Techniques for Precise Recording of Gray-Scale Images from Computerized Scintigraphic Displays

W. L. Rogers and John W. Keyes, Jr.

University of Michigan Medical Center, Ann Arbor, Michigan

Accurate, reproducible recording of gray-scale images from a computer requires careful calibration and control of the factors that affect photographic exposure. These include exposure time, CRT brightness and contrast, film type, and photographic processing. A method is described for calibrating the imaging system; it accounts for nonlinear CRT phosphor and film response and permits the recording of any desired gray scale. The key to this technique is a graphical method for correlating the measured film response with the desired gray scale in order to develop a translation table that will in turn produce the desired gray scale on film. The technique is applicable to any computerized nuclear medicine display system.

J Nucl Med 22: 283–286, 1981

There has been a steady improvement in the quality of nuclear medicine computer displays. Today such displays can rival the quality of the best analog displays. In addition there has recently been considerable interest in the question of the optimum gray scale for the display of scintigraphic images (*1–4*), and in the effects of various display scales, whether black and white or color, on the accuracy of image interpretation (*5,6*). Almost no attention, however, has been paid to the question of how to achieve the optimum gray scale physically in the display or how to preserve the desired gray scale during photographic recording. We present here the results of our investigations into the factors that affect the gray-scale photographic recording of digitized scintigraphic images, and the techniques we have developed to generate and record gray scales of any desired character.

THEORY OF OPERATION

Figure 1 illustrates the chain of steps that take place in a typical computer system to convert the numbers stored in memory into a displayed image. Within the computer memory a digitized image is stored as a matrix of numbers or pixels, each pixel representing the number of counts accumulated over a small area or element of the camera crystal.

The numbers in different pixels of a single image may vary from zero to several thousand. In addition, the total range spanned may vary widely from image to image. Since the computer system can display only a limited number of discrete intensity levels, each image must be scaled to match the range of intensity levels available. This scaling converts the number of counts in each image pixel to a fraction of some maximum number. This maximum may be the maximum count in the image, the maximum count in a series of images, or an arbitrary count level specified by the user. We will refer to this scaled value as the "percent of maximum."

After scaling, a translation table is used to assign a display-level number to the pixel. For example, if 200 display levels are to be evenly divided over the count range from zero to maximum in an image (i.e., a linear translation table), then pixels containing counts between 0 and 0.5% of maximum would be assigned a display-level number of one; pixels containing counts between 49.5 and 50% of maximum would be assigned level number 100, and so forth. The number of display levels available is the figure that is commonly used to express the number of shades of gray that the system can display.

The display controller produces a discrete output voltage for each display-level number. The appropriate output voltages are then fed to the display amplifier. The actual brightness is governed by two amplifier controls: the gain, usually labeled as the contrast control, and the offset, usually labeled as the intensity or brightness control. The contrast control varies the relative brightness of the various levels, while the intensity control varies the brightness of all levels uniformly. As indicated in Fig. 1, the display amplifier is usually separate from the display controller. The output from the display controller may actually be used to drive several independent displays, each with its own amplifier and controls.

There are three individual variables that must be controlled in

Received Aug. 14, 1980; revision accepted Oct. 31, 1980.

For reprints contact: John W. Keyes, Jr., MD, Div. of Nuclear Medicine, University Hospital Box 021, Ann Arbor, MI 48109.

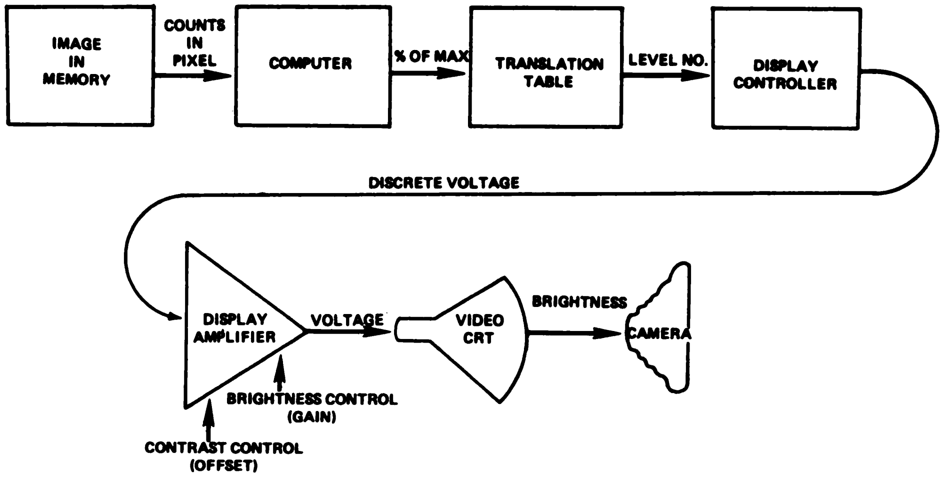

FIG. 1. Schematic diagram of steps to convert stored digitized image into photographic image.

order to produce a defined intensity range on the display scope, namely, the values in the translation table and the brightness and contrast settings of the display amplifier.

In photographic recording, not only the brightness and contrast settings, but also the length of exposure and effective f-stop affect the final film density. In addition, the characteristics of the film itself and the CRT's phosphor response must be considered. The brightness response curve of the CRT phosphor is usually quite nonlinear (*8*), and this, combined with the nonlinear exposure curve of photographic film, produces a final gray scale that can be quite complex and is strongly dependent upon the display amplifier's settings. Figure 2 illustrates the exposure curves resulting from a linear translation table with the brightness, contrast, and exposure settings all held constant. These results illustrate the central problem in recording a defined gray scale: the need to compensate for the film-phosphor response in addition to controlling all of the variables that overtly affect film exposure.

It should be obvious from the foregoing that the optimum translation tables and amplifier settings for direct viewing will be different from those for photographic recording and will also be different for different films. The remainder of this paper will discuss the techniques we have developed for adjusting all of these variables for photographic recording. Similar techniques could be developed for optimizing the system for direct viewing, but this is a considerably more difficult problem because of the psychophysical factors involved.

MATERIALS AND METHODS

The computer* used in these studies includes an interlaced video display capable of displaying an image up to 512 elements wide by 480 high. For the purpose of this study the images were restricted to 256 × 256 elements. The display controller is capable of generating 256 discrete output voltages corresponding to 256 possible display-level numbers. The translation table may use all of these levels or any subset to represent the count range from zero to maximum. A large library of different translation tables can be stored on disk and easily recalled for different imaging situations or for testing purposes. New translation tables are particularly easy to generate with this system, because the operator need only specify a few points (typically nine) of the desired table and the computer will perform a cubic spline fit to these points and calculate the remaining values of the table automatically.

The unit for image recording† can record in three formats: either 1, 4, or 25 positive or negative images on a single sheet of 8- by 10-in. film. The studies reported here were all conducted in the 4-on-1, negative format.

The densities of the recorded images were measured with a

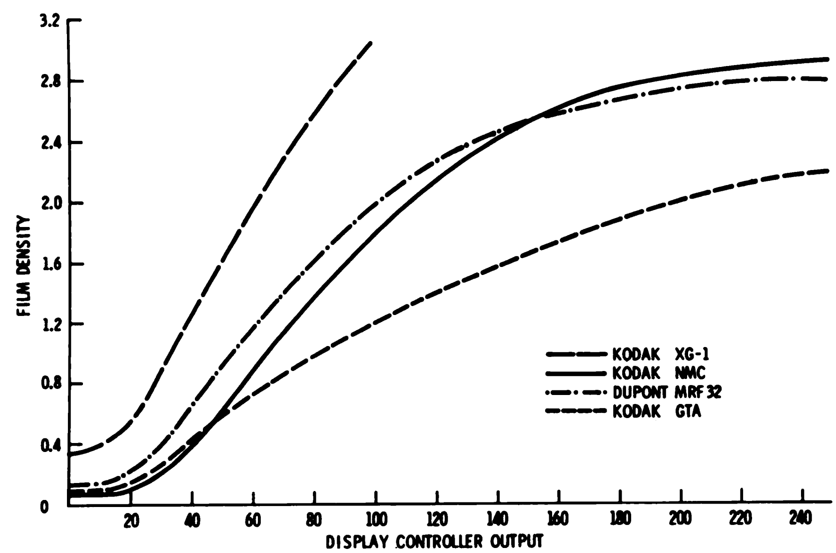

FIG. 2. Film-density response curves for several films commonly used in nuclear medicine. Exposure, brightness, contrast, and processing were identical for all films.

densitometer.[‡] A photographic light meter[‖] was used for initial calibration of the brightness and contrast of the display scope.

A series of synthetic "field floods," consisting of uniform matrices of numbers corresponding to known percentages of a predefined maximum count, were created and stored in the computer for calibration and testing. Twenty-five such matrices were used to sample uniformly the entire range of possible display-controller outputs.

One of the aims of this study was to be able to accomodate several films of varying sensitivity and contrast without having to make any hardware adjustments. Consequently the initial setup of the imager had to ensure that the lowest possible intensity level produced a film density at or just detectably above the fog level of the most sensitive film, and that the maximum level (256) was bright enough to saturate the least sensitive film. The display brightness and contrast and the exposure time were adjusted empirically to accomplish these goals. Typically base-plus-fog values were 0.04–0.05 O.D., zero-level exposures were set to give 0.06 O.D., and maximum exposure gave values of 2.5–3.0 O.D., depending upon the film used.

Ideally the brightness and contrast controls would operate independently, with the brightness control adjusting the lower-level exposure and the contrast control the upper-level exposure. In practice, however, adjustments to one contol affect the other, and it is often necessary to make an iterative series of adjustments to reach the final settings for both controls.

Once the settings to give the proper exposure range had been found, the intensities of the displayed image on the video screen at zero and maximum were measured with the photographic light meter. These readings were used as an approximate check on calibration. It was found, however, that these measurements were not sufficiently accurate to restore the system to exact calibration, and test exposures were used for "fine tuning." The system was found to be stable enough over several weeks so that small adjustments in exposure time were adequate to keep the system in calibration.

The exposure-response curves of the films to be used were determined by photographing the series of synthetic field floods using a linear translation table covering the entire range of display-controller outputs, and plotting the resulting film densities as a function of display-controller output level. The results for several films commonly used in nuclear medicine laboratories are shown in Fig. 2. Kodak NMC film was used for all further studies described.

The procedure used to generate translation tables to produce specific gray scales in the final photographic image is illustrated in Fig. 3. This method is similar to one we have previously described for use with refresh-type CRT displays (*7*) and is related to the methods used in graphic arts for calibrating photographic negatives or printing intermediates in order to produce a desired gray scale in the final print (*8*).

In the lower right-hand corner, the desired gray scale is plotted as a function of the percent maximum count in the image. Note that over the useful density range of the film, any gray scale can be selected, and that this gray scale must be predetermined by the user before the system can be calibrated.

In the upper left-hand corner the measured film-density response is plotted as a function of display-controller output. This is the curve that was measured in the preceding step and corresponds to the film response that would be given by a linear translation table. Note that the curve plotted here must be for the film that will be used.

The corresponding densities from these two curves are then cross-plotted onto the graph at the lower left to give a curve corresponding to the translation table that must be used to correct the measured film response to the desired response. In the example shown, the points corresponding to a film density of one have been plotted. With the system described, approximately nine points are plotted, and the computer then generates the remainder of the curve by using a cubic spline fit to the points. The resulting translation table is then stored on disk for future use.

The fitted curve should be examined on the computer display to be sure that it is smooth. This step is important, since any small ripples in this curve produce very objectionable effects in the final images. It may be necessary to change the input values slightly or to reduce the number of points to be fitted in order to obtain a smooth translation table.

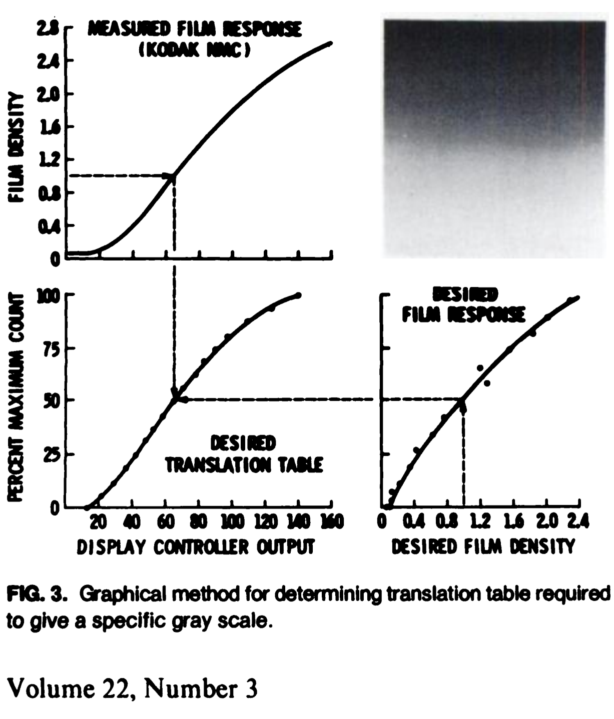

FIG. 3. Graphical method for determining translation table required to give a specific gray scale.

RESULTS

The dots superimposed on the curve at the lower right in Fig. 3 correspond to measured densities from a series of test images obtained using the calculated curve. Those points that deviate appreciably from the desired curve do so as a result of vignetting caused by the off-axis optical system in the video formatter. The resulting gray-scale image of a ramp display is shown at the upper right.

As has been noted, any gray-scale response can be reproduced

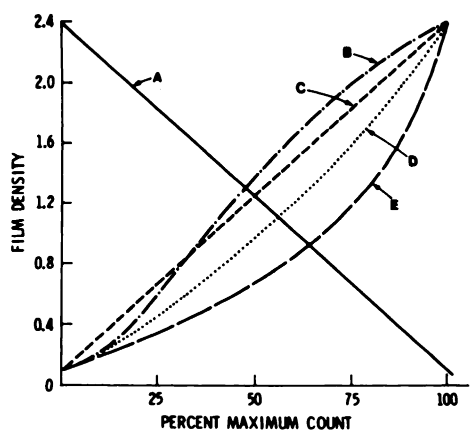

FIG. 4. Five representative gray-scale curves produced on Kodak NMC film by varying the translation table while holding constant all other factors affecting exposure.

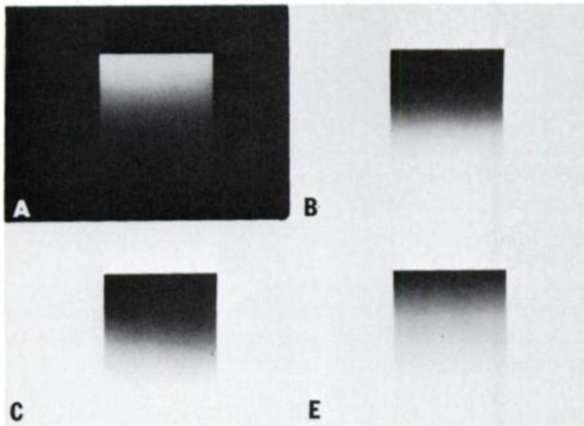

FIG. 5. Ramp displays photographed on Kodak NMC with four of the translation tables shown in Fig. 4. This print fails to capture the true gray scales of the original transparencies, but alterations that can be achieved by varying the translation table are apparent.

by this approach within the limits set by the film being used. Figure 4 shows five gray scales that have been tested. Curve C is a linear gray-scale response on film. Curve A is also a linear film response but going from black to light—i.e., a positive image. This result was achieved solely by altering the translation table rather than reversing the recording polarity of the video formatter. Curve E corresponds to the "optimum" gray scale presented by Chang and Blau (*2*), while B and D are curves that were generated empirically.

Figure 5 illustrates the ramp displays obtained with curves A, B, C, and E. All of these images were obtained on Kodak NMC film with the same contrast, brightness, and exposure-time settings. Only the translation tables have been altered.

DISCUSSION

We have presented these techniques in a generalized form. Modifications will be required to adapt them to specific systems, but we believe that they are applicable to all of the current generation of nuclear medicine computer systems. The design of the video multiformatter system used can strongly affect the specific calibration procedures that are used. Although we have had experience only with the Matrix system, we feel that the users of many systems may require assistance from the manufacturer in order to calibrate these systems properly. In fact, a strong argument can be made that such calibration procedures should be part of the initial setup of the equipment by the manufacturer and that detailed instructions for the construction of translation tables should be provided by all manufacturers of computer systems, if they do not already do so. We can provide for those interested a detailed description of the specific calibration procedures for the Matrix unit, which is somewhat complicated due to its internal calibration system.

Even with perfect calibration and translation-table construction, the resulting gray scales frequently will not be absolutely precise. The problem of vignetting due to optical-system design has already been mentioned. In addition, for systems that offer multiple formats, calibrations established for one format may not be suitable for another. Variations in processing can produce similar effects. Although film processing is not explicitly considered here, we should emphasize that reproducible results can be achieved by these techniques only if film processing is also carefully standardized. An excellent review of the subject is available (*9*).

New calibrations for exposure time may be required for each display option provided by the computer system—e.g., different matrix sizes and video interlace on or off. In addition, separate tables are required for each type of film used even if the calibration settings do not require alteration. We feel that there is enough flexibility in translation-table design so that one type of film is all that is needed to meet any imaging situation.

The availability of good-quality video computer displays, and the ability to control accurately the gray scale of these displays, opens the door to many fascinating possibilities. It should now be possible to study the best gray scale for specific imaging situations with the knowledge that if an optimum gray scale can be determined it can be reliably reproduced. Although the problem of actually defining an optimum gray scale is outside the scope of this paper, we can probably state safely that multiple gray scales will be needed to meet a variety of imaging problems. With proper calibration and quality control, users can count on the gray scale of their images being constant and not subject to variations such as an individual operator's subjective impression of image quality, which is frequently the case when photographs are obtained from scopes that are also used for direct viewing. Finally, it now becomes possible to assign a quantitative value to the relationship between the relative count values in the digitized image and the optical density of the final photograph.

FOOTNOTES

* A^2 System, Medical Data Systems.

† Multiple Format Video-Imager, Matrix Instruments.

‡ Macbeth TD-500 Densitometer.

‖ Gossen Luna-Pro.

ACKNOWLEDGMENT

This work was supported in part by NIH Grant Nos. GM 16188 and HL 21707.

The authors thank Diane Vecellio for secretarial assistance.

REFERENCES

1. WHITEHEAD FR: Minimum detectable gray-scale differences in nuclear medicine images. *J Nucl Med* 19:87–93, 1978

2. CHANG W, BLAU M: Optimization of the gray scale for photoscanners: concise communication. *J Nucl Med* 20:57–59, 1979

3. WHITEHEAD FR: Re: optimization of the gray scale for photoscanners. *J Nucl Med* 20:996–997, 1979

4. CHANG W, BLAU M: Reply. *J Nucl Med* 20:997, 1979

5. WIENER SN, FLYNN MJ, EDELSTEIN J: Observer performance with computer-generated images of ^{201}Tl-Cl myocardial perfusion. *Radiology* 136:181–185, 1980

6. HOUSTON AS: A comparison of four standard scintigraphic TV displays: concise communication. *J Nucl Med* 21:512–517, 1980

7. KEYES JW, ROGERS WL, HALL DR: Digitized image recording—techniques for quality improvement. In *Proceeding of Seventh Symposium on Sharing of Computer Programs and Technology in Nuclear Medicine, Computer Assisted Data Processing,* Conf. 770101, ERDA Technical Information Center, Springfield, VA 1977, pp 368–377

8. NELSON CN: The theory of tone reproduction. In *The Theory of the Photographic Process.* 3rd ed, Mees CEK, James TH, Eds. New York, Macmillan, 1966, pp 464–498

9. *Second Image Receptor Conference: Radiographic Film Processing,* HEW Publication (FDA) 77-8036, Washington D.C., 1977