Oct. 23, 1945. D. McLACHLAN, JR 2,387,704

X-RAY RADIOGRAPHY OF INCLUSIONS

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Fig. 1.



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X-RAY RADIOGRAPHY OF INCLUSIONS

Original Filed March 23, 1943 6 Sheets-Sheet 2

Fig. 2.



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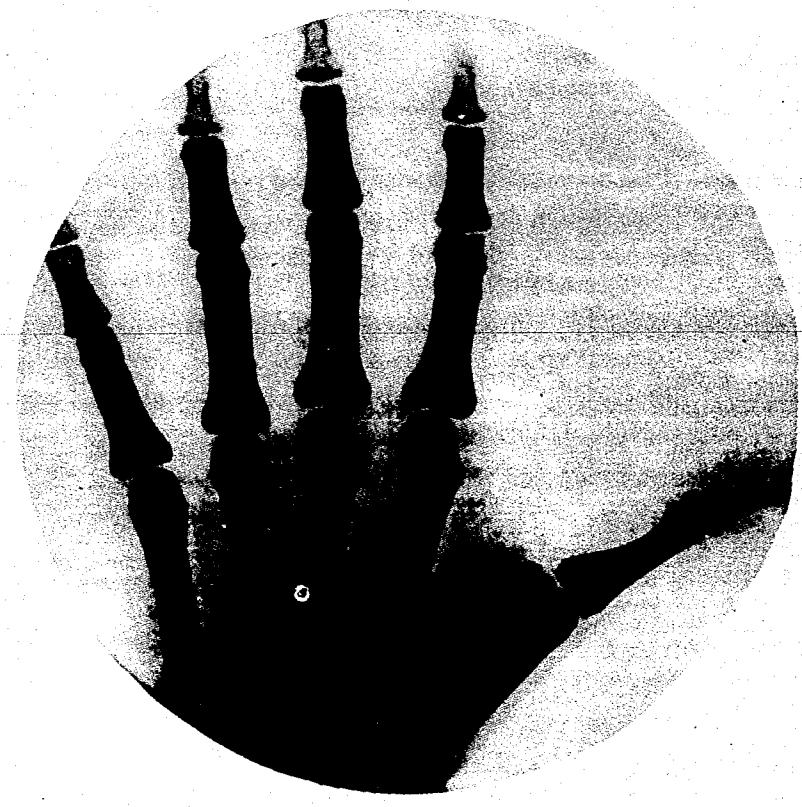
106-272 CROSS REFERENCE EXAMINER

Oct. 23, 1945. D. McLACHLAN, JR 2,387,704

X-RAY RADIOGRAPHY OF INCLUSIONS

Original Filed March 23, 1943 6 Sheets-Sheet 3

Fig. 3.



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Oct. 23, 1945. D. McLACHLAN, JR 2,387,704

X-RAY RADIOGRAPHY OF INCLUSIONS

Original Filed March 23, 1943 6 Sheets-Sheet 4

Fig. 4.



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Oct. 23, 1945. D. McLACHLAN, JR 2,387,704

X-RAY RADIOGRAPHY OF INCLUSIONS

Original Filed March 23, 1943 6 Sheets-Sheet 5

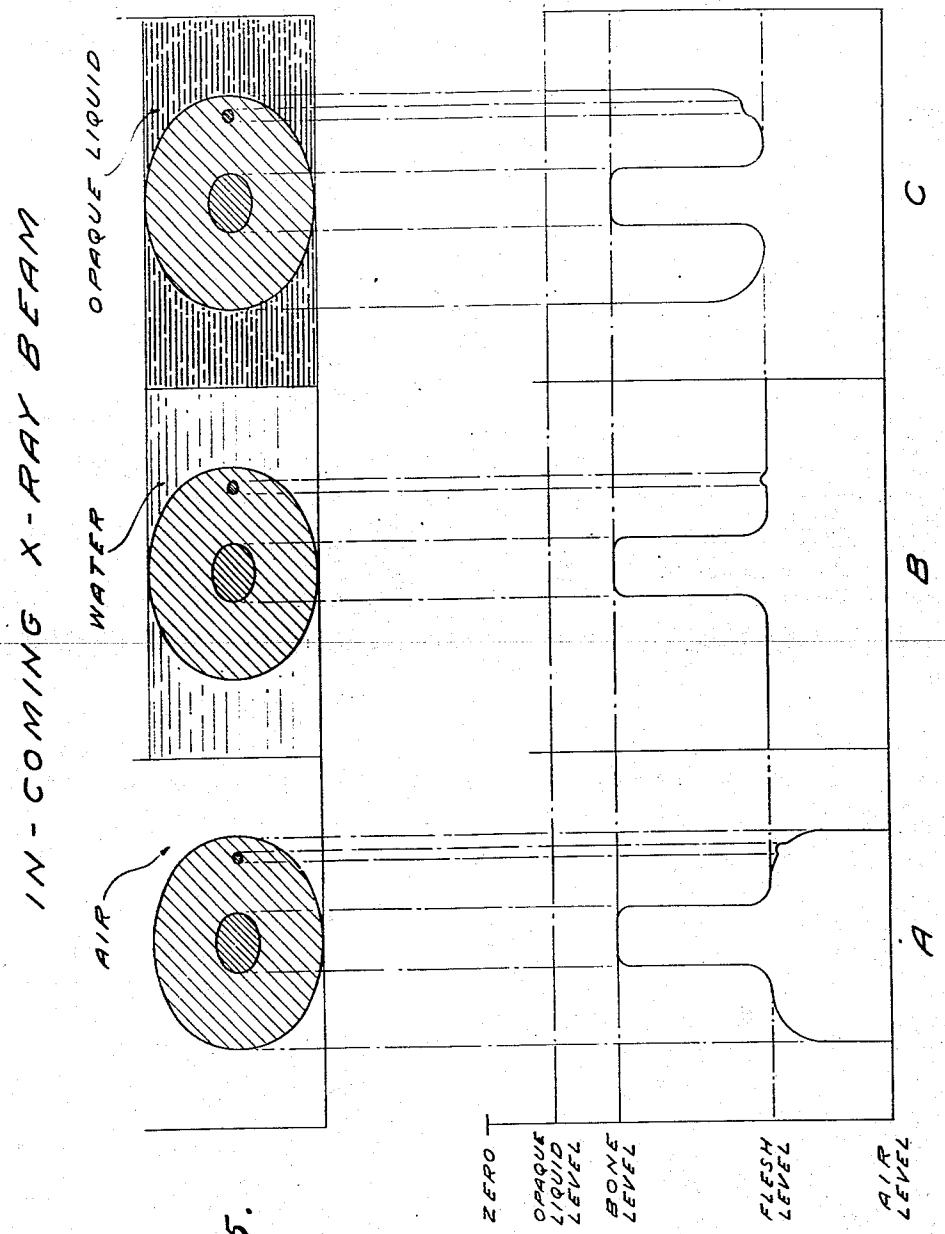


Fig. 5.

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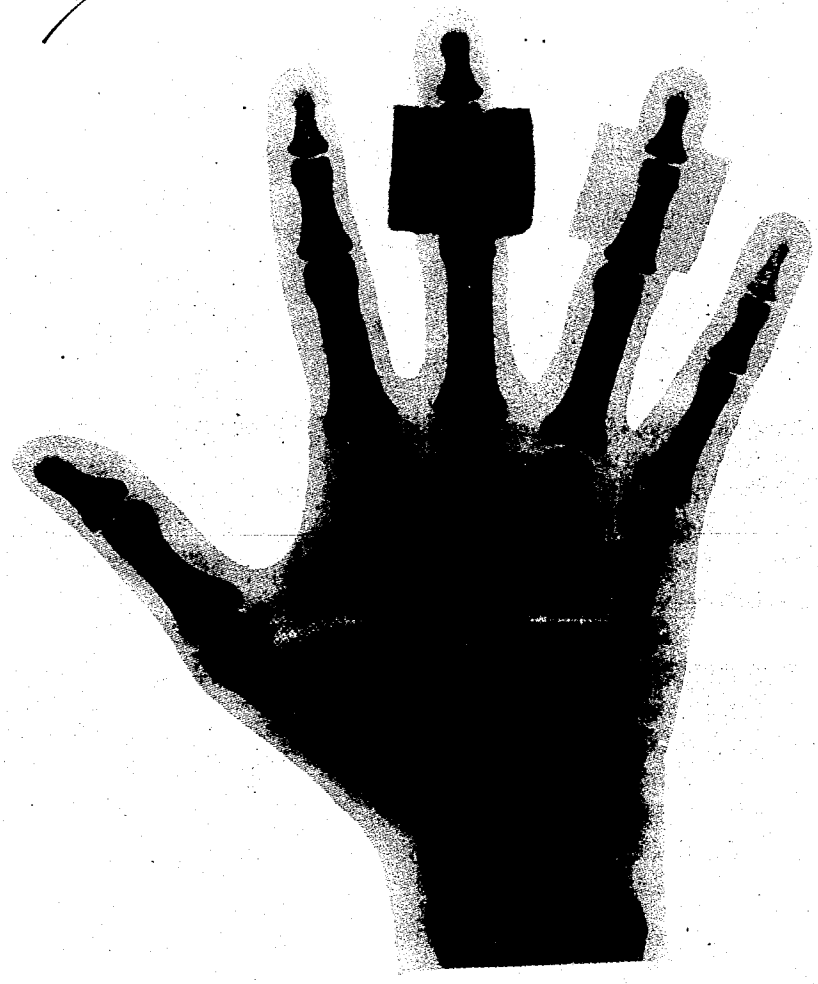
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X-RAY RADIOGRAPHY OF INCLUSIONS

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Fig. 6.



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UNITED STATES PATENT OFFICE

2,387,704

X-RAY RADIOGRAPHY OF INCLUSIONS

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Original application March 23, 1943, Serial No. 480,151. Divided and this application February 18, 1944, Serial No. 522,885

1 Claim. (Cl. 250—108)

This invention relates to an improved X-ray technique and to preparations useful for carrying out X-ray diagnoses and fluoroscopic observations. More particularly, it embraces a new and improved procedure embodying the use of an immersion and embedding technique for surface, internal and foreign body radiography. In addition, this invention discloses the use of a number of immersion liquids and embedding pastes necessary for carrying out this new immersion technique.

Heretofore, no combination of voltage, milliampere-time, or type of film could be found which would reveal satisfactorily the details of structure within and on the surface of commercial and medical objects subjected to X-ray examination. However, the embedding technique herein described and the use of the immersion technique of this invention have greatly extended the usefulness of X-ray examination in the field of medical radiography.

The specific problem solved by the method and technique of this invention involves a means and method for increasing the relative contrast of the images produced on a roentgenogram by the various particles and bodies being radiographed.

It is a particular object of this invention to reveal the details of bodies and inclusions within a particular body containing such inclusions so as to render the same readily perceptible.

In the drawings, forming a part of this disclosure:

Fig. 1 is a roentgenogram of a hand X-rayed in the usual manner, showing that the X-rays are attenuated more by the bones than by the fleshy part of the hand;

Fig. 2 is a roentgenogram of a hand X-rayed while immersed in water, showing only the bones in the fully immersed fingers, the X-rays being equally attenuated by the pure water and by the fleshy part of the fingers in this region;

Fig. 3 is a roentgenogram of a hand X-rayed in the usual manner, showing only two particles of glass as clearly discernibly in the flesh of the hand, one above the second joint of the thumb and one to the right of the second joint of the index finger;

Fig. 4 is a roentgenogram of the same hand shown in Fig. 3 but immersed in water and shows four particles of glass indicated by the fogging within the circles as clearly discernible in the flesh of the hand;

Fig. 5 is a diagrammatical illustration of the effect of using various immersion techniques showing the leveling effect of water immersion as contrasted to ordinary air radiography; and

Fig. 6 is a roentgenogram of a hand X-rayed in air but having the second or middle finger embedded in a paste of greater opacity more nearly matching the flesh of the hand.

Although this invention is not to be deemed limited by any theory as to its operation, a somewhat lengthy discussion of the theoretical considerations involved herein is believed necessary to the further understanding of its modus operandi.

Since all radiographs are shadow-graphs which are taken with the object between the source of radiation and the film, a discussion of the transmission of X-rays through matter underlies any attempt to explain the use of the products and processes involved herein. The fundamental law of attenuation of transmitted light, known as Lambert's law of optics forms the basis of any explanation of absorption and transmission of X-rays through matter. Lambert's law states that:

$$I = I_0 e^{-\mu t} \qquad (1)$$

where

I is the intensity of the transmitted radiation

I_0 is the intensity of the radiation incident upon the object

t is the thickness of the object

and

μ is the linear absorption coefficient of the material forming the object

The linear absorption coefficient μ for any substance depends upon the state of the substance, i. e., whether it be a solid, a liquid or a gas. Thus, the intensity of an X-ray beam is not decreased as much by traversing one centimeter of water vapor or steam as it is by passing through one centimeter of water. Among other factors determining the value of the linear absorption coefficient μ are principally the mean atomic number of the material in question, the specific gravity of that material and the wave length of the radiation employed.

A more useful relationship is that obtained by dividing the linear absorption coefficient μ by the density ρ to obtain the mass absorption coefficient

$$\frac{\mu}{\rho}$$

which is the same regardless of the state of the substance (i. e., liquid or vapor) and expresses the fraction of the intensity lost per unit of mass having unit cross-section. This ratio

$$\frac{\mu}{\rho}$$

gives the absorption of a substance in any state for a given X-ray wavelength; its value, however, decreases rapidly with decreasing atomic weight and decreasing wave length. It measures

the ability of a substance to absorb energy from an X-ray beam.

This energy absorption or the factors preventing an X-ray beam from going directly through an object without attenuating the beam consists of two portions,

$$\frac{\mu}{\rho}=\frac{\delta}{\rho}+\frac{\sigma}{\rho} \quad (2)$$

where

$$\frac{\delta}{\rho}$$

is the mass photo absorption coefficient and

$$\frac{\sigma}{\rho}$$

is the mass scattering coefficient. However, the mass scattering coefficient is usually so small that it can be omitted without introducing an error of any great importance in the final calculations. Moreover, where scattering is of appreciable degree, the scattering factor can be reduced by the use of a cone or filter or a Potter-Bucky diaphragm. Thus, it becomes obvious that the mass photo absorption coefficient or the power of the material to convert the X-radiation into radiation of longer wave length such as visible light and heat is the principal factor determining the value of the mass absorption coefficient

$$\frac{\mu}{\rho}$$

and for practical purposes

$$\frac{\mu}{\rho}$$

and

$$\frac{\delta}{\rho}$$

may be used interchangeably.

For certain wave lengths, however, discontinuities occur in the mass photo absorption coefficient, particularly in the vicinity of the critical absorption wave lengths at which the characteristic spectral lines known as the K, L, M, N, etc., series of the various elements are produced. At such wave lengths, the value of

$$\frac{\mu}{\rho}$$

is less above each critical wave length than it is below, and between these discontinuities the value of

$$\frac{\mu}{\rho}$$

increases with increasing wave length approximately in accordance with the equation:

$$\frac{\mu}{\rho}=CZ^4f(\lambda) \quad (3)$$

where C is a constant depending upon the atomic number of the absorbing element and changes abruptly at the critical wave lengths, Z is the atomic number of the element and $f(\lambda)$ is a function of the wave length λ, $f(\lambda)$ taking values such as $\lambda^{5/2}$, λ^3, etc., depending upon the wave length of the X-radiation and on the elements X-rayed.

The following table gives the mass photo absorption coefficients and hence approximate values for the mass absorption coefficients

$$\frac{\mu}{\rho}$$

of some common substances as a function of the wave length of the X-radiation.

TABLE I

Mass absorption coefficients of some chosen substances

Substance	Specific weight	Chemical composition	Mass photo absorption coefficient
Water	1.0	H_2O	$2.506\lambda^3$
Albumen		C 52%, H 7%, N 16%, O 24%, S 1%.	$1.78\lambda^3$
Fat (human)	0.9	C 75.6%, H 12.6%, O 11.8%	$1.135\lambda^3$
Muscle		W 72%, E 20%, F 7.6%, Sa 1%.	2.57
Blood	1.06	W 80%, E 19.1%, Sa 0.9%	2.61
Transudate	1.008	W 96.8%, E 2.4%, As 0.9%	2.72
Exudate	1.02	W 93.3%, E 5.9%, As 0.8%	2.69
Pus	1.06	W 90.6%, E 7.8%, F 0.8%, Sa 0.8%.	2.67

The mass absorption coefficients of some of the more common elements found in organic compounds are given below in Table II at 30 kv., the mean effective wave length being approximately .63 Å.

In Table I where the chemical composition is not indicated by the atomic symbol representing the element present, the following notation explains the composition: W=water, E=protein, F=fat, Sa=salts, As=ash, Ch=chloresterin.

Table I*a* is a supplementary table giving the mass absorption coefficients of additional substances.

TABLE I*a*

Substance	Specific weight	Chemical composition	Mass photo absorption coefficient
Sinew (connecting tissue)	1.1	W 62.9%, E 34.7%, F and related substances 1.9%, inorganic Sa 0.5%.	2.37
Fat tissue	0.92	W 11.7%, E 21%, F 86%, As 0.2%.	1.37
Liver	1.06	W 76%, E 20%, F 3%, As 1%.	2.61
Spleen	1.05	W 78%, E 16%, F 5%, As 1%.	2.61
Lung		W 80.1%, E 16%, F 2.7%, As 1.2%.	2.69
Thyroid gland	1.06	W 82%, E 16%	2.70
Mamma (old atrophied)	0.96	W 45%, E 9.7%, F 44.8%, As 0.5%.	1.93
Placenta	1.06	W 85%, F 0.85%, As 0.9%, E 13.25%.	2.75
Nerves	1.03	W 76%, E 7%, Ch and Lipoide 13.5%, As 1.5%.	3.12
Bone cortex	1.9	W 26%, E 24.5%, F 23%, As 47.2%.	13.24
Cartilage	1.11	W 72%, E 26.3%, As 1.7%	2.70
Hair	1.3	C 50.5%, H 6.4%, N 17.1%, O 20.7%, S 5%, As 0.3%.	2.89
Finger nail		C 51%, H 6.8%, N 16.9%, O 21%, S 3%, As 1%.	2.57
Rectal odenocarcinoma.	1.06	W 76%, E 22.9%, As 1.1%	2.67
Chemical glassware.	Ca 2.6	SiO_2 77%, K_2O 7.7%, Na_2O 5%, CaO 10.3%.	15.05
Sand stone	2.3-2.9	SiO^2	10.25
Iron	7.86	Fe	107.7
Kidney	1.06	W 83.5%, E 15.7%, As 0.8%.	2.6

TABLE II

The mass absorption coefficients of some of the more common elements

Chemical element	Symbol	Mass absorption coefficient $\frac{\mu}{\rho}$ at λ=.63 Å.
Oxygen	O	.90
Hydrogen	H	.435
Carbon	C	.467
Nitrogen	N	.610

From this table it is possible to calculate the mass absorption coefficient

$$\frac{\mu}{\rho}$$

of water, noting however, that when a material is composed of more than one element, each element contributes its share of the total absorption in proportion to the concentration C_1, C_2, etc., of the elements present in accordance with the following equation:

$$\frac{\mu}{\rho}=\left[C_1\left(\frac{\mu}{\rho}\right)_1+C_2\left(\frac{\mu}{\rho}\right)_2+C_3\left(\frac{\mu}{\rho}\right)_3\right]\rho \qquad (4)$$

where

$$\left(\frac{\mu}{\rho}\right)_1$$

is the mass absorption coefficient of the element of which C_1 is the fraction of that element present, etc., and where ρ is the density of the material or compound made up of the fractions C_1, C_2, C_3, etc.

Thus, for example, the mass absorption coefficient of water for X-radiation produced at a potential of 30 kv. and hence having a mean effective wave length of .63 Å. is obtained by substituting in Equation 4 the mass absorption coefficient of hydrogen at this wave length, namely, .435, and of oxygen, namely .90, and noting that water is composed of 11% hydrogen and 89% oxygen and has a density of unity:

$$\left(\frac{\mu}{\rho}\right)H_2O=[.11\times.435+.89\times.9]1=.85$$

This value .85 for the value of

$$\frac{\mu}{\rho}$$

for water checks almost exactly with the mass absorption coefficient of water obtained from Table I, $f(\lambda)$ being taken as the function $\lambda^{5/2}$ or λ^3, $\lambda^{3/2}$, etc., most appropriate for the wave length of .63 Å. and making some small allowance for the relative importance at such comparatively short wave lengths of the absorption due to the mass scattering coefficient of the elements present.

The mass absorption coefficients of some common compounds have been calculated from the values given in Table II and are included in the following table:

TABLE III

Mass absorption coefficients of some organic compounds

Compound	Percent O	Percent H	Percent C	Percent N	Density	μ .63
Formic acid	69.6	4.35	26.2	0.0	1.22	.943
Urea	26.7	6.66	20.0	46.7	1.33	.86
Water	89.0	11.0	0.0	0.0	1.0	.85
Methyl alcohol	50.0	12.5	37.5	0.0	0.79	.54
Ethyl alcohol	34.8	13.0	52.2	0.0	0.80	.49
Propyl alcohol	26.7	13.3	60.0	0.0	0.80	.46
Butyl alcohol	21.6	13.5	64.8	0.0	0.81	.45
Cyclohexane	0.0	14.3	85.7	0.0	0.66	.31
Nujol	(A petroleum fraction)				.87	.41
Paraffin	(A petroleum precipitate)				.89	.42

A summary of the above statistical facts discloses briefly, that X-rays are attenuated as they pass through matter by interaction with the materials or tissues through which they pass. In each case the amount of attenuation depends upon the kind of material and the thickness of the tissue through which it passes. Thus, a ray passing through one or two centimeters of bone is greatly attenuated because of the relatively high density of the elements Ca and P in the bone while a ray passing through 10 centimeters of inflated lung tissue is only slightly attenuated.

Rewriting Equation 1 as follows:

$$I=I_0e^{-\left(\frac{\mu}{\rho}\right)\rho t}. \qquad (15)$$

shows clearly that the intensity of transmitted radiation depends on the value of the product of (1) the mass absorption coefficient, (2) the density and (3) the thickness of the material and hence the visibility of an image produced on a film is affected by a predominance of any one of these 3 factors or by a combination of all three.

The fundamental problem of roentgenography is to choose such technical procedures as to produce roentgenograms that have a minimum of observable unsharpness and an image having a predetermined optimum of density and contrast. Hence for an object to cast an image which can be distinguished from the background of a photographic film, it is necessary that the intensity of the radiation striking the film at that point be sufficiently different from that striking the neighboring points as to give rise to a discernible photographic density difference. The density of a particular small area of a roentgenogram depends in general upon the sensitiveness of the film and the intensifying screen used, the film processing methods, the X-ray tube voltage and current, the focal spot-film distance, and exposure time, as well as the X-ray absorbing properties of the irregularly truncated conical volume of tissue or material whose base is the particular small area of the film, and extending from this area towards the focal spot of the X-ray tube.

Usually, a distinct image can be obtained by the use of reasonable care provided there is a difference of at least 2% between the intensity striking the film at the image and that striking the immediately surrounding areas and also provided the applied kilovoltage is so adjusted that about 82% of the X-rays are absorbed in going through the object. The second requirement for a distinct image is fulfilled upon adjusting the kilovoltage in accordance with the instructions given in various radiographic manuals depending upon the thickness of the body being observed.

In the case of the radiography of a piece of metal containing a blow-hole, the bubble will be visible only if its diameter exceeds about 2% of the thickness of the metal block. From an inspection of the values given in Table I it is to be noted that if mass absorption coefficients were the only factors involved, fat tissue, bone, and various other body substances would be visible against a background of muscle. But, in accordance with Formula 5 other factors enter, and, moreover most of the individual tissues and organs of the human body are so small in thickness compared to the effective thickness of the subject and are so often so interpositioned and intertwined that they do not produce a distinct image. In addition, various other factors contribute to the obliteration or unsharpness of the image, such as variations in the outside shape of the object, or variation in the thickness of the object.

Various auxiliary roentgenographic devices have been devised to improve the results obtained by the conventional methods where the objects are radiographed in air in order to produce an image having a minimum of observable unsharpness and a predetermined optimum aver-

age density and contrast. Among such devices may be mentioned the Potter-Bucky diaphragm to reduce fogging of the film due to scattering, the use of a cone to reduce scattering of X-rays in air, the choosing of exposure factors such as X-ray tube voltage, exposure time, and the like.

The present invention utilizes a technique embodying the immersion or embedding of the body to be radiographed in liquids or pastes of selected opacities, particularly of opacities equaling those of the external part or of the continuous phase of the heterogeneous object being radiographed in order to obtain improved photographic results.

In order to explain the process of this invention more clearly, a number of actual roentgenograms are reproduced herein. Fig. 1 illustrates the results obtained from the usual practice of radiographing the hand surrounded by air. This figure shows clearly the outline of the flesh at the finger tips. It is to be noted that the flesh also shows up with varying degrees of blackness because of its different thickness in various parts of the hand. The immersion technique of this invention was utilized in obtaining Fig. 2 by radiographing the hand while the latter was immersed in water. This figure shows the flesh as practically eliminated from the resulting roentgenogram.

This result can be explained on the basis of mass absorption and Lambert's Formula 1. Reference to Table I shows the value of the mass absorption coefficient of water

$$\frac{\mu}{\rho}$$

to be approximately 2.506 $f(\lambda)$ while that of muscle, finger nails and similar tissue is about 2.50. Since these values are almost the same, little or no contrast is produced in the film due to the contours of the flesh and hence only the bone structure is prominent. Since the water did not cover a part of the hand, especially at the wrist, in Fig. 2, the outline of the flesh is still perceptible in the lower part of Fig. 2. The covered portion of the hand and fingers is immersed in water having parallel upper and lower surfaces; thus the X-rays pass through a medium which absorbs the rays traversing the medium in equal amounts whether or not the rays encounter flesh. Hence the opacity throughout this path is the same except where bone was encountered.

This immersion technique greatly facilitates the location of splinters of glass, bone, resin and similar small objects embedded in the flesh, as may be seen by comparing the roentgenograms of Figs. 3 and 4. Fig. 3 shows an X-ray photograph taken by the ordinary methods in air. This figure shows only two glass particles to be visible, one above the second joint of the thumb and one to the right of the second joint of the index finger. Fig. 4 shows the same hand, subjected to the same exposure conditions but X-rayed under water. Fig. 4 shows four glass particles to be visible, as indicated by the fogging within the circles. Of the two additional glass fragments, one is located at the base and to the right of the little finger and the other at the base and to the left of the forefinger. Neither of these fragments are visible in the X-ray picture of Fig. 3. In this photograph of a clinical case, four pieces of glass were actually extracted from a patient's hand, only two of which would normally have been disclosed by the use of the ordinary roentgenographic technique in air.

Thus, by eliminating the effect of thickness differences by the immersion technique herein described the improved roentgenographic immersion technique of this invention shows the presence of several small glass fragments very clearly. The greater visibility of the images produced by the glass inclusions in an immersed specimen depends on the fact that slight photographic density differences are seen most clearly when they occur against a uniform background. The graphical representation of this density leveling effect is clearly understood by referring to Fig. 5 where the upper half of the diagram shows the incident X-ray beams which are attenuated in intensity in accordance with the projected representations shown in the lower half of the diagram. In A the drawing depicts a finger radiographed in air, in B the finger is radiographed while immersed in water, while in C an opaque liquid such as a 7% solution of barium chloride in water is used as the immersion liquid. The image of the foreign body falling on the field of uniform density in B shows diagrammatically that the contrast effected by the contiguous uniform densities on the film in B in the neighborhood of the foreign body facilitates the discovery of the body as compared to the unsharpness and non-uniformity of the contiguous densities in A and C in the neighborhood of the foreign body.

In a similar manner, this immersion technique may be used to obtain clearer roentgenograms of shattered bones and small pieces of bone embedded in flesh.

In those cases where it is practically impossible to utilize a liquid immersion technique the use of a paste or jelly packing of suitable consistency and having parallel upper and lower surfaces may be resorted to. Thus, in Fig. 6 two pastes of different opacities have been packed about the fingers of a hand. The third finger is embedded in a paste having an opacity equal to that of water. Such a paste is obtained by mixing 100 parts of petrolatum with 50 parts of beeswax and adding 2% of barium sulfate.

The paste shown around the second or middle finger of Fig. 6 has an opacity equivalent to that of a 7% solution of barium chloride in water. Such a paste is obtained by starting with a radiolucent paste such as that obtained from mixing 100 parts of petrolatum with 50 parts of beeswax and blending in measured quantities of very finely divided or ground barium sulfate, zinc oxide, or the like. Thus the addition of .885 gram of finely ground zinc oxide to about 75 grams of the radiolucent paste gives a paste having an opacity equal to that of water. Further additions of zinc oxide give a paste of still greater opacity.

Among various other commercially available powders which are non-toxic and capable of being added to a paste-like mixture of 100 parts of petrolatum and 50 parts of beeswax to produce an X-ray paste having an opacity approximately that of human flesh are the following:

Substance	Grams of substance to be added per 100 grams of above mixture
MgO (magnesium oxide smoke)	14.7
Al_2O_3 (alumina)	13.55
CuO (copper oxide black)	1.31
SnO ₂ (tin oxide putty powder)	2.07

This case is a division of U. S. Serial No. 480,151, filed March 23, 1943, by the applicant.

It is to be understood that the examples and processes above described are merely illustrative and not limitative embodiments of the invention the scope of which is encompassed within the appended claim and equivalents thereof.

I claim:

A stable radiolucent paste comprising 100 parts of petrolatum and 50 parts of beeswax together with sufficient amounts of radiopaque substances to give a paste having a mass absorption coefficient for X-rays of predetermined wave-length equivalent to that of flash for X-rays of the same wave-length.

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