Medical electroradiography — its potential and limitations

K. R. Peschmann

"Electrophotography", which is now well known because of its widespread application in copying machines, is also employed in medical diagnostics, where it is called 'electroradiography'. One important reason for research on electroradiography is that it makes no use of silver, unlike conventional X-ray photography. Another attraction is the range of possibilities offered by the developing process: the picture information can be processed to improve the 'readability'.

The studies in electroradiography at the Philips research laboratories in Aachen have been mainly concerned with the possibilities and the limitations both in the formation of the latent charge pattern — sensitivity and resolution — and in making this visible (the 'development'). The article deals mainly with the system in which the X-ray radiation is detected with the aid of a compressed gas.

Introduction

Electrophotography has become generally known as a result of the widespread use of copying machines. The subdivision of electrophotography in which an X-ray field is used to provide the input information is known as electroradiography. Because electrophotography does not use silver to produce pictures, this in itself is sufficient reason for investigating the possibility of using it for medical diagnostics. Even though the combination of X-ray image intensifiers and television systems and the associated magnetic-memory technique has been with us since about 1960, the amount of silver-based film used for X-ray photography in North America in 1974, for example, still averaged out at 0.4 m² per head of the population. It should, of course, be pointed out that recovery of silver from the used silver bath is relatively simple and as long as the price of silver keeps on increasing recovery will be used more and more. Silver can also be recovered from old X-ray photographs and this is being done, particularly in the United States.

In medical radiography internal structures in the human body are made visible by using X-rays and the principle of shadow projection. In electroradiography the X-ray radiation attenuated by the object is absorbed by an X-ray photoconductor, thus creating charge carriers. Under the influence of an electric field the charge carriers come to rest on a dielectric film (called an insulating 'foil') where they produce an (invisible) charge pattern of the tissue structure being photographed. This pattern is made visible by means of 'electrophotographic development'.

Another important feature resulting from the changeover from conventional to electrophotographic image recording is that the electrophotographic developing process can be varied and this presents us with an extra 'dimension'. It offers us a relatively simple method of 'picture processing'. It is possible, for example, to attenuate the background caused by scattered radiation. Another well-known example of the processing of picture information is contour enhancement in the reproduction of weak contrasts in xerography. This is accompanied by a loss of information, however, when relatively large homogeneous parts and areas of average-to-high contrasts in the object are being reproduced. In certain cases the nature of the picture may also be altered to such an extent that considerable experience is necessary for interpreting it.

Whatever the method used, the patient should not be exposed to a higher dose of radiation. The objective of our investigation is therefore to develop systems in which the dose of radiation required is not greater than for film radiography with an intensifying screen, but in fact rather smaller. Xerography is already being used for mammography, particularly in the U.S.A. This system is somewhat insensitive,
however, so that the required dose of radiation is high. Experiments with gas ionography — an electroradiographic system with a gas as the photoconductive medium — have yielded results that are more promising; it has been shown that the radiation dose

A radiographic system is said to be limited by quantum noise if the resolution of detail in the image is limited by statistical fluctuations in the flow of X-ray photons and not by the sources of noise inherent in the system or by effects that reduce the sharpness of the image. A calculation we made for mammography\(^1\) shows that about \(10^8\) photons per cm\(^2\) must be incident on the recording medium for microcalcifications with a cross-section of 150 \(\mu\)m to be detected. This is equivalent to a dose of 7.5 mR (1 R = 2.58 \(\times 10^{-4}\) coulombs/kg) for a mean quantum energy of 26 keV. If it is assumed that the object has a mean transmission of 60\% then the dose of radiation to which the patient is exposed is about 120 mR.

The calculation holds for a system limited by quantum noise in which the detective quantum efficiency is set at 1 (we shall return to the concept of detective quantum efficiency later) and it has been assumed that the system operates linearly, i.e. the optical density is proportional to the flux density of the X-ray photons. It is easy to see that the required dose becomes greater as the particles to be imaged become smaller.

In the sections that follow we shall look first at the physical processes that give rise to the formation of an electroradiograph, and then at two systems of electroradiography, the high-pressure gas ionographic system\(^2\) and the lead-oxide/gas-layer system, for which we have made a special study of the sensitivity and resolution. The possibilities offered by the

<table>
<thead>
<tr>
<th>Table I. Comparison between three electroradiographic systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production of an electroradiograph</td>
</tr>
<tr>
<td><strong>X-ray photon</strong></td>
</tr>
<tr>
<td><strong>absorption</strong></td>
</tr>
<tr>
<td><strong>high-energy electrons and photons</strong></td>
</tr>
<tr>
<td><strong>thermalisation</strong></td>
</tr>
<tr>
<td><strong>charge carriers</strong></td>
</tr>
<tr>
<td><strong>drift and transfer</strong></td>
</tr>
<tr>
<td><strong>electrostatic image</strong></td>
</tr>
<tr>
<td><strong>electrophotographic development</strong></td>
</tr>
<tr>
<td><strong>electroradiograph</strong></td>
</tr>
</tbody>
</table>

here can be reduced compared with conventional systems.

The objective of the investigation is not so easy to define for the 'picture quality' in general as it is for the required radiation dose. Many factors affect the picture quality; specially adapted systems have to be used for the various methods of investigation. In practical terms, this means that the basic system of X-ray source and recording medium must be optimized for all applications.

Any of the possible recording systems is subject to certain limitations. There are two main reasons for this. Firstly, the radiation is not completely absorbed, i.e. not all the X-ray photons contribute to the formation of the image. More primary photons are therefore necessary than in an ideal system. Secondly, the processes used for image formation are subject to noise, which degrades the resolution of details.
Fig. 1. Calculated effective X-ray absorption $A_{\text{eff}}$ as a function of the photon energy $E$ in photoconductors used in different radiographic systems. The fact that part of the fluorescent radiation and the scattered radiation do not contribute to the image information is taken into account. The dip on the left can be attributed to the absorption of the electrode at the entry side. A striking feature is the relatively low effective absorption of the compressed xenon gas (maximum about 40%). The 80 μm PbO layer has the highest absorption.

The development of the charge pattern will then be examined; a great deal of the knowledge obtained in this field is based on investigations carried out in our laboratories. Finally, a more detailed examination is made of the advantages and disadvantages of electroradiographic systems.

Electroradiographic systems

In this section an explanation of the operation of electroradiographic systems will be given, with the high-pressure ionographic system and the lead-oxide/gas-layer system as examples. The two methods are compared in Table I, which also includes selenium xeroradiography for completeness. This system will not be discussed further here, however [3].

The left-hand column of the Table indicates the stages in the process of making an electroradiograph. The other columns give special features of the three systems. These columns start with a short description of the photoconductor, which absorbs the X-ray radiation that passes through the object under examination. In ionography the photoconductor consists of a compressed heavy inert gas, e.g. xenon or krypton, while in the PbO system the photoconductor is in the form of a layer of lead-oxide crystals in a binder that has an effective thickness of 80 μm. As a result of the absorption processes a spectrum of high-energy photons and electrons is produced. The electrons — together with the L fluorescence photons from the lead oxide and the L and K fluorescence photons from the selenium — are slowed down by the absorbing medium, each high-energy electron generating several hundred to two thousand secondary charge carriers. The calculated effective absorption has been plotted in fig. 1 for the three systems. As the figure shows, the PbO system with the 80 μm layer has the highest effective absorption in the total energy range, up to almost 90%, whereas only 40% of the radiation is used effectively in the high-pressure gas system with xenon. (Hasty conclusions should not be drawn from this figure, since the effective absorption is only one of the criteria used to assess the electroradiographic systems.)

An electric field pulls the mobile secondary charges in the direction of the electrodes. In the high-pressure gas system the charge transport ends when the charge carriers have reached an insulating foil. In the PbO system this transport is terminated as soon as the charge carriers arrive at the surface of the photoconductor, provided they have not previously been trapped. Charge transfer takes place from the surface of the photoconductor through the gas layer to an image-bearing foil. In both cases a charge pattern has been formed on a foil — an electrostatic surface-charge distribution whose density is proportional to the X-ray radiation field attenuated by the object. The final stage is the conversion of the charge pattern into a visible picture.

Ionography with a compressed gas

Secondary spectrum and detective quantum efficiency

Fig. 2 is a diagram showing how a charge pattern is formed by means of ions of a compressed gas. The X-ray photons to be detected enter the gas space $G$, which contains a gas such as xenon as the absorbing medium, through the pressure-tight window electrode $W$. The secondary radiation generated by the internal photoelectric effect and by scatter consists of high-energy photons and electrons. The photoelectric effect is the dominant source of secondary radiation, and the secondary electron yield is generally high.

energy electrons and photons whose calculated spectra are reproduced in fig. 3. The area of the regions bounded by these curves is proportional to the energy of the particular secondary-radiation component. The figure clearly shows that the absorbed radiation energy comes mainly from the fast electrons. When these are decelerated in the gas a number of ion/electron pairs are created, and these are charge carriers that will form the charge pattern. The photons (dashed curves) that are simultaneously formed with the fast secondary electrons are lost because they cover a few millimetres in the gas and are therefore not absorbed until they are a considerable distance away from the point of origin — and may even reach the wall of the ionographic chamber.

The extent to which the radiation incident on the chamber is used for the information present in the X-ray picture is expressed by the detective quantum efficiency DQE. The value of this indicates directly the radiation dose required in an actual system as compared with that required in an ideal system (DQE = 1). If for example DQE = 0.25, then the dose of radiation must be four times as high if the same image information (limited by quantum noise) is to be obtained as in an ideal system. The detective quantum efficiency is defined as follows [4]:

\[
\text{DQE}(E) = \left( \frac{n_0(E)}{\delta_0(E)} \right)^2 \div \left( \frac{n_{\text{det}}(E)}{\delta_{\text{det}}(E)} \right)^2,
\]

in other words, as the square of the noise-to-signal ratio of the X-ray radiation incident on the chamber, divided by the square of the noise-to-signal ratio of the signal produced by the charges generated in this chamber. Fig. 4 shows the result of a calculation of this quantity for xenon or krypton as the medium [6]. The curves show that under the conditions as described in the caption to the figure, a maximum DQE of 40% is obtained with a photon energy of 21 keV and that for xenon there is a second maximum of 23% at 50 keV, whereas the DQE for krypton is only half as high. For mammography, which employs photon energies of less than 40 keV, krypton is more suitable as the medium than the much more expensive xenon. For the radiography of other organs harder radiation is used. In these cases xenon is therefore more suitable, and as we shall see, it has a greater sensitivity.

A word or two of explanation should be given about the derivation of the somewhat complicated-looking equation (1) [4]. The average number of X-ray photons in a small energy interval \( \Delta E \) around \( E \) incident on one square centimetre of the ionography chamber during an exposure is represented by \( \Phi(E) \Delta E \). For the associated energy signal \( \delta(E) \) we have:

\[
\delta(E) = \Phi(E) \Delta E E.
\]

Because the photon flux is subject to fluctuations the standard deviation of the number of X-ray photons is \( [\Phi(E) \Delta E]^1 \) for Poisson statistics. This gives:

\[
\sigma_d(E) = [\phi_d(E) \Delta E]^1 E,
\]

for the standard deviation of the energy signal. The ratio \( \sigma_d/\delta_d \) is called the natural noise-to-signal ratio of the X-ray radiation detected.

The calculation of the noise-to-signal ratio \( n_{\text{det}}(E)/\delta_{\text{det}}(E) \) for the charges generated in the chamber is a little more difficult. Different absorption cross-sections have to be taken into account because they determine the probability of the individual absorption processes. Because the radiation is attenuated by the window, incomplete absorption in the gas, scattering processes and fluorescence radiation (see fig. 3) the associated energy signal is weaker than the signal that would be supplied directly by the X-ray radiation detected. Because the noise-to-signal ratio has also become larger, DQE always has a value smaller than one.

**Sensitivity**

While the DQE is a criterion for assessing the effectiveness of X-ray radiation in the image formation, the sensitivity of the ionographic chamber is a criterion for assessing the density of the surface charge produced on the foil. A high sensitivity means a high charge density, which in turn is a precondition for high optical density. A high maximum value for the optical density or a wide range for the density scale makes it possible to obtain developed images that contain a large number of grey levels.

From the definition of the radiation (ion) dose expressed in röntgens (R), it can be shown that \( N_t \)
to the method used for determining coefficient of air while the indices 'tot' and 'a' relate photons with an energy radiation dose of with the harder radiation used for example for chest X-rays xenon DQE is about 40% for the two gases; at 50 keV xenon has a second maximum of about 8 mm. The maximum window for the incident radiation (thickness 8 mm). The maximum (1), as a function of the photon energy Fig. 4. Calculated detective quantum efficiency DQE(E), equation (1), as a function of the photon energy E for xenon and krypton of 10 bar cm. Graphite-fibre-reinforced epoxy resin is used as the input window of the ionographic chamber. \( f(E) A(E) \) is the absorption in the gas, reduced by the quantity of fluorescent radiation, and \( W \) is the conversion value for the medium. This value indicates the quantity of radiation energy (in eV) necessary for the generation of a single pair of charge carriers. For xenon \( W \) is equal to 22 eV/pair, which means, for example, that a photoelectron with an energy of 30 keV creates a maximum of 1400 pairs of charge carriers. In equation (3) \( e \) represents the charge of the electron \( (e = 1.6 \times 10^{-19} \text{ coulomb}) \). The sensitivity \( S(E) \), expressed as the quantity of charge released per milliröntgen, is equal to the ratio of (3) and (2):

\[
S(E) = 5.10 \times 10^{-18} \frac{[1 - A_p(E)] f(E) A(E)}{\mu_{tot,a,L}(E)} \text{ mR}^{-1} \text{ eV}^{-1}
\] (4)

The conversion value \( W \) from the expression (3) is included in the constant; the coefficient \( \mu_{tot,a,L} \) for air can be calculated from a table [7]. The calculated curve of \( S(E) \) for an absorbing layer of xenon or krypton is illustrated in fig. 5a; it has been assumed that the absorption in the window is negligible.

The sensitivity \( S \) to polychromatic radiation with a distribution \( N(E) \) is obtained by integrating (4) with respect to the energy. Fig. 5b shows the variation for diagnostic X-ray radiation when xenon and krypton are used. The lower curves were obtained with the radiation from an industrial X-ray tube with a tungsten anode — the same kind of radiation as is used in mammography.

The sensitivity of the high-pressure gas-ionographic system can be increased considerably with the aid of electron multiplication by collision, by employing the Penning effect [8]. In this case a dose of 10 \( \mu \text{R} \) is sufficient to produce a charge density of \( 2 \times 10^{-8} \text{ C/cm}^2 \).

In comparison with fig. 5b this amounts to an improvement by a factor of 100. This method, however, has the disadvantage that the resolution is reduced to 1 to 2 line pairs/mm because of the lateral diffusion of the electrons (see also fig. 9b).

\[ \text{photons with an energy } E \text{ (in keV) are equivalent to a radiation dose of } \]

\[ 1.425 \times 10^{-11} \mu_{tot,a,L}(E) N(E) E \text{ röntgens, } (2) \]

where \( \mu_{tot,a,L} \) represents the linear photoabsorption coefficient of air while the indices 'tot' and 'a' relate to the method used for determining \( \mu \). These \( N(E) \) photons generate a quantity of charge (either positive or negative) in the gas of the order of

\[
N(E) E [1 - A_p(E)] f(E) A(E) \frac{1}{W} e \text{ coulombs, } (3)
\]
S(E)

Fig. 5. Sensitivity of an ionography chamber 1 cm thick filled with krypton or xenon (10 bars). Voltage across the ionography chamber 12 kV. a) Spectral curve for the sensitivity S(E). In the calculation of the curves the K and the L fluorescent radiation is considered to have been lost and the absorption in the window has been neglected. The test points were obtained with highly filtered radiation with photon energies of about 37 keV, 55 keV and 80 keV and a beryllium window whose absorption was only a few per cent. For comparison, the dashed-line curve gives the calculated sensitivity of an 'ideal' chamber (complete absorption in the gas and no loss in the window; the numerator in equation (4) is then 1). The shape of this curve is determined by the definition of the ion dose (röntgen). b) The sensitivity S as a function of the tube voltage V_{rad} for diagnostic X-ray radiation. The solid curves were obtained with the radiation from an industrial X-ray tube with a tungsten electrode and its own filter, i.e. with radiation as used for mammography. The phantom filter was a 4 cm thick layer of acrylic resin. The chain-dotted curve was obtained with radiation from a tube with a tungsten electrode operating at 10 mA with a 6-pulse generator; the radiation was filtered by 1 mm of aluminium and 15 cm of water to simulate the human body.

Resolution

The resolution that can be obtained in gas ionography is always limited by two physical effects. The first effect has been illustrated in fig. 6. When a photoelectron is decelerated, a 'cloud' of pairs of secondary charge carriers is formed and the size of this cloud depends on both the initial energy of the electron and the nature and pressure of the gas. It has been estimated that the distance between the point at which the primary photon is absorbed and the centre of gravity of the ion cloud produced in xenon at a pressure of 10 bars by an electron with an energy of 30 keV is about 0.15 mm. It is shown diagrammatically how a jump in the intensity profile results in a continuous change of the density in the charge pattern.

The second effect is the lateral diffusion of the electrons and ions during their drift; see fig. 7a. The electrons diffuse farther than the ions, since for each elastic collision with a xenon atom they can only lose one millionth part of the energy they have received from the applied field. This leads to a very fast, statistically distributed movement (with an electron temperature of several tens of thousands of degrees kelvin), in which the distance covered is 300 times as long as the path in the direction of the field. Because of this, a charge pattern consisting of electrons results in a radiographic image that is much less sharp than the ion image. It is possible to improve the situation, however, by adding to the rare gas a small quantity of another gas that has the property of retaining an electron at a collision. A negative ion is then formed whose lateral drift behaviour is much the same as that of a positive xenon ion; see fig. 7b. A simple model has shown that the blurring of the ion-formed charge pattern caused by the diffusion is independent of the gas pressure and inversely proportional to the square root of the applied field.

To determine how the resolution of an ionographic system depends on the electric field we have prepared radiographs of a line structure made of lead foil.
Fig. 7. Limitation of the resolution by lateral diffusion of charge carriers (schematic). The charge carriers that are formed when the fast electrons are decelerated move under the influence of the voltage $V$. In this case the positive ions go to the top and the negatively charged particles to the bottom. $W, F$ are the same as in fig. 2. a) The electrons (−) diffuse further than the ions (⊙), since for each collision with a xenon atom they can only lose a small fraction of their kinetic energy. This has an adverse effect on the resolution. b) This disadvantage can be overcome by adding to the working gas a small quantity of a gas that retains the electrons at a collision. The negative ions (⊙) formed in this way have much the same kind of lateral movement as the positive xenon ions.

25 μm thick ('Funk-Raster'). A magnifying glass or a low-power microscope was used to determine the resolution of ionographs prepared with a linear very fine-grained liquid developer. The result is illustrated in fig. 8; the experimental conditions are given in the caption. Reproductions of subsequently enlarged ionographs are shown in fig. 9. It is possible to distinguish more than eight pairs of lines per mm in the ion image (fig. 9a) and one pair of lines per mm in the electron image (fig. 9b).

Fig. 8. Experimentally determined resolution $R$ (in pairs of lines per mm) of an ionography chamber (thickness of gas layer 1 cm, working gas xenon (7·8 bars), no gas amplification by electron multiplication), as a function of the electric field-strength $E$. Primary radiation: 35 kVp, tungsten anode; object of measurement: line structures of 25 μm and 50 μm lead foil ('Funk-raster'); fine-grained liquid developer. Region a: electron image; curve b: positive ion image; curve c: negative ion image, formed by the addition of an electron-absorbing gas.

The modulation transfer function is a useful criterion for assessing a radiological system. It gives a quantitative description of the extent to which an image system is capable of reproducing certain details of the object. The modulation transfer function of our experimental ionographic system is illustrated in fig. 10.

The lead-oxide/gas-layer system

Sensitivity

In the section on 'Electroradiographic systems' the PbO system has already been mentioned briefly in Table I; fig. 11 is a diagram of this system. Electrode
E, foil F and gas layer G are almost completely transparent to the radiation detected. The absorption takes place in PbO crystals, which are held together by a binder (layer L). In fig. 1 we saw that this 80 µm layer has a high absorption efficiency. This satisfies an important condition if a layer of this kind is to be used as a photoconductor in a radiographic system, because the sensitivity of a system depends in part on the absorption.

Another precondition for high sensitivity is to have as low a conversion energy as possible for generating image-forming charge carriers. In this case, i.e. in a solid, this means that the loss due to the disappearance of charge carriers by capture in traps and by recombination has to be kept to a minimum. Experiments on single crystals of different semiconductor materials have shown that this conversion energy is about three times the energy gap. In the case of crystalline tetragonal PbO this rule of thumb gives us a value of about 7 eV. In practice, however, a higher value will be found for several reasons (capture of charge carriers, recombination, non-single-crystal nature of the layer, charge transfer via gas layer).

In the laboratories in Aachen the X-ray photoconductor layer was prepared by sedimentation on a metal substrate of very pure tetragonal lead oxide with a mean crystallite size of 10 to 20 µm from a resin solution. This method produces layers that contain, in addition to lead oxide, about 1 wt% of organic binder and about 70 vol% of air. Fig. 12 illustrates a cross-section of such a photoconducting layer. Because of the sponge-like structure it is impossible for the charge pattern on the photoconducting layer to be electrophotographically developed directly. This is why the system shown in fig. 11 has been used. At a distance of about 100 µm from the layer is an insulating foil 6 to 30 µm thick that captures the charge pattern. At the back of the foil is an electrode with a relatively high sheet resistance (about 10^7 Ω/□). If a voltage of 1750 to 2000 V is applied between this electrode and the photoconductor substrate, the X-ray exposure causes the charge to be transferred to the foil, thus producing the image. For the present no quantitative model has as yet been devised for the physical processes that occur, but the pre-ionization of the gas (usually air at normal pressure) by secondary radiation from the...
lead oxide could be an important factor. Under the conditions described here an effective conversion energy with a reproducible value of about 20 eV has been measured.

Resolution

Like the ionography system, the PbO system is also subject to unavoidable sources of noise that have an adverse effect on picture quality. One of the reasons for the noise is the fact that on average there are 5 to 6 crystallite layers one above the other in the binder layer. As a result of the exponential attenuation of the radiation penetrating the binder these layers make very different contributions to the formation of the charge pattern. Other reasons are that the crystallites are not uniformly distributed in the binder layer. The exponential attenuation of the radiation produces a smeared out charge pattern that originates from the different layers. Additionally, the inherent noise of the ionization process and the noise due to the electronic equipment have a considerable effect. The noise in the lead-oxide system is the factor that makes the detective quantum efficiency much lower than the quantum absorption shown in fig. 1. The picture in fig. 13 is a radiograph of a lead-foil ‘Funk-Raster’ obtained using a lead-oxide system with a dose of 20 mR. The limit of resolution of detail is equivalent to a resolution of 10 line pairs per mm.

The development of grey levels

Principle

The last stage in the production of the electroradiograph is making the latent charge pattern that has been produced on the foil visible by electrophotographic development. The method of development has a marked effect on the total sensitivity of the electroradiographic system and on the image quality. To clarify the concept of ‘total sensitivity of the system’ it should be noted that, in addition to the ‘sensivity’ that has been discussed in the previous section and is expressed in coulombs/milliröntgen, a ‘development sensitivity’ also has to be taken into account: this refers to the deposition of pigments per coulomb.

Besides the well-known developing method that uses a cloud of powder, there is also another electrophotographic developing procedure, ‘liquid development’, which we have investigated. In an apparatus such as the one shown in fig. 14 the charge pattern on the foil F is brought into contact with the suspension S of electrically charged particles of pigment in an insulating liquid. The liquid also contains ions, together with additives that have a complicated composition for regulating the charge of the pigment particles and maintaining stability. During the development process the charged particles move along the lines of force of the electric field, which originates from the charge pattern, and settle on the insulating foil. The electrode M, the ‘developer electrode’, which is a short distance from the charge pattern in
the picture of fig. 14, and parallel to it, is constructed in the form of a sieve. This ensures that the greatest possible number of the lines of force leaving the charge pattern extend perpendicularly into the space occupied by the developer liquid, so that the field-strength there is at a maximum. The result is that the pigment is precipitated rapidly and over a wide area. In this way the image formed on the image carrier displays grey levels like those obtained in a conventional X-ray film photograph. Finally, the image has to be fixed; this can be done with a thin layer of lacquer.

**Nature of the image**

The use of the term ‘picture processing’ in the introduction has already given some indication that it is possible to change the nature of the image. A certain period of time is necessary for neutralizing the charge pattern and this time increases as the mobility and the concentration of the pigment particles and the ions in the developer liquid decrease. If development is stopped before the charge pattern has been completely neutralized, an image is obtained of the non-homogeneous fields present in the developing space as a result of the original charge distribution, because the charged particles mainly tend to follow closely spaced lines of force near transitions between adjacent image fragments. This favours the high spatial image frequencies, or in other words it is primarily contours that are enhanced. These are shown as a double line with a high and a low pigment concentration. This ‘edge effect’, which is not present in the latent image, is purely the result of the developing procedure. This case is called nonlinear development [15].

If we wait until the development is completed, in other words until the charge pattern has been completely neutralized, then the quantity of pigment that has been precipitated, and hence the total optical density of the image, is approximately proportional to the original local surface-charge density. This is called linear development. If moreover the surface charge is proportional to the X-ray exposure, then the entire radiographic system is linear: the nature of the image is the same as that obtained from the familiar silver film. In practice, however, the methods have to be based on a quasi-linear system and development is stopped before the charge pattern has been neutralized.

There are also other methods in which the nature of the image can be influenced in a very simple manner. It is possible to restore the contrast that has been lost owing to scattered radiation. Fig. 14 shows that a bias voltage can be applied between the carrier $T$ and the developer electrode $M$ during the development. Let us assume that a radiograph is being made of a simple object $O$ as illustrated in fig. 15. Some of the radiation detected behind detail $B$ originates from the scattered radiation from region $A$ — a recurrent problem in radiography. In terms of intensity, the scattered radiation can assume values that are comparable with those of the primary radiation transmitted. The application of a bias voltage $V$ during the development reduces the effective surface potential $V_{\text{eff}}$ by the same amount for all picture elements (pixels). Fig. 15 illustrates the variation of the surface potential with

![Diagram](image)

**Fig. 15.** Suppression of scattered radiation. When a radiograph is being made of object $O$, some of the radiation detected behind detail $B$ originates from region $A$ where this radiation has been scattered. The application of a bias voltage $V$ to the developer electrode $M$ in fig. 14 reduces the effective surface potential $V_{\text{eff}}$ of the charge pattern by the same amount for all pixels (dashed line). This compensates for the contribution to $V_{\text{eff}}$ caused by scattered radiation.

**Limits to the sensitivity of development**

The question now arises as to what is the development sensitivity that can be obtained. For a given charge density of the latent image it will be possible to obtain a higher optical density or blackening for a lower charge-to-mass ratio $q/m$ of the separate particles of pigment. The charge $q$ cannot however be made arbitrarily small — it cannot be smaller than the
electronic charge and the mass \( m \) may not be arbitrarily large because the precipitate would then have too coarse a grain.

A detailed analysis \cite{16} shows that there is yet another stipulation in practice: development must not take longer than 30 to 60 s. This gives an optimum for the charge of the pigment particles; if \( q \) is too small, then too small a fraction of the image charges is neutralized within a given development time.

A further limit to the sensitivity occurs if the electrical force acting on the pigment becomes comparable with the forces produced by gravitation and the convection of the liquid. In practice this means that the development equipment also has to be optimized.

It is necessary to keep to a minimum the concentration of the ions in the developer liquid that have the same polarity as the pigment particles and compete with these particles in neutralizing the charge pattern. The required life and stability of the pigment suspension is a practical limitation to this \cite{17}.

Fig. 5b has shown us that, depending on the quality of the radiation, the surface-charge density of the charge pattern is normally \( 0.5-2.5 \times 10^{-9} \text{C cm}^{-2} \text{mR}^{-1} \).

To obtain an optical density of 2, a charge density of about \( 2 \times 10^{-9} \text{C cm}^{-2} \) is required for very sensitive development of grey levels. The required radiation dose for the foil (not to be confused with the much higher dose required for the object) for a high-pressure gas-ionography system of the type described is therefore less than 4 mR and greater than 0.8 mR. These values are comparable to film-foil systems with an average-to-high sensitivity.

**Final comments**

It has already been pointed out in the introduction that all electroradiographic systems have the common advantage that they do not use silver. Now that the principles of electroradiography in general and the ionography system in particular have been discussed in somewhat more detail, an attempt will be made to enumerate some of the other advantages and disadvantages of the electroradiographic method compared with methods employing silver film.

All electroradiographic methods now in existence have the disadvantage that they are insufficiently universal. It is not possible, for example, to make several exposures per second as it is with a film cassette changer. Tomography is difficult because of the following factors. The ionographic system is complicated by the thickness (1 cm) and the curved shape of the photoconductor. An acceptable lateral resolution can only be obtained when the electric lines of force between the electrodes in the chamber are directed towards the focus of the X-ray tube. Very complicated technical constructions would have to be made if ionography were to be used for conventional tomography \cite{18}.

On the other hand, subtraction techniques are easier to apply than with film because the direction of movement of the charge carriers can be reversed. In pictures of blood vessels made with and without contrast medium only the differences between the two pictures are made visible, because the charge pattern that has been formed during the first exposure is partially or completely destroyed during the second. When the development has been completed, only the structures are visible in each image that have allowed radiation to pass through to varying degrees during the exposure.

Another special radiological method is mammography, but this has become the subject of debate in the last few years because of the risk of damage from the radiation. The requirements for picture quality are extremely high. These requirements can be met by (conventional) film mammography, because for film exposures the intensifying screen, which reduces the required radiation dose, is omitted and very soft (low-energy) radiation is used; this is largely absorbed in the tissue. Attempts — and these have often been criticized — to use intensifying screens here mean that a compromise has to be made between reducing the radiation dose and reducing picture quality.

Xeroradiography is now being used for mammography, particularly in the United States. This can be done because selenium has a useful primary absorption at the low radiation energies to be used (see fig. 3, a maximum of about 80% effective absorption at about 26 keV). Nevertheless, the radiation dose is still very high because of the high conversion energy and the associated low sensitivity of the system. This cannot be compensated for by the particular electro-photographic method used for development.

Gas ionography is also being tried out for mammography. A phantom model has been used to determine the dose incident on the radiation-sensitive parenchyma for three systems: xeromammography, film-foil combination and mammography by ionography. The doses for the three systems have

---


\cite{18} Offenlegungsschrift 2826127 (German Patent Office publication).

\cite{19} U.S. Patent 4,057,728.
been shown to be in the ratio of 4:2:1 \[^{[19]}\]. One of the
the ionography system is that the composition of the
developer liquid has to be closely controlled, as dis-
cussed in the previous section. Also, the focus of the
X-ray tube must be at a particular distance from the
gas chamber and focused on it accurately. This system
is not therefore compatible with existing X-ray mam-
mography units.

For the reasons given above, it is impossible to say
at this moment to what extent electroradiography will
take over from film-foil radiography. It should also
be remembered that a method that is analogous to
silver-film recording will not solve the troublesome
problems of storing large numbers of X-ray photo-
graphs. Future developments that come to mind here
include electronic recording methods, which offer the
advantages of automated information processing and
the transmission of X-ray photographs over large
distances (‘Computer Radiography’, CR).

\[^{[19]}\] E. P. Muntz, M. Welkowsky, E. Kaegi, L. Morsell, E. Wilkin-
son and G. Jacobson, Optimization of electrostatic imaging
systems for minimum patient dose or minimum exposure in
L. Stanton, T. Villafana, J. L. Day, D. A. Lightfoot and
R. E. Stanton, A study of mammographic exposure and detail
visibility using three systems: Xerox 125, Min-R, and Xonics

Summary. Economy in use of silver and new methods of develop-
ment motivated studies to find out whether electroradiographic
systems are suitable for use in medical X-ray diagnosis. Two elec-
troradiographic systems — the high-pressure ionography system
and the lead-oxide/gas-layer system — are discussed in detail, with
a description of the formation of the latent charge pattern. At the
Philips research laboratories in Aachen a special investigation of
the sensitivity and resolution of the two systems has been made. In
the section on the development procedure (making the latent charge
pattern visible) consideration is also given to the possibility of
‘picture processing’ and the composition of the developer. Finally,
the advantages and disadvantages of electroradiographic methods
are compared with those of conventional radiography with silver
films.
Scientific publications

These publications are contributed by staff of laboratories and plants which form part of or cooperate with enterprises of the Philips group of companies, particularly by staff of the following research laboratories:

- Philips Research Laboratories, Eindhoven, The Netherlands
- Philips Research Laboratories, Redhill, Surrey, England
- Laboratoires d'Electronique et de Physique Appliquée, 3 avenue Descartes, 94450 Liméil-Brévannes, France
- Philips GmbH Forschungslaboratorium Aachen, Weißhausstraße, 51 Aachen, Germany
- Philips GmbH Forschungslaboratorium Hamburg, Vogt-Kölln-Straße 30, 2000 Hamburg 54, Germany
- Philips Research Laboratory Brussels, 2 avenue Van Becelaere, 1170 Brussels (Boitsfort), Belgium
- Philips Laboratories, N.A.P.C., 345 Scarborough Road, Briarcliff Manor, N.Y. 10510, U.S.A.


H. C. de Graaff: Review of models for bipolar transistors (pp. 283-306). E

H. C. de Graaff: High current density effects in the collector of bipolar transistors (pp. 419-442). E

H. C. de Graaff: Emitter effects in bipolar transistors (pp. 443-460). E

F. M. Klaassen: Survey of 1P modelling (pp. 519-537). E

F. M. Klaassen: Review of physical models for MOS transistors (pp. 541-571). E

F. M. Klaassen: Characterization and measurements of MOST devices (pp. 573-588). E

F. M. Klaassen: A MOST model for CAD with automated parameter determination (pp. 739-750). E

Volume 39, 1980, No. 1 pages 1-36 Published 30th July 1980