X-Ray Exposure Reduction Using Rare-Earth Oxysulfide Intensifying Screens[1]

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ABSTRACT—The characteristics of terbium-activated gadolinium oxysulfide and lanthanum oxysulfide are compared with those of calcium tungstate. The new rare-earth phosphors have higher x-ray absorption in the 38 to 70 keV region relative to calcium tungstate. They also exhibit a larger x-ray-to-visible light energy conversion efficiency. Rare-earth phosphors, however, emit primarily in the green spectral region and thus poorly match the spectral response of blue-sensitive x-ray film. Despite this disadvantage, gadolinium oxysulfide screens allow a significant x-ray exposure reduction relative to calcium tungstate screens providing equivalent resolution. An additional exposure reduction is anticipated when faster green-sensitive x-ray film becomes available.

INDEX TERMS: Screens • Diagnostic Radiology, apparatus and equipment

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In 1896, film intensifying screens made of calcium tungstate ($CaWO_4$) were used for the first time. Today, more than seven decades later, $CaWO_4$ remains the principal phosphor used in x-ray intensifying screens. To its credit, $CaWO_4$ has a relatively high x-ray absorption coefficient and is a physically hardy material. However, its x-ray-to-light conversion efficiency is poor, typically 3 to 5% (1, 2).

The physical properties of two green-emitting x-ray conversion phosphors, terbium-activated lanthanum oxysulfide (La_2O_2S:Tb) and terbium-activated gadolinium oxysulfide (Gd_2O_2S:Tb), have been described previously (3). The most noteworthy characteristics of these phosphors are their unusually high x-ray absorption coefficients, especially above the K-edge of the particular host metal ion, and their high x-ray-to-light conversion efficiencies of 13 and 18%, respectively.

It is the purpose of this communication to compare the properties of the new rare-earth phosphors with those of $CaWO_4$ and to evaluate these new phosphors as constituents in x-ray film intensifying screens. X-ray film is typically most responsive to blue light, being well matched to the emission from a $CaWO_4$ screen. It shows almost no response in the green. The two oxysulfide phosphors have very little emission in the blue, and thus the rare-earth phosphors have a significant disadvantage when used as intensifying screens with present x-ray film. Despite this fact, our experiments have shown that intensifying screens made of Gd_2O_2S:Tb allow x-ray exposure reduction of a factor of two even when used with conventional x-ray film at 70 kVp and above.

If a green-sensitive film, equivalent in all other respects to present blue-sensitive film, were to become widely available, the exposure reduction over $CaWO_4$ could possibly be increased by a factor of 20. The development of such an equivalent green-sensitive film is feasible,[2] but to the present time there has been no motivation for such a specialized development. In addition to the direct reduction in radiation exposure to the patient, such a screen-film combination would decrease the need for more powerful x-ray generators, would extend tube and equipment life and, if screen thicknesses were to be reduced in proportion to the gain in total sensitivity, would make possible much higher resolution than can be achieved with the $CaWO_4$ intensifying screens.

In the following sections, the relevant properties of the two rare-earth phosphors will be compared with those of $CaWO_4$, and then detailed results of film exposure measurements will be reported. Finally, direct comparisons of radiographs obtained using the new Gd_2O_2S:Tb screens with radiographs obtained using commercial intensifying screens will be presented.

COMPARISON OF PHYSICAL PROPERTIES OF PHOSPHORS

The rare-earth oxysulfide phosphors can be produced as crystalline powders of controlled

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[2] We have already had discussions with several manufacturers of x-ray film who state that such a green-sensitive x-ray film can be manufactured.

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keV	X-Ray Absorption in a 100 μm Screen (%) 40	60	80	Intrinsic Efficiency (%)
Gd_2O_2S:Tb	37	51	28	18
La_2O_2S:Tb	73	33	17	13
$CaWO_4$	33	13	27	4

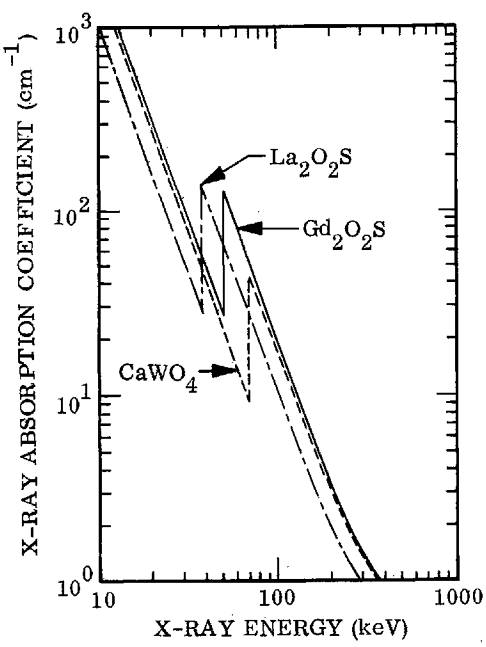

Fig. 1. Lower figure. X-ray attenuation coefficient of La_2O_2S, Gd_2O_2S, and $CaWO_4$ *versus* energy.
Upper figure. Absorption coefficient of screens 100 μm thick at three x-ray energies and the intrinsic x-ray-to-visible light conversion efficiencies.

particle size by a variety of techniques (4). Terbium-activated gadolinium oxysulfide and La_2O_2S:Tb are closely related to Y_2O_2S:Eu, an important red-emitting color television phosphor. Such phosphors are now produced commercially on a large scale. The phosphors, once produced, are chemically stable and physically hardy. Thus screen life can be expected to be the same or better than that of presently used screens.

Figure 1 shows the x-ray absorption coefficients *versus* x-ray energy from 20 to 400 keV for La_2O_2S, Gd_2O_2S, and $CaWO_4$. From 50 to 70 keV, Gd_2O_2S has an advantage of 4 to 5 × over $CaWO_4$. Lanthanum oxysulfide has a somewhat lower x-ray absorption than $CaWO_4$ above 70 keV and below 38 keV but has a factor of two advantage over $CaWO_4$ between 38 and 70 keV. The distribution of x-ray energy which reaches the intensifying screen after passing through the patient depends on the kVp settings used, but in most practical situations a significant fraction of the energy available will fall in the 38 to 70 keV range. In

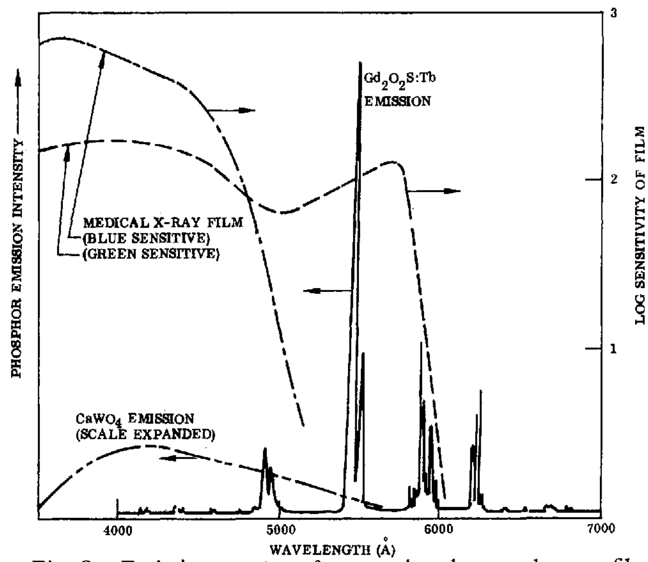

Fig. 2. Emission spectra of x-ray phosphors and x-ray film spectral response curves. The vertical scale has been expanded for $CaWO_4$ emission spectrum to make it visible on the same plot. It can be seen that the blue-sensitive film has no measured response at 5440 Å whereas the green-sensitive film responds almost equally well to the blue $CaWO_4$ emission and the principal emission peak of Gd_2O_2S:Tb. Note how well the spectral sensitivity of the blue-sensitive x-ray film matches the emission spectrum of $CaWO_4$.

many situations much of the energy will be in the narrower 50 to 70 keV range where Gd_2O_2S has the advantage. Thus intensifying screens made of these two rare-earth phosphors will typically absorb and usefully convert to visible light more incident x rays than will $CaWO_4$ screens of the same thickness.

The x-ray-to-light conversion efficiencies of the rare-earth phosphors are also significantly greater than that of $CaWO_4$. The numbers previously reported (3) for La_2O_2S:Tb and Gd_2O_2S:Tb, using electron excitation techniques, are 13% and 18%, respectively, whereas the $CaWO_4$ efficiency falls in the range from 3 to 5% (1–2). The efficiency as defined here is watts of optical power output per watt of x-ray (or electron) power absorbed, expressed as a per cent. The maximum conversion efficiencies are obtained for materials containing approximately 0.3 atom-per cent of terbium replacing lanthanum or gadolinium.

The spectral emission of the rare-earth phosphors is produced by the terbium ion. The terbium emission has a very strong peak at 5440 Å in the green with less intense emission peaks in the blue, blue-green, yellow, and red. The blue peaks in Gd_2O_2S:Tb are stronger than in La_2O_2S:Tb, and can be enhanced somewhat further by lowering the terbium concentration below what would otherwise be the optimum value. The degree of exposure of blue-sensitive x-ray film by the oxysulfide screens depends strongly on the proportion of this relatively weak blue emission in the total output spectrum.

In Figure 2, the emission spectra of $Gd_2O_2S:Tb$ and $CaWO_4$ are plotted *versus* the spectral response of both blue-sensitive x-ray film and a presently available, though less sensitive, form of green-sensitive medical x-ray film which is generally used for photofluorographic applications.

If one makes a comparison of the rare-earth phosphors and $CaWO_4$ using x-ray film having the spectral characteristics shown in Figure 2, one obtains two very important pieces of information. First, a comparison of the two phosphors in screen form made with blue-sensitive film provides quantitative data on any advantage to be gained by replacing $CaWO_4$ screens with the rare-earth oxysulfide screens and continuing to use the present blue-sensitive x-ray film. Second, a comparison of the same screens made using the green-sensitive x-ray film provides a quantitative measure of the advantage of the rare-earth phosphors relative to $CaWO_4$ which would be possible if a film could be manufactured with the spectral sensitivity of the green-sensitive film, but having a speed equivalent to that of the blue-sensitive film. These comparisons will be described in the following section.

COMPARISON OF X-RAY SCREEN PERFORMANCE

Of the two rare-earth phosphors under discussion, $Gd_2O_2S:Tb$ has the higher x-ray absorption and the higher x-ray-to-light conversion efficiency. In addition, its emission makes a somewhat better match to the response characteristics of presently used x-ray film than does the emission of $La_2O_2S:Tb$. For these reasons we have chosen to make the majority of our direct comparisons between screens composed of $Gd_2O_2S:Tb$ and $CaWO_4$. Test screens were made by dispersing powders of $Gd_2O_2S:Tb$ and x-ray phosphor grade $CaWO_4$ of essentially identical particle sizes in a binder of methyl methacrylate and drawing down the mixture with a doctor blade on a substrate of translucent Mylar. The phosphor coatings of the screens were five mils thick, quite comparable to commercial $CaWO_4$ Par-speed screens. These screens were used to conduct a direct comparison of film exposure.

To compare $CaWO_4$ and $Gd_2O_2S:Tb$ screens, half of the x-ray film was covered with a $CaWO_4$ screen and the other half covered with a $Gd_2O_2S:Tb$ screen. Each exposure was made in such a way that a portion of a narrow x-ray beam fell on the $CaWO_4$ screen while the remaining portion of the beam fell on the $Gd_2O_2S:Tb$ screen. It was thus assured that the exposure for the two screens was identical. A representative example of an exposed green-sensitive film resulting from such an exposure series is shown in Figure 3.

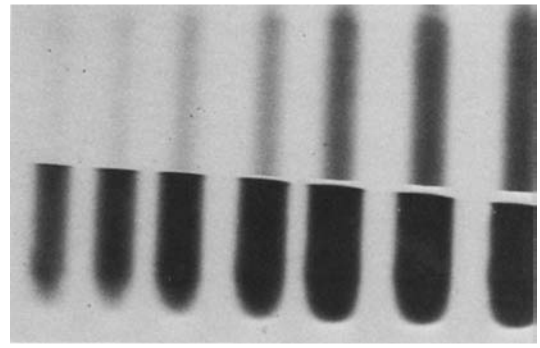

Fig. 3. Typical film exposure. The upper section of this film was exposed from the $CaWO_4$ screen, and the lower section was exposed from the $Gd_2O_2S:Tb$ screen (Kodak medical x-ray, green-sensitive, photofluorographic film).

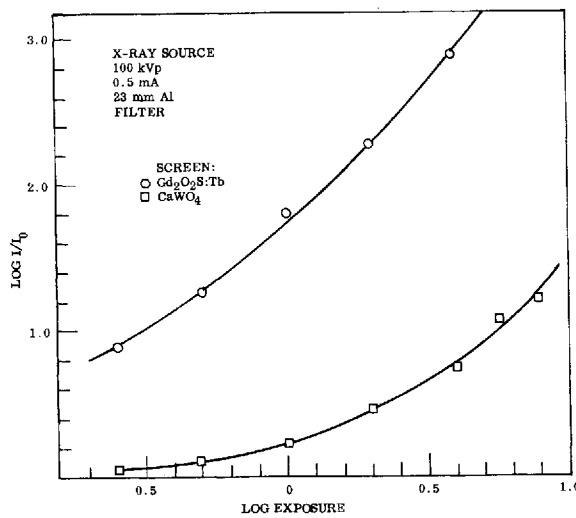

Fig. 4. Measured film density *versus* exposures; Kodak medical x-ray, green-sensitive, photofluorographic film (single coated).

The exposed film was next measured with a densitometer. The densitometer readings were plotted *versus* the log of the exposure. Such a plot is shown in Figure 4. By drawing a horizontal line across the figure at an optical density of 1, the relative exposure necessary to produce equivalent film darkening can be obtained. Relative intensification factor (RIF) will be defined as the ratio of the time to expose the film to unit density using the $CaWO_4$ screen to the time necessary to expose film to unit density using the $Gd_2O_2S:Tb$ screen. From Figure 4 we deduce that the RIF is 20 at 100 kVp. That is to say, it takes approximately 20 times the amount of x-ray exposure using the $CaWO_4$ screen to obtain equivalent film darkening to that obtained using the $Gd_2O_2S:Tb$ screen. The RIF value at 80 kVp is 12.5. These values are indicated in TABLE I. The RIF values indicated in TABLE I are for an arbitrary film density of 1. These values would be smaller (less advantage for the rare-earth phosphor) at densities

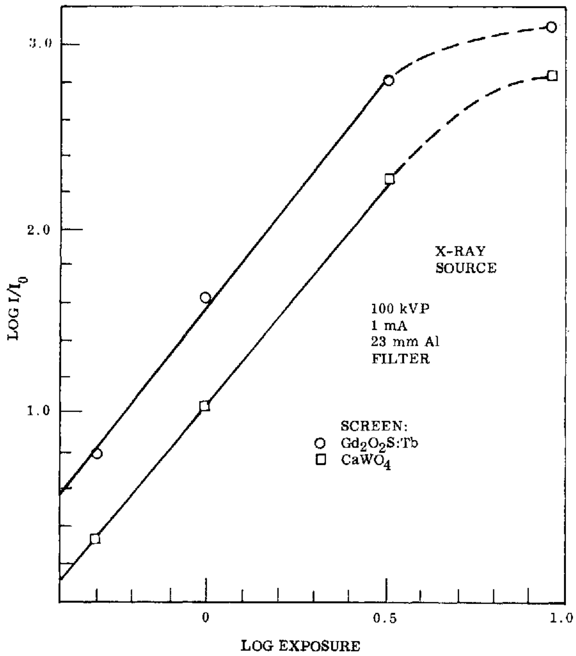

Fig. 5. Measured film density *versus* exposure; Kodak medical x-ray, blue-sensitive film (single coated).

TABLE I: EXPERIMENTAL DETERMINATION OF RELATIVE INTENSIFICATION FACTORS FOR BLUE- AND GREEN-SENSITIVE FILM AS A FUNCTION OF kVp SETTINGS

Medical X-Ray Film Type	kVp	RIF = T($CaWO_4$)/ T(Gd_2O_2S:Tb)
Blue-sensitive	80	2
Green-sensitive	80	12.5
Green-sensitive	100	20

less than 1 and would be larger (more advantage for the rare-earth phosphor) at densities greater than 1. The increase of RIF values with increasing kVp is the result of the stopping power of Gd_2O_2S:Tb relative to $CaWO_4$ as more and more of the x-ray emission intensity falls within the 50 to 70 keV range.

It can be observed from these data that because of the increased x-ray stopping power and the higher intrinsic luminescent efficiency of Gd_2O_2S:Tb relative to $CaWO_4$, significant x-ray exposure reductions can be achieved using Gd_2O_2S:Tb screens. The exact amount of exposure reduction that can be achieved in practice by using green-sensitive film will be determined by either the ultimate sensitivity limit (speed) of the green-sensitive film which film manufacturers will be able to achieve or the limit imposed by quantum mottle. At present we do not know which limit will be reached first. Use of the presently available green-sensitive photofluorographic film results in RIF of about 2.5. Exposure curves of Gd_2O_2S:Tb and $CaWO_4$ screens using this higher speed blue-sensitive medical x-ray film are shown in Figure 5. From these data it can be seen that there is sufficient overlap between the sensitivity of the blue film and the emission spectrum of the Gd_2O_2S:Tb to yield some advantage over $CaWO_4$. The RIF value for blue film is 2. This means that one can reduce exposure by one-half simply by changing from $CaWO_4$ to Gd_2O_2S:Tb screens and continuing to use conventional blue-sensitive x-ray film.

COMPARISON OF RADIOGRAPHS

Radiographs of a skull phantom have been obtained with a commercially prepared (Du Pont) Par-speed $CaWO_4$ screen and with a Gd_2O_2S:Tb screen of comparable thickness and resolution. Figure 6 shows such a comparison taken with a 3-phase generator at 80 kVp using Cronex 4 film and 90-second processing. As can be seen in the figure, 40 mAs gives a satisfactorily exposed film using the Par-speed screen. This same exposure produces an overexposed film when the Gd_2O_2S:Tb screens are used. Reducing the Gd_2O_2S:Tb screen exposure to 20 mAs still gives a slightly darker radiograph than the Par-speed screens provide at 40 mAs.

Figure 7 shows a similar series taken at 60 kVp. At this lower voltage fewer x-ray photons have energies in the 50 to 70 keV range, and the advantage of the Gd_2O_2S:Tb screen is diminished accordingly. Nonetheless, it can be seen that the Gd_2O_2S:Tb screen still provides a reduction in exposure of at least 1/3 relative to the Par-speed screen.

These radiographs were made with experimental screens of Gd_2O_2S:Tb of the same front-and-back thickness which did not have reflecting layers or protective coatings. The binder material has not yet been optimized to give the maximum light output from the screen, and no dyes were added to improve definition. Therefore, it may be anticipated that commercially prepared screens of Gd_2O_2S:Tb could be improved considerably by incorporating many of the improvements that have been made to $CaWO_4$.

Because these rare-earth oxysulfides have different x-ray absorption spectra than $CaWO_4$, slight differences in contrast might be anticipated. Their relatively greater sensitivity to the higher energy x-ray photons passing through a dense media would tend to diminish contrast. They would also be expected to have a relatively lesser sensitivity to scattered low-energy x-ray photons and thus show improved contrast. Thus far, in trial radiographs, no significant differences in contrast have been observed.

DISCUSSION

It has been shown that the rare-earth oxysul-

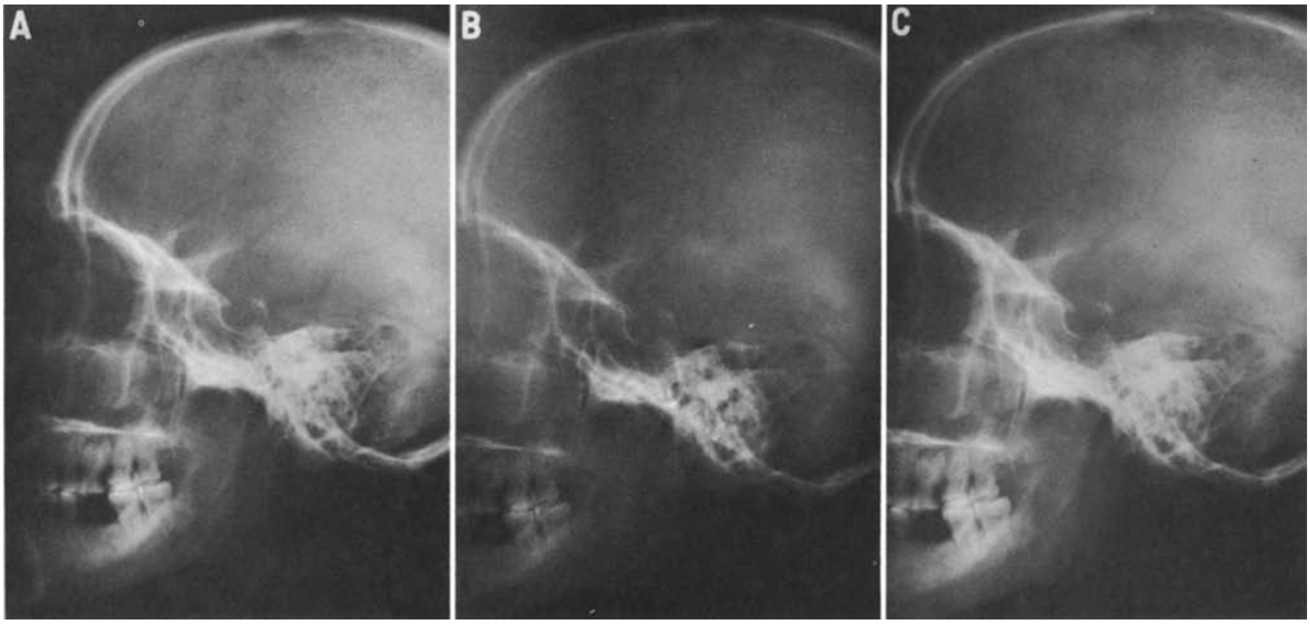

Fig. 6. Comparison of radiographs of a skull phantom taken with a 3-phase generator at 80 kVp using Cronex 4 film and 90-second processing. A. Par-speed screen, 40 mAs.
B. Gd_2O_2S:Tb screen, 40 mAs.
C. Gd_2O_2S:Tb screen, 20 mAs.

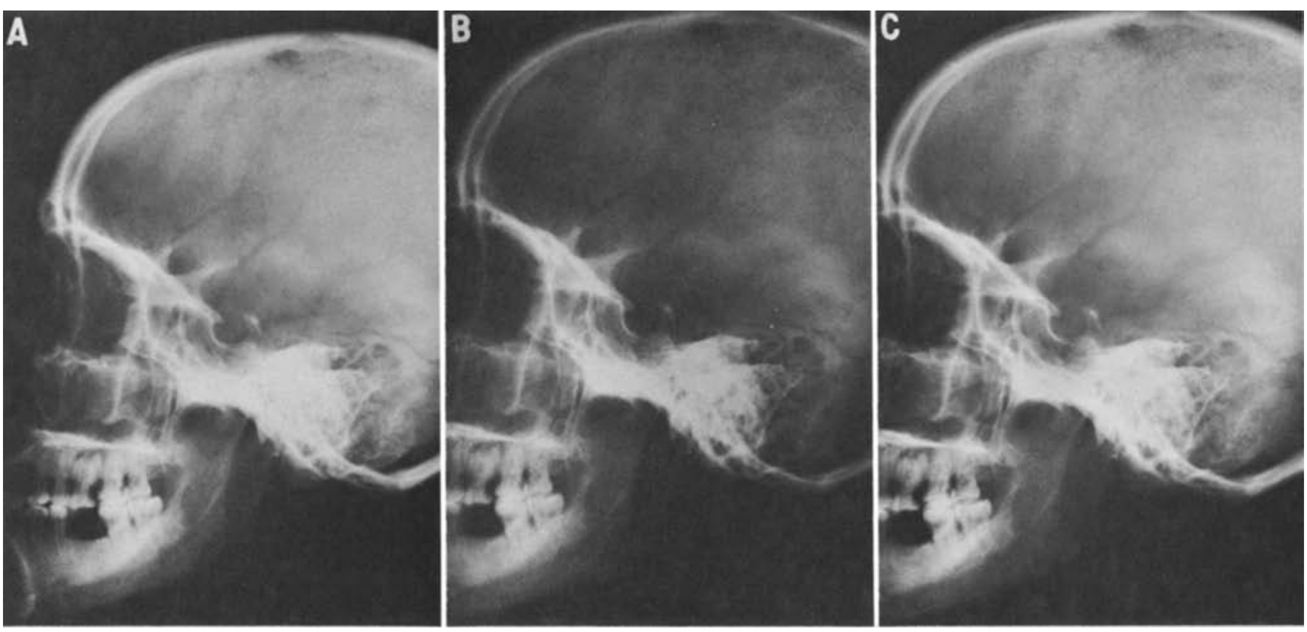

Fig. 7. Comparison of radiographs of a skull phantom taken with a 3-phase generator at 60 kVp using Cronex 4 film and 90-second processing. A. Par-speed screen, 200 mAs.
B. Gd_2O_2S:Tb screen, 200 mAs.
C. Gd_2O_2S:Tb screen, 140 mAs.

fides have great promise for making improved x-ray intensifying screens because of their increased x-ray stopping power and higher intrinsic luminescent efficiency. Exposure reductions of two or greater are achievable at 70 kVp and above using screens of Gd_2O_2S:Tb and standard blue-sensitive x-ray film. Significantly larger exposure reductions are anticipated with improved manufacturing techniques and the development of a faster green-sensitive film. The ultimate exposure reduction may depend upon the limit set by quantum mottle. This refers to the fact that as fewer and fewer x-ray photons are used to produce the radiographic image, the random statistical fluctuation of photons will eventually result in a loss of image detail.

The exposure reduction could also be traded for an increase in resolution by using thinner screens of smaller particle size. Very high resolution screens of rare-earth oxysulfides may find application in areas where intensifying screens are not currently considered acceptable because of insufficient resolution.

These new rare-earth phosphors also have a considerable advantage in x-ray stopping power over cadmium zinc sulfide (Cd,ZnS) and they also have a comparable conversion efficiency. This means that the new phosphors should be useful for making higher efficiency fluoroscopic screens than can be made using Cd,Zns. Recently, Gd_2O_2S:Tb has replaced Cd,ZnS as the input phosphor in the Machlett x-ray image intensifier tube.

In the more than seven decades since $CaWO_4$ intensifying screens were introduced no new phosphor material has been developed which improves screen performance as dramatically as these rare-earth phosphors.

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