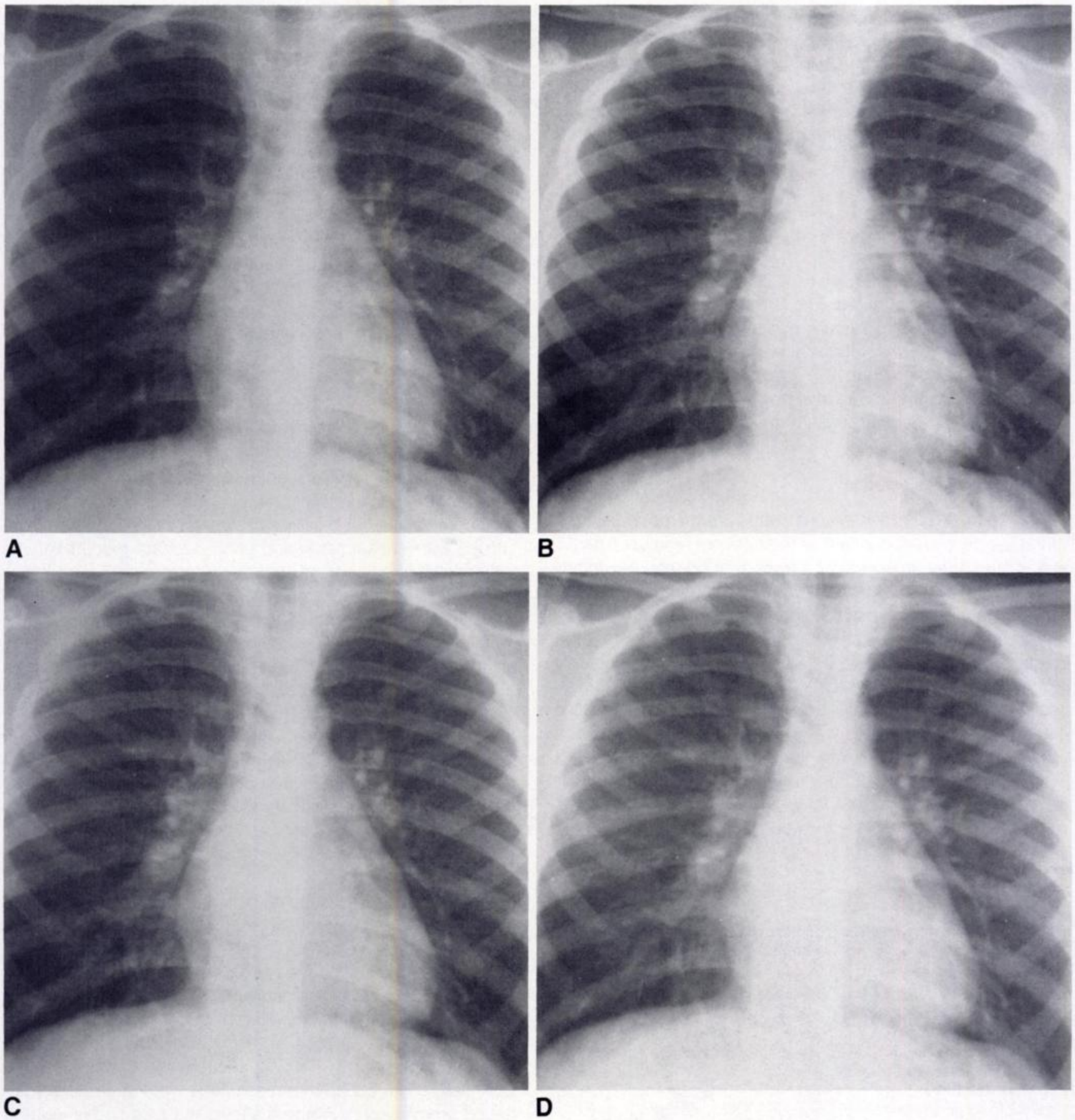

Fig. 2.—Chest radiographs showing images at four resolutions for one case in the study. *A*, 5 lp/mm. *B*, 2.5 lp/mm. *C*, 1.25 lp/mm. *D*, 0.625 lp/mm.

digital radiology department may be around 2.5 lp/mm (2048 × 2048). Checklist data on seeability of structures and comparisons of all resolutions give information on specific changes that are occurring as the resolution is decreased, and, when included with the receiver-operating-characteristic data, they become a major component in development of a resolution standard.

Although the results of this study are intriguing, a statement on the resolution requirements for a total digital radiology department must be tempered. The results are based on a small number of images and a small number of radiologists, with a relative paucity of data for constructing the receiver-

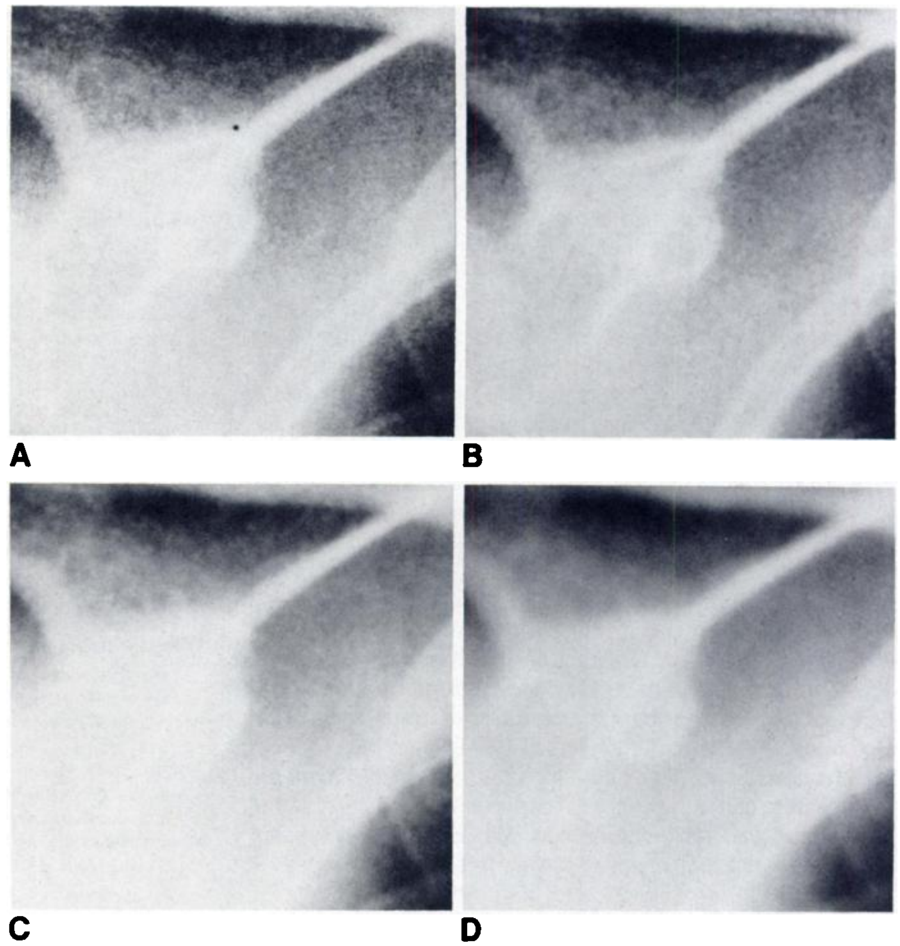

Fig. 3.—512 × 512 section taken from 2048 × 2048 matrix that made up digital images. Each shows upper left-hand corner of corresponding image in Fig. 2. *A*, 5 lp/mm. *B*, 2.5 lp/mm. *C*, 1.25 lp/mm. *D*, 0.625 lp/mm.

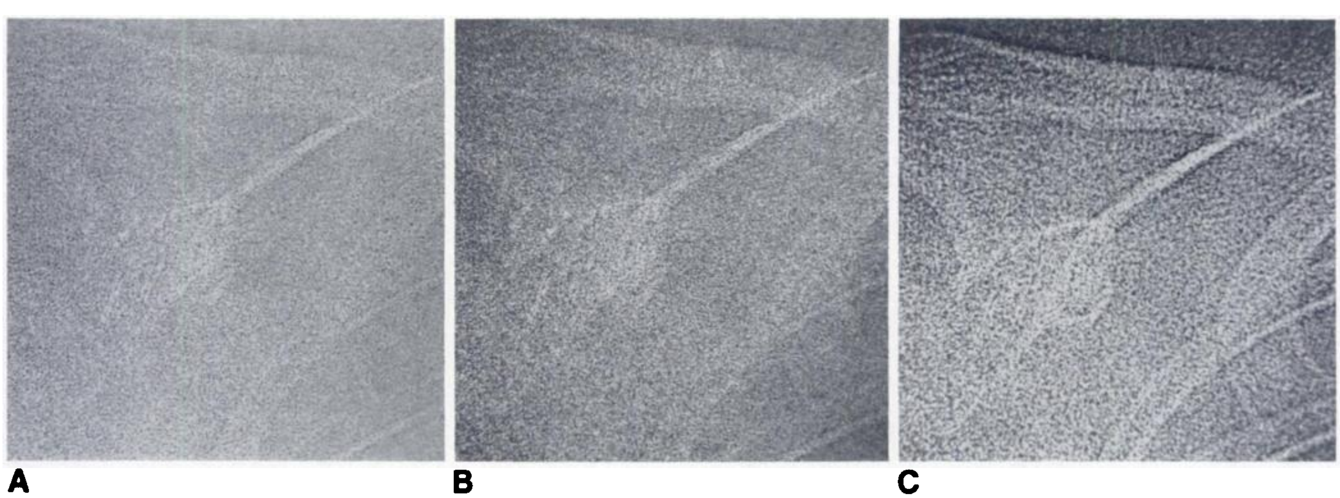

Fig. 4.—Resulting images from a subtraction of all lower resolution sections from 5.0 lp/mm image in Fig. 3A. Amount of structure lost as resolution is decreased can now be seen. *A*, Subtraction of 2.5 lp/mm section. *B*, Subtraction of 1.25 lp/mm section. *C*, Subtraction of 0.625 lp/mm section.

operating-characteristic curves. However, the images selected were the most demanding in terms of spatial-resolution requirements. In addition, even in the first phase of this pilot study [8, 9] when only two radiologists were being analyzed per resolution level, the same results were found.

The findings of similar results with as few as two observers per resolution level and the demonstrable loss of adequately visualized structures lead us to anticipate similar results in the larger scale studies that we have planned. If this occurs, then the problems of building a total digital radiology department may not be insurmountable.

In the resolution-comparison phase of this study, many of the radiologists were surprised that resolutions such as 1.25 lp/mm compared so favorably to the original in the quality of diagnostic information. They pointed out that this was the first time they were able to see, at one time, all the resolutions that are referred to in the literature. All of them suggested that although 1.25 lp/mm images might be adequate for most cases, they favored 2.5 lp/mm as a standard.

This study also shows that with proper care, all aspects of the experimental situation—from the selection of the images, through the generation of the experimental images, to the actual data-taking—can be controlled well enough to provide consistent and useful data. In addition, taking three different types of data during the experiment gives a much broader picture of what happens when spatial resolution is reduced than using only receiver operating characteristics. This type of research can never find "the answer" because all the possibilities can never be tested with the finite time and resources available. However, having three different types of data that correspond so consistently increases the certainty that the results actually reflect true phenomena.

A more comprehensive study is now in progress with more cases (50) and more radiologists (20). The results from that study will be reported subsequently.

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