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Optical versus Radiographic Magnification for
Fine-detail Skeletal Radiography

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Abstract

Fine-detail radiographic techniques for peripheral skeletal imaging have gained wide clinical acceptance. In this study, the imaging properties and clinical applications of the optical magnification technique, which employs fine-grain industrial film and a large focal spot, have been compared quantitatively and qualitatively with those of three slow screen-film techniques, namely, contact exposure with a large focal spot, 2X radiographic magnification with a 0.3 mm focal spot, and 4X radiographic magnification with a 50 μ focal spot. The modulation transfer functions (MTF's) of the recording systems and focal spots have been obtained and film sensitometry has been performed. Clinical comparisons for patients with metabolic, arthritic and neoplastic skeletal disorders have been made. The results illustrate the superiority of the optical magnification technique over contact or 2X magnification techniques using slow screen-film systems. If a microfocus tube is used, however, direct radiographic magnification may provide images comparable in resolution, noise and contrast to those made with the optical magnification technique, and at lower radiation exposure to the patient.

Key words: fine-detail skeletal radiography; image quality; optical and radiographic magnification.

Fine-detail skeletal radiography using industrial film and optical magnification has found wide clinical application, and the resulting enhanced diagnostic capability has been well documented.^{2,14-19,30,31,40} We have employed this technique in over 2,000 patient examinations during the past two years and have previously reported on its efficacy in rheumatoid arthritis,²⁷ primary hyperparathyroidism^{18,19} and the shoulder-hand syndrome.²⁴ In addition, we have examined in depth the physical parameters of image quality in fine-detail skeletal radiography and have reported achieving a near optimization of this technique for practical clinical purposes.¹⁰ Nevertheless, several inherent disadvantages remain: 1) High radiation dose to the patient; 2) occasional motion unsharpness, 3) the need for manual or industrial film processing; and 4) the requirement of special viewing procedures. As an alternative, direct radiographic magnification techniques for detail skeletal imaging have been advocated by some clinical investigators.^{5,22,39} These procedures employ smaller focal spot x-ray tubes in conjunction with slow screen-film systems, and may overcome some of the limitations of the optical magnification technique.

The purpose of this study is to examine several of the high resolution radiographic techniques, both quantitatively and qualitatively, comparing basic imaging properties as well as clinical applications.

Experimental Design

Four techniques have been compared, as shown in Table 1. The first is the fine-detail technique incorporating optical magnification of 4 to 10X,²⁶ which we have been using clinically for hand radiography.¹⁶⁻¹⁹ This is a non-screen technique in which Kodak Type M film is exposed with 50 kVp and a 1.2 mm focal spot.* For contact radiographs of the hand, a magnification of 1.02 is assumed on the basis of a mean object plane-film distance of 24 mm and a focus-film distance of 120 cm.^{12,16} For the three screen-film techniques, Kodak RP film with DuPont Detail screens is used. The first of these is a conventional contact exposure with a 1.2 mm focal spot. The second consists of 2X radiographic magnification with a 0.3 mm focal spot,* and the final technique is 4X radiographic magnification with a microfocus tube[†] having a nominal focal spot size of 50 microns. The latter technique, unlike the former three, uses 65 kVp, which is the minimum setting obtainable with this x-ray tube. Thus, the non-screen optical magnification technique will be compared with three screen-film techniques, namely, contact exposure, 2X, and 4X radiographic magnification.

* Philips, superrotalex x-ray tube.

† Siemens, Bi 125/3/50 RG x-ray tube.

Methods and Measurements

In order to assess the speed and contrast of these techniques, film sensitometry has been performed and the resulting characteristic curves for Type M and RP-Detail systems have been obtained. The slope or gradient has been derived from the first derivative of the characteristic curve and indicates the contrast of the recording system.²¹ The radiation exposure to the patient for the four techniques has been estimated from the H & D curves and the magnification factors.

The modulation transfer function describes the signal transmitting capability of the imaging system in the spatial frequency domain.^{2,35} In this study, the MTF's of the recording systems have been obtained from the digital Fourier transformation of 1 μ slit images.^{16,35,36} The MTF's are derived for the object plane rather than for the image plane in order to facilitate the comparison of imaging performance for various techniques having different radiographic magnifications;⁹ i.e., the imaging capability of each technique is evaluated with respect to the original object size.

The MTF of geometric unsharpness is obtained from the MTF of the focal spot and the magnification factor.^{11,34} The MTF's of the 1.2 mm and 0.3 mm focal spots are determined experimentally by means of digital Fourier transformation of

slit images.¹¹ The MTF of the microfocal spot is derived theoretically, assuming a 100 μ focal spot size with a uniform distribution. This size was selected on the basis of preliminary measurements on our own microfocus tube, and is similar to the measurements reported by Takahashi's group.³⁸ The MTF for contact exposure with the 1.2 mm focal spot assumes a magnification factor of 1.02 as indicated above.

The total MTF's for these four systems are derived from the product of the component MTF's of geometric unsharpness and the recording system.^{36,37} The resulting data indicate the overall resolution for each technique.

For qualitative study, microwire meshes have been radiographed with the four techniques. The test object contains cyclic fine structures having fundamental spatial frequencies of 4, 8, 13, 16, and 20 cycles per millimeter, and provides a means of comparing qualitative and quantitative results. A steel wool object containing a random distribution of fine wires, 10 to 30 μ in diameter, has also been radiographed with the four techniques. This test object may approximate fine skeletal structures more closely than the cyclic microwire mesh.

The effect of noise^{35,37} on the imaging performance for very small, low contrast objects is assessed by qualitative inspection of the microwire mesh and steel wool test objects.

Quantitative assessment by means of Wiener spectrum analysis is currently in progress.^{7,10}

Clinical examples have been obtained using the three commonly available high-resolution techniques and, in some cases, using the 4X magnification technique as well. The clinical material has been drawn from patients with rheumatoid arthritis, reflex neurovascular dystrophy, pseudogout, primary hyperparathyroidism, renal osteodystrophy, and bone tumors.

Results

Image quality studies. The characteristic curves and gradients for Type M and RP-Detail systems are shown in Figure 1. The greater speed and latitude of the screen-film system can be appreciated from the H & D curves.²¹ It is apparent from the gradient curves that, for optimal contrast, an average photographic density of approximately 1.5 is selected for hand radiographs using the RP-Detail system while a density of 2 or greater is selected for radiographs using Type M film. Thus, the contrast for the Type M technique is greater than that of the screen-film system, but necessitates high intensity illumination for viewing.

The estimated relative patient exposures for the four techniques are shown in Table 2. The radiation exposure per unit area of the patient when Type M film is used is approximately 75 times that needed for contact exposure with RP-Detail. With increasing radiographic magnification, the patient

exposure increases approximately as the square of the magnification factor.⁸ Thus, with 4X radiographic magnification the patient exposure increases to approximately 16 times that of contact exposure, yet is about 1/5 of that of the Type M technique.

The MTF's of the recording systems are shown in Figure 2 and are displayed for the object plane. The curve for Type M film shows a 1% decline in the spatial frequency range demonstrated, i.e., up to 20 cycles/mm. The MTF for RP-Detail with contact exposure is quite poor by comparison. With 2X and 4X radiographic magnification, the MTF of the recording system in the object plane improves due to the wider image distribution relative to the screen-film system.^{1,5,6}

Figure 3 represents the MTF of geometric unsharpness. The MTF for contact exposure with a 1.2 mm focal spot is considerably better than those for the direct radiographic magnification techniques. The geometric unsharpness resulting from 2X magnification with a 0.3 mm focal spot is quite large and results in considerable loss of detail resolution.

The total MTF's for the four systems are displayed in Figure 4. The curve for the Type M technique indicates the greatest detail resolution, whereas the poorest resolution occurs with the 2X magnification technique (except in the very low spatial frequency range where it is similar to that of contact

RP-Detail). The total MTF for the 4X magnification technique appears to be better than that for contact RP-Detail, particularly in the low spatial frequency range.

Qualitative results with microwire meshes corresponding to the MTF data are presented in Figure 5. The images have been made equal in size photographically to facilitate visual comparison of image quality relative to the object. With Type M technique all the wire meshes are resolved, as predicted by the total MTF in Figure 4. Likewise, the poorest resolution occurs with the 2X magnification technique in which the largest wire mesh corresponding to 4 cycles/mm is barely resolved. Both the contact and 4X screen-film techniques resolve the two largest wire meshes. In Figure 6, images of the steel wool test object are shown. These minute structures are well visualized with the Type M technique and can be seen with the 4X magnification technique. Neither the contact RP-Detail nor the 2X RP-Detail methods image the steel wool.

The effect of noise on image quality is also well demonstrated in Figures 5 and 6. The fine grain emulsion of Type M permits superior visualization compared to RP-Detail techniques. However, it should be noted, that with increasing radiographic magnification, the system noise diminishes relative to image size due to increased signal-to-noise ratio.⁹ Thus, for the screen-film techniques, the imaging performance of 4X

magnification is superior as a result of improved noise effect, as well as better total MTF.

Clinical studies. A comparison of the three commonly available high-resolution techniques in a patient with rheumatoid arthritis is demonstrated in Figure 7. The Type M technique reveals subtle, but definite erosion of the metacarpal head. This ragged, dot-dash or saw-toothed appearance is an early and important manifestation of erosive articular disease in rheumatoid arthritis^{2,15,27,28} and is not detected with the two screen-film techniques. The contact exposure with RP-Detail has less unsharpness, but greater noise than the 2X magnification technique. Similar results for the proximal interphalangeal joint are shown in figure 8.

The capacity of the three techniques for assessing bone resorption²⁴ in reflex neurovascular dystrophy or shoulder-hand syndrome is demonstrated in Figure 9. The Type M technique reveals aggressive bone destruction with both endosteal and intracortical bone resorption. The smaller, more subtle resorptive cavities can be seen only with this technique; however, the larger resorptive spaces can be detected with all three systems. Disease progression or response to therapy is best assessed with the Type M technique. For the two screen-film systems demonstrated, the contact exposure and 2X magnification techniques appear to be of equal diagnostic value.

Radiographic demonstration of chondrocalcinosis is an important adjunct in the diagnosis of pseudogout^{25,28} (calcium pyrophosphate dihydrate crystal deposition disease). In Figure 10, subtle cartilage calcifications are detected with Type M technique, whereas the two screen-film techniques fail to image these calcium deposits. More advanced chondrocalcinosis can be visualized with any of these radiographic techniques.

High-resolution radiographic techniques are essential for detecting the subtle skeletal manifestations of primary hyperparathyroidism.^{18,19,40} In Figure 11, the three commonly available techniques plus 4X radiographic magnification are demonstrated for a patient with this disorder. Type M technique reveals subtle subperiosteal bone resorption, evidenced by irregular lysis of the outer cortical margin of the phalanx. These manifestations are beyond the resolution of the contact and 2X magnification techniques. 4X magnification demonstrates these findings, but not as well as Type M due largely to lower contrast which results from the higher kilovoltage and lower gradient of this technique.

Equally important in the diagnosis of primary hyperparathyroidism is the assessment of intracortical striation or tunneling.^{18,19,31} In Figure 12, Type M film demonstrates these fine, low contrast, linear striations in the metacarpal of a hyperparathyroid patient and indicates increased bone

turnover. The contact and 2X RP-Detail techniques fail to image these striations because of poor resolution, low contrast and high noise levels. The 4X technique clearly demonstrates these striations, and appears to contain diagnostic value equivalent to the Type M technique.

The radiologic assessment of renal osteodystrophy^{5,13,16,27,31} is becoming increasingly important as a guide for therapy in chronic renal disease, i.e., dialysis and parathyroidectomy. Figure 13 demonstrates striking subperiosteal bone resorption indicating advanced secondary hyperparathyroidism and detectable by all four techniques. The superior images with Type M and 4X magnification techniques, however, permit better characterization, and earlier detection of therapeutic response. In figure 14, osteosclerosis with thickening of trabeculae and periosteal new-bone formation in a renal patient following subtotal parathyroidectomy is shown. Neither the contact nor 2X RP-Detail techniques demonstrates these findings adequately for evaluation.

The high-resolution radiographic techniques have had limited application in assessing primary bone tumors in vivo. In Figure 15, radiographs of the forearm of a child with Ewing's sarcoma are shown. The superior imaging performance of Type M technique compared with contact exposure using RP-Detail may permit improved assessment of the aggressiveness of the neoplasm and better delineation of the geographic extent of disease.

As one moves from the peripheral skeleton to the more proximal regions where neoplasms generally occur, the body parts become thicker and the fine-detail technique with Type M film becomes less feasible. The limitations are due to the high radiation exposure required and to a degradation of image quality related to increasing geometric and motion unsharpness, and x-ray scatter. Direct radiographic magnification with the microfocus tube provides a reasonable alternative. In Figure 15D, the 4X radiographic magnification image appears to be of equivalent diagnostic value to that of the Type M technique. The two images demonstrate similar resolution, contrast and noise, yet the former required approximately 1/5 the patient exposure.

Discussion

Clinical applications. Clinical studies using fine-detail skeletal radiography are not new. Fletcher,¹⁵ in 1952, reported on his experience with the use of fine grain film and photographic enlargement in the study of rheumatoid arthritis. In 1969, Behrens and Lin² published a monograph on their findings in rheumatoid arthritis using industrial film and optical magnification. More recently, Meena,^{30,31} Weiss,⁴⁰ Genant,¹⁶⁻¹⁹ and Mall²⁷ have reported extensive experience with this technique in metabolic and arthritic bone disorders. Thus, the importance of fine-detail radiography with optical magnification for assessing selected skeletal disorders appears well established.

Clinical applications of *direct radiographic* magnification for skeletal radiography, on the other hand, have received far less attention. Calenoff⁵ reported his results in renal osteodystrophy using 2X magnification in conjunction with a 0.3 mm focal spot and a slow screen-film system (Kodak RPP film with Dupont Detail screens). He advocated this technique for detecting subtle changes in the phalanges but did not compare it with contact exposure using the same recording system, or with the optical magnification technique. Recently, Ishigaki²² employed 6X magnification with a microfocus tube (nominal focal spot size of 50 μ) and a medium speed screen-film system (Fuji RX film and Kyokko MS screens) to detect early radiographic manifestations of gout in the foot. He compared this technique in a quantitative manner with contact exposure using a slow screen-film system (Fuji KX film and Kyokko FS screens) and found the magnification technique to be superior.

Image quality studies. The physical factors governing image quality in fine-detail radiography with industrial film have been investigated and delineated only recently.^{10,12,16,17} This is due, at least in part, to the technical difficulties in performing these measurements on extremely sharp images. Fletcher and Rowley,¹⁴ in the 1950's, discussed qualitatively some of the physical aspects of imaging using the fine grain technique, but did not supply any quantitative information. We recently reported

quantitative data on the effect of geometric unsharpness and noise in fine-detail radiography,¹⁰ and have concluded that the technical parameters currently employed (see Methods and Measurements) are nearly optimal for practical purposes.

The physical factors affecting image quality in direct radiographic magnification have received wide attention as applied to angiographic procedures.^{1,3,4,9,20,32,33,37} Only limited basic research has been directed at imaging of the skeleton with this technique.³⁹ Many of the techniques and measurements derived from blood vessel imaging studies, however, can be applied to direct radiographic magnification skeletal radiography.

Comparison of optical and radiographic magnification techniques.

A comprehensive analysis comparing the imaging properties and clinical applications of the optical and radiographic magnification techniques for skeletal radiography has not been previously reported. In this study, we have examined the fine-detail optical magnification technique and three high resolution screen-film techniques, namely, contact exposure with a large focal spot, 2X magnification with a 0.3 mm focal spot, and 4X magnification with a 50 μ focal spot. We have examined system contrast and speed by film sensitometry, and overall resolution quantitatively by means of total MTF and qualitatively by means of test objects and clinical cases. The effect of noise on high resolution skeletal imaging has been demonstrated qualitatively. Clinical examples employing these

techniques have been drawn from a variety of skeletal disorders which frequently show subtle abnormalities undetected with conventional radiographic techniques.

From the results of this study the following conclusions can be drawn:

1. Of the three commonly available high-resolution radiographic techniques, Type M film with optical magnification results in superior skeletal images due to improved resolution and contrast, and lower noise levels. This improved imaging capability is considered essential for detecting subtle skeletal abnormalities in metabolic and arthritic disorders, and justifies the added radiation exposure as well as the inconvenience of manual or industrial film processing.
2. If a faster imaging system is required, due to patient motion or exposure considerations, contact exposure with a slow screen-film system and a large focal spot should be used rather than 2X radiographic magnification with a 0.3 mm focal spot. The latter technique requires approximately four times the patient exposure and results in images inferior or, at best, comparable to contact exposure. For demonstration of gross lesions to group audiences,

however, 2X magnification may be warranted due to the improved visual effect of the larger image.

3. If a microfocus tube is used, particularly for thicker skeletal parts, direct radiographic magnification with the screen-film system may produce images comparable in resolution and noise to the optical magnification technique, and at lower radiation exposure to the patient.

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TABLE LEGENDS

TABLE 1. The four high-resolution radiographic techniques to be compared are shown. On the left is the fine-detail technique (A) which incorporates optical magnification. The three techniques on the right (B, C, and D) employ a slow screen-film system in conjunction with variable focal spot size and radiographic magnification.

TABLE 2. The estimated relative radiation exposure per unit area of the patient for the four techniques are shown. The skin dose to the hand with Type M technique (A) is approximately 1 rad.¹⁸

FIGURE LEGENDS

FIG. 1. Characteristic and gradient curves for Type M and RP-Detail systems are shown. On the left the greater speed and latitude of the screen-film system can be appreciated from the H & D curve. The gradient of the two systems is plotted against photographic density on the right. For optimal contrast, an average photographic density of approximately 1.5 is selected for hand radiographs using RP-Detail while a density of 2 or greater is selected for radiographs with Type M film.

FIG. 2. The modulation transfer functions (MTF's) of the recording systems are shown and are displayed for the object plane. The MTF curve for Type M film shows 1% decline in the spatial frequency range demonstrated. The MTF for RP-Detail with contact exposure is quite poor by comparison. With 2X and 4X radiographic magnification the MTF of the recording system improves due to the wider image distribution relative to the screen-film system.

FIG. 3. The MTF's of geometric unsharpness, obtained from the MTF's of the focal spots and the magnification factors are shown. The MTF's of the 1.2 mm and 0.3 mm focal spots are determined experimentally, whereas the MTF of the microfocal spot is derived theoretically. The MTF for contact exposure with a 1.2 mm focal spot is considerably better than those of the direct radiographic magnification techniques.

FIG. 4. The total MTF's for the four systems are shown. The curve for Type M technique indicates the greatest detail resolution. Conversely, the poorest resolution occurs with the 2X magnification technique. The total MTF of 4X magnification appears better than that of contact RP-Detail, particularly in the low spatial frequency range.

FIG. 5. Microwire meshes radiographed with the four techniques and made equal in size photographically are shown. Type M technique (A) resolves all the wire meshes; the poorest resolution occurs with the 2X magnification technique (C). The contact (B) and 4X (D) screen-film techniques each resolve the 2 largest wire meshes. The effect of noise on image quality is also well demonstrated.

FIG. 6. Images of a steel wool test object radiographed with the four techniques are shown. These tiny structures are well visualized with the Type M technique (A) and can be seen with the 4X magnification (D) but not with the other two screen-film techniques.

FIG. 7. The 3 commonly available high-resolution techniques in a patient with rheumatoid arthritis are shown. Type M technique (A) reveals subtle, but definite, surface erosion of the metacarpal head, not detected with the two screen-film techniques. The contact exposure with RP-Detail (B) has less unsharpness, but greater noise than the 2X magnification system (C).

FIG. 8. Early surface erosion and subchondral demineralization of the proximal interphalangeal joint in rheumatoid arthritis are shown. These subtle findings are seen with the Type M technique (A) but not with the other two commonly available high-resolution techniques.

FIG. 9. The capacity of the 3 common techniques for assessing bone resorption in reflex neurovascular dystrophy is shown. Type M technique (A) reveals aggressive bone destruction with both endosteal and intracortical bone resorption. The smaller, more subtle, resorptive cavities can only be seen on the left, however; the larger resorptive spaces can be detected with all 3 systems.

FIG. 10. Chondrocalcinosis of pseudogout is demonstrated. The Type M technique (A) shows subtle cartilage calcifications, whereas the contact (B) and 2X (C) RP-Detail systems fail to image the small calcium deposits in this case.

FIG. 11. Subtle skeletal manifestations of primary hyperparathyroidism are shown with the four techniques. Type M technique (A) reveals subtle subperiosteal bone resorption as evidenced by the irregular lysis of the outer cortical margins of the phalanx. These manifestations are beyond the resolution of the contact (B) and 2X magnification (C) techniques in the middle. 4X magnification (D) demonstrates this finding, but not as well as Type M, due largely to lower contrast.

FIG. 12. The assessment of intracortical striation or tunneling in primary hyperparathyroidism is shown. Type M film demonstrates these fine, linear striations in the metacarpal of a hyperparathyroid patient. The contact (B) and 2X (C) RP-Detail techniques fail to image these striations because of poor resolution, low contrast and high noise levels. The 4X technique (D) clearly demonstrates these striations, and appears to contain diagnostic information equivalent to the Type M technique.

FIG. 13. Striking subperiosteal bone resorption, in a child with renal osteodystrophy indicating secondary hyperparathyroidism. The superior images with the Type M (A) and 4X magnification (D) techniques permit earlier detection and better assessment of response to therapy.

FIG. 14. Renal osteodystrophy before and after subtotal parathyroidectomy is shown. A1 demonstrates advanced bone resorption of secondary hyperparathyroidism using Type M technique. Following parathyroidectomy, osteosclerosis with thickening of trabeculae and periosteal new bone formation can be seen (A2-D). Neither the contact (B) nor 2X (C) RP-Detail techniques adequately demonstrates these findings for serial evaluation.

FIG. 15. The forearm of a child with Ewings sarcoma is shown radiographed with Type M (A) contact RP-Detail (B) and 4X magnifications (D) techniques. The superior imaging performances in A and D may permit improved assessment of the aggressiveness of a neoplasm, and better delineation of geographic extent. Type M and 4X techniques demonstrate similar resolution, contrast and noise, yet the latter required approximately 1/5 the patient exposure.

TABLE I

FOUR RADIOGRAPHIC TECHNIQUES EXAMINED

A	B	C	D
TYPE M	RP - DETAIL	RP - DETAIL	RP - DETAIL
CONTACT	CONTACT	MAGNIFICATION	MAGNIFICATION
M = 1.02	M = 1.02	M = 2.0	M = 4.0
1.2 mm F.S.	1.2 mm F.S.	0.3 mm F. S.	50 μ F. S.
50 KV	50 KV	50 KV	65 KV

TABLE II

RELATIVE PATIENT EXPOSURE (APPROXIMATE)

A	B	C	D
TYPE M CONTACT	RP-DETAIL CONTACT	RP-DETAIL 2X MAGN.	RP-DETAIL 4X MAGN.
75	1	4	16

CHARACTERISTIC CURVES

GRADIENT CURVES

MTF'S OF RECORDING SYSTEMS

MTF'S OF GEOMETRIC UNSHARPNESS

TOTAL MTF'S OF FOUR TECHNIQUES

Fig. 6

Figure 1

CHARACTERISTIC CURVES

GRADIENT CURVES

Figure 1

Figure 2

Figure 3

Figure 4

Figure 1

Figure 2

Figure 8

Figure 9

Figure 9

Figure 10

Fig. 11

Fig. 12

Figure 13

Figure 14

A

B

D

Figure 15