PHYSICAL LIMITATIONS OF VISION AND TELEVISION IN X-RAY FLUOROSCOPY

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PROF. DR. K. W. TACONIS

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. . . je reconnois estre beaucoup
redevable à ceux qui ont commencé
les premiers à dissiper l'obscurité
estrange où ces choses estoient
enveloppées . . .

CHRISTIAAN HUYGENS,
Traitée de la Lumière, 1690

The investigations described in this thesis were carried out in the Institute of Radiopathology and Radiation Protection, in the [illegible] Department of the University Hospital at Leiden. The author [illegible] his [illegible] in this department (Director: Prof. Dr. [illegible]) and all those who helped him. The work was done under the [illegible] of Dr. J. H. [illegible], Reader of Medical [illegible] Physics. He was [illegible] [illegible] the experiments. [illegible]

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CHAPTER I

INTRODUCTION

1.1 Image formation in x-ray fluoroscopy

All methods of x-ray fluoroscopy are based on the penetrating power of x-radiation and on the ability of the human vision to perceive light and shadow patterns. Both x-rays and light are electromagnetic waves of which the physical properties are widely different. In every fluoroscopic process, which is in fact a frequency conversion of the invisible x-radiation into light, we must distinguish four essential components: the x-ray source, the irradiated object, the fluoroscopic screen or system and the human eye acting as a detector. Observation in fluoroscopy is influenced by the properties of all these components; this is what makes fluoroscopy a complicated process.

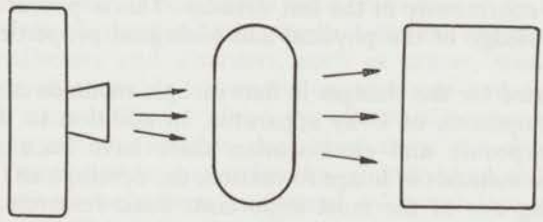


Fig. 1. Set-up for x-ray fluoroscopy.

The most important characteristic of x-radiation is its strong penetrating power. When parts of the object under observation have different x-ray attenuations, a pattern of local variations in x-ray intensity will be formed behind the irradiated object. The above mentioned x-ray intensity pattern must be converted into a pattern of local intensity variations of visual light. In the simplest fluoroscopic methods the frequency conversion is obtained by a single fluoroscopic screen, which consists of a layer of luminescent material in a suitable binder. The low efficiency of the frequency conversion process is the main limit of this simple fluoroscopic method. Roentgen himself used barium-platinocyanide as luminescent material; in later years other luminescent materials were used having a somewhat better stability and efficiency. Edison (51) was the first experimenter who succeeded in making more stable screens, undoubtedly applying the famous percentages mentioned by him. Many hundreds of experiments, with as many mixtures of various substances, resulted in a new type of luminescent screen, more stable and with a higher luminescence, in which the basic material was calcium tungstate. The fluoroscopic screens which are at present in use are the result of many years of technological research; their efficiency, however, is still very low. The low brightnesses obtained in the conventional fluoroscopy and the important loss of time for dark-adaptation were the main reasons for starting in later years the development of a series of brightness intensifying systems. The need for these higher brightness systems was stressed by Chamberlain in a famous lecture (35).

1.2 Applications of x-ray fluoroscopy and photography

It is a well known fact that the penetrating power of x-rays plays an important part in many non-destructive investigations both in the industrial and in the medical field. The mechanical constructions of bridges, ships, spacecraft and aircraft are frequently tested by means of x-radiation, while x-ray diffraction methods have proved valuable for the structure analysis of complicated inorganic and organic compounds (166). Finally, there are not many organs in the human body that cannot at least partially be examined with the aid of x-radiation. The fluoroscopic methods of investigation have changed enormously in the last decades. This is primarily due to the increased knowledge of the physical and biological properties of ionizing radiations.

A second cause for the changes in fluoroscopic methods can be found in technical developments of x-ray apparatus. In addition to the protection against over-exposure and electrocution there have been a number of advances in the methods of image formation, the development of the image-intensifier being one of the most important. Basic research work on frequency conversion was done in the thirties, under direction of Holst (115). The first image intensifiers for fluoroscopic purposes were described by Coltman (40) and Teves (207).

1.3 Vision in x-ray fluoroscopy

In all fluoroscopic methods the human eye is used as the final observing element. Both the sensitivity of the eye and its acuity depend on the spectral distribution and the intensity of the light. Each fluoroscopic system must therefore be considered in close relation to the properties of the eye, under the conditions involved in the system. The interpretation of an image consists mainly of a series of mental processes. In experimental psychology there is a difference between the concept of detection of a visual impression (e.g. the perception of a very weak light flash) and the observation of images. The latter is a process, based on the detection of many visual impressions at the same time or rapidly following each other and the handling of this information by the observer. That integral observation is more than a summation of visual impressions is due to the possibility of recognizing general patterns. The interpretation of fluoroscopic images in radiology is only possible when the observer has knowledge of the anatomical structures and their fluoroscopic image.

1.4 Television in x-ray fluoroscopy

In the last few years apparatus have been designed where a combination of an image intensifier and closed circuit television is used. It is now possible to separate the place where the image is formed and the place where it is observed. This is important for some industrial applications of radiology where the stray radiation is very intense. Another group of applications can be found in the medical field, where under certain circumstances a fluoroscopic image may be made available in moderately lit rooms. A definite advantage is the dose reduction for patients and personnel. The image transmission is also of importance where discussion between medical workers over a certain distance is necessary and for educational purposes.

1.5 Biological effects of x-radiation

Soon after the discovery of x-rays it was known that this radiation provokes certain biological effects. These effects were first revealed by the occurrence of erythema of the skin and radiation burns. Later the effectiveness of x-rays in producing diseases and disorders, such as cancer, was demonstrated after clinical irradiations and in radiation accidents and experiments. At present much more is known about the effects of acute exposure of the human body to a high radiation dose than about the effects of chronic exposure to low radiation doses. Studies of individual cells, tissues and complete organisms have been performed to reveal the mechanisms of radiation damage. The dissipation of radiant energy is only one step in this process. The energy is used in the direct interaction with the living structures and also in a number of radiochemical reactions producing substances which threaten the life of the cells. For many effects there is strong evidence that no threshold exists below which radiation produces no effect. The biological changes are sometimes irreversible and in many cases it is not easy to find a simple relationship between the irradiation and its effects.

1.6 Dangers of x-radiation

Working with x-radiation is in many respects not without danger (176). An adequate protection of radiological workers by defining maximum permissible doses is therefore always necessary, and in many countries it is required by law. (38, 140, 213). Biological and medical research have revealed correlations between irradiation and all kinds of diseases and disfunctions due to the somatic and genetic effect. (83, 113, 134, 138, 154, 177, 198, 203). Radiation hazards are sometimes divided into somatic, genetic and social-economic effects. (38). The biological effects of radiation vary considerably with the quality and quantity of the radiation used and the tissue irradiated. (10, 131, 132, 133).
Because of the biological effect all radiological work should be carried out

with the lowest possible radiation burden. A very great hazard of x-radiation is its effect on the gonads the result of which may be that hereditary changes are transmitted to future generations. It must be realized that in the more developed countries of the world, the lion's share of the human genetic dose is the contribution to the gonadal dose due to medical diagnosis (213). Accurate measurements of the gonad and bone marrow dose in practical situations are needed in order to estimate the risk involved in the application of ionizing radiation (11, 46, 50, 54, 64, 89, 141, 161, 201, 211, 221, 226, 227 228). In radiodiagnosis the body inevitably receives a certain radiation burden, which can sometimes be diminished by improving both fluoroscopic procedures and apparatus.

1.7 Image quality and radiation dose

As far as fluoroscopic image formation is concerned an optimum must be achieved between the image quality obtainable and the radiation dose needed. These two factors form the subject of this study. The correlation of image characteristics and radiation dose have been examined here, as much as possible, on a numerical base. Some concepts and methods derived from optics, electronics and communication theory are used. Although physical and technical factors are important in this relation, they do not completely form the natural limits of x-ray fluoroscopy, as the nature of the human eye also imposes limitations. The second chapter of this study is devoted to the theoretical backgrounds of x-ray fluoroscopy. A survey is given of the essential properties of x-radiation and the basic concepts of radiation dosimetry. Attention is also paid to the general methods of image quality assessment and the properties of human vision. Various fluoroscopic methods and systems are discussed in chapter III.
In chapter IV the results are given of a large number of measurements of the luminous output and the image quality. A comparison is made between the older fluoroscopic methods with screens and the modern ones based on image-intensification, television and magnetic recording. In addition to the methods based on the determination of the modulation transfer function, subjective perception tests have been used. The results of these tests are shown in chapter V. Measurements of the radiation dose and the incident radiation are discussed in chapter VI. Chapter VII gives a survey of the results obtained and concludes with some recommendations.

CHAPTER II

THEORETICAL ASPECTS OF X-RAY FLUOROSCOPY

2.1 Introduction

In this chapter the main properties of x-radiation, the concept of radiation dose and image formation are outlined. The human eye has variable properties which have to be taken into account in the evaluation of the various fluoroscopic methods. Some properties of human vision are therefore considered. Various methods of image quality assessment are discussed; it becomes clear that certain concepts of communication theory and optics can be successfully applied to x-ray fluoroscopy. The determination of the modulation transfer function, which is a usual method for the quality assessment of optical systems, may be extended to the field of x-ray fluoroscopy. The use of modulation transfer functions leads to an elegant study of the relationship between contrast and detail in an image. It is shown that an easy transposition is possible to the bandwidth criteria used in video techniques. At the end of this chapter attention is paid to the choice of certain technical parameters in television systems in relation to the resolution.

2.2 Physical properties of x-radiation

X-radiation is generated in practice by bombarding metals with fast electrons. In modern x-ray tubes an electron beam, formed by thermal emission in a cathode, is accelerated towards the anode under the influence of a strong electric field between the cathode and the anode. The electrons are abruptly stopped at the anode. In the interaction with the atoms of the anode their kinetic energy is converted into x-radiation and heat. Normally only a small part of the energy is transformed into x-radiation. The efficiency of this process, as well as the angular distribution of the generated x-ray energy, depends on the energy of the bombarding electrons (129). The large quantities of heat delivered at the anode make high demands on the material to be used (high melting point and good heat conduction) and on the cooling of the x-ray tube.

The x-ray spectrum is a combination of a continuous and a line spectrum; the former has a discrete minimum limiting wavelength. In practice the longest wavelengths generated will be absorbed by the vacuum tube's glass wall and envelope. The highest frequency generated can be easily calculated, when we assume the kinetic energy of the electrons to be completely converted into radiant energy. This can be expressed as:

$$eV = h\nu = h\frac{c}{\lambda} \qquad (1)$$

where: e is the electric charge of an electron, V is the potential difference between anode and cathode, h is Planck's constant, c is the velocity of light, ν is the frequency, λ is the wavelength of the radiation.

It is assumed here that the electron loses all its kinetic energy in a single head-on collision with an atom of the anode. There will however also be electrons losing their energies in a series of succesive collisions, which correspond to the generation of lower energy quanta. Theoretically we can imagine the continuous x-ray spectrum extending to infinity from a definite limiting wavelength determined by formula 1. The relation between the maximum photon energy and the kinetic energy of the electrons, which leads immediately to the calculation of the limiting frequency, was first given by Duane and Hunt as:

$$(h\nu)_{max} = T \tag{2}$$

where h is Planck's constant, ν is frequency, T is kinetic energy of the electron. Substituting the appropriate values we find for the limiting wavelength (in A°) in relation to the tube voltage (kV):

$$\lambda_{min} = \frac{12.4}{kV} \tag{3}$$

Besides the continuous x-ray spectrum there are a number of lines having discrete energies. These lines result from dislocations of electrons from the atoms of the anode material. When such an electron is dislodged it leaves a vacancy in one of the atomic shells. This vacancy is immediately afterwards filled with an electron from another shell or from outside the atom. Since the differences in energy levels are known for the various elements, the anode material determines the line spectrum. The photon energies of the characteristic lines due to removal of the K-electrons will be highest; characteristic x-ray quanta resulting from transitions to vacancies in the L-, M-, or N-shells, respectively, are less energetic.

When radiation passes through matter a great number of processes occur, which can be best demonstrated by the phenomena of absorption of the direct x-ray beam and scatter inside and outside the absorbing medium.

The attenuation coefficient consists of four components, caused by the following effects; the formation of photoelectrons, Rayleigh scattering, the Compton effect and electron-positron pair formation. The latter occurs only for photon energies which are higher than 1.022 MeV and it is therefore not important here because the energies used seldom exceed 100 keV in medical fluoroscopy and 200 keV in industrial fluoroscopy. The scatter coefficient is due to Compton and Rayleigh scattering processes. The number dN of monoenergetic x-ray photons disappearing from the original beam due to a thin layer dx is proportional to the number of incident x-ray photons N_o so that:

$$dN = -\mu N_o dx$$

After integration this gives the relation between the number of incident x-ray photons N_o and the number of photon N_d emerging from a thin absorbing layer with thickness d.

$$N_d = N_o \, e^{-\mu d} \tag{4}$$

The linear attenuation coefficient μ is the sum of three coefficients due to respectively the photoelectric effect, the radiation scatter and pair formation. The value of the attenuation coefficient varies widely with the frequency.

2.3 Measurements of x-radiation

X-radiation is measured indirectly by its physical and chemical effects, e.g. the ionization of air, calorimetric and photographic effects, scintillations in crystals etc. Dosimetric measurements are normally based on the ionization of air; the quantity of radiation exposure is based on this effect. After a long and varied history (143) the quantity is now defined as the quotient of the sum of the electrical charges of one sign produced in air (when all electrons liberated by photons in a volume element of air are completely stopped in air) and the mass of that volume element. In physical terms this means that one roentgen is equivalent to the liberation of a charge of 2.58×10^{-4} coulombs per kilogram of air. Corrections must be made for measurements at other temperatures and pressures or sometimes for the water vapour pressure. Although accurate measurements of the exposure require many precautions in the form of standard chambers, to fulfill the conditions set in the definition of the unit, there exist good secondary dosemeters to measure, under practical circumstances, the radiation dose or the dose-rate. An important requirement is that the walls of the ionization chamber are made out of an air equivalent material. This prevents a spoiling of the measurement by a number of disturbing effects on the walls, e.g. extra ionization due to the generation of photoelectrons and recoil electrons.

The measurement of the ionization in air is not only important in the quantitative determination of the radiation dose; it plays also a part in the qualitative assessment of the radiation. The spectral analysis of x-radiation by means of scintillation or diffraction techniques is rather cumbersome and not of great value for the practice of dosimetry. The quality of a radiation is normally quoted as the thickness of a layer of a certain substance (often aluminium or copper) which is necessary to reduce by its attenuation the original x-ray exposure rate to half its value. The so-called half value layer (h.v.l.) is a measure of the penetrating power of the x-radiation; it varies with the voltage and its wave form.

2.3.1 Absorbed dose and incident energy

There is a tendency to determine the integral absorbed dose in the irradiated body (56, 111, 152, 163). Biological effects can be expected only from the absorbed radiant energy. For the determination of the integral absorbed dose the body is considered to be subdivided into a large number of small elements of volume dV and density ρ, the absorbed dose in the centre of particular element being D. The integral absorbed dose Σ is defined as:

$$\sum = \int_v D\rho dV \qquad (5)$$

This quantity is normally expressed in gramrads or kilogramrads (1 kilogramrad being equal to 0.01 Joule). Mayneord was the first to give a method for the calculation of what was then called the integral dose of an irradiated water volume. Assuming a dose distribution in flat parallel planes and an attenuation of the beam according to formula 4, we obtain for $\rho=1$:

$$\sum = 1.44\ AD_o\, d\left\{1+2.88\,\frac{d}{f}\right\} \qquad (6)$$

Where A is the field size, D_o is the exposure at the centre of the incident beam surface, backscatter included, d is the depth of the irradiated volume where the dose has decreased to half the surface dose and f is the source surface distance.

In clinical fluoroscopy there is a continuously varying beam size during the examination which makes it difficult to apply formula 6. Several methods of evaluating the integral dose have been recently developed (172, 184, 185, 229). By placing a flat ionization chamber in the radiation beam, perpendicular to the beam's axis, it is possible to measure the surface integral of the exposure. This is done by means of electronic integration of the discharging current of the ionization chamber. The surface integral of the exposure is generally expressed in $R \times cm^2$. To obtain the incident energy, this surface integral is to be multiplied by a factor which depends on the radiation quality. (4, 18, 172, 184). Not all radiant energy is absorbed however and much experimental work was therefore done to determine the ratio of the incident and the absorbed energy. This was done theoretically by application of Mayneord's formula and experimentally by measurements in phantoms (33, 142, 144). It turned out that it is generally not justified to assume that the total amount of incident energy is actually absorbed by the body. The absorption depends on various factors, e.g. the spectral distribution of the incident radiation, the field size and the dimensions of the irradiated object.

2.4 The formation and observation of fluoroscopic images

An object penetrated by x-rays can be visualized due to conversion of x-radiation into light. The visual pattern formed is due to the effect of luminescence in the fluoroscopic screen.

The light emission of a screen is related to the number of x-ray photons absorbed by it. A high absorption might be expected with low energy photons and thick screens, which is not easy to harmonize with the other requirements of high penetrating power and perception of detail.

Only a small part of the light finally reaches the observer's retina. It has been calculated that many thousands of x-ray photons incident on the body are needed for each light photon incident on the retina (9, 44, 162, 209, 210). The process of observation is based both on visual perception and on the observer's previous experience with the type of image in question.

Detection of an image is only possible when there is a certain difference in brightness between the image and its adjacent surroundings. The perceptible contrast threshold varies enormously and the contrast necessary in the twilight perception may be ten times greater than that in daylight. The brightness levels in x-ray fluoroscopy extend over an enormous range, from approx. 0.001 to 0.1 $cd.m^{-2}$ in conventional fluoroscopy to approx. 0.5 to 50 $cd.m^{-2}$ in modern fluoroscopy. This means that the observer's eye is used under completely different conditions in the two procedures. The eye can adapt itself to a wide range of brightness levels (about ten decades). The light flux admitted into the eye is primarily controlled by variations in the pupil diameter. The large variations in visual sensitivity must however be explained by different factors in the retina (22, 60, 77, 169, 173, 200). The retina contains two kinds of visual receptors, known as rods and cones. The cones, which are concerned with the accurate perception at high brightness levels, are mainly found concentrated in a relatively small area near the axis of the eye lens. The rods are important in twilight perception; they are much more sensitive than the cones (of the order of 10000 times more).They are situated in the peripheral parts of the retina. There are peripheral cones, but they are much less densely distributed than those in the fovea centralis. One central cone is connected to one fibre in the optic nerve by its own bipolar and ganglion cell, whilst hundreds of peripheral rods may be connected to only one ganglion cell. These two mechanisms of vision involve a remarkable difference in visual acuity, which is defined as the reciprocal of the angle subtending two objects which can be recognized separately. For daylight vision this angle is of the order of 1minute of arc, in the region of conventional fluoroscopy of the order of 10 minutes, which argues for brightness amplication. Apart from the low sensitivity and acuity the eye has a considerable time-lag at low brightness levels.

The number of light photons which contributes to perception varies with the eye's conditions, e.g. the pupil diameter, integration time, the fraction of incident photons and that eventually absorbed in the retina and the conversion in the retina of absorbed photons into nerve signals (16, 21, 22, 23, 24, 29, 39, 45, 93, 119, 121, 169). Much research has been done on the contrast threshold of the human eye and the perception under different circumstances (169, 170, 182, 214, 215, 217, 218, 219). On the basis of experiments it was possible to derive a simple numerical relationship between the brightness, B, the contrast between detail element and background, C, and the dimensions of the detail element, d. The contrast is in this case defined as the ratio of the brightness difference between detail and background and the brightness of the background.

Assume two neighbouring square detail elements with a length d, which are focused on the retina. The number of photons emitted by the two details per unit of area and per unit of time is equivalent to n_2 and n_1 respectively. Perception is possible if the difference in number of incident photons exceeds the square root of the photon flux k times, thus if

$$n_1d^2 - n_2d^2 = k\sqrt{n_1d^2}$$

$$(n_1 - n_2)d^2 = k\sqrt{n_1d^2} \qquad (7)$$

Squaring this form and rearranging the variables we get

$$n_1 \left(\frac{n_1 - n_2}{n_1} \right) d^2 = \text{a constant } K_1$$

When we realize that n_1 is equivalent to the brightness B and that $\frac{n_1 - n_2}{n_1}$ equals the contrast C, we can write:

$$BC^2d^2 = K_1 \tag{8}$$

At low exposure rates the fluctuations in the quantum flux are the limitation (204). With regard to x-ray fluoroscopy, an expression was derived from this formula relating the diameter, d, of an object, its contrast, C, and the number of x-ray quanta, n, absorbed by a screen during the integration time of the eye, t.

$$d = \frac{K_2}{C\sqrt{nt}} \tag{9}$$

2.5 The assessment of image quality

In addition to the experiments on the limits of human vision, many test methods have been devised for the determination of the image quality of radiodiagnostic systems, with or without considering the dose (30, 31, 32, 36, 57, 65, 127, 193, 222). The methods of determining quality can be divided into two groups; methods for the testing of the complete procedure (fluoroscopic system with object) and methods devised to test the fluoroscopic system and its components. The first group is of great importance for those using fluoroscopic systems, the second group is most appreciated by those who develop and design apparatus. It will be evident that both types of tests yield information concerning the essential properties of a certain fluoroscopic method.

In the first group of tests one tries to reproduce as accurately as possible the situation in x-ray fluoroscopy. Different phantoms, often made of tissue equivalent materials and containing bone structures, are used as a substitute of the patient's body during an examination. We have introduced a test method of this type in which special attention is paid to the elements of movement and unpredictibility.

In the second group of tests one tries to eliminate as much as possible the influence of the process of visual observation and to describe the system in physical terms. These methods of image quality assessment are closely related to similar methods used in optics and communication techniques. A modern fluoroscopic system may be regarded as a series of links in an information processing chain, e.g. image intensifier, lens systems, television circuit, video tape recorder, film camera etc. Knowledge of the information transfer in each link (or its composing elements, such as screens, pick-up tubes etc) can contribute to an optimal design of a complete system. In this case spatial distributions of light patterns are used instead of electric signals varying with time as they are used in electronics. (17, 26, 27, 28, 135, 194, 195, 196).

The metric information capacity (C_i) of an image is correlated with the rarity of its appearance and defined as:

$$C_i = \log_2 p^N = {}^N \log_2 p \text{ bits} \tag{10}$$

when the image plane is assumed to be divided into N elements, each of which may have one out of p possible luminance values. The information capacity is unity for an image consisting of only element, which has only two possible luminance values. The number of bits per square cm dealt with per second is rather low in fluoroscopy (of the order of 50000), in radiography it is much higher.

At each link in the information processing chain information is lost e.g. due to scatter in screens, bandwidth limitations, noise, and optical aberrations. This becomes clear when we compare the object or input pattern with the final image produced by the system. The quality assessment of the classical optical systems (such as microscopes and telescopes) was based on their power to produce separate images of neighbouring light spots. The concept of resolving power was later based on a practical criterium given by Lord Rayleigh which says, that two image spots can be separately observed until the maximum of the light distribution of one spot lies in the first dark Airy ring, in the light distribution of the second spot (1, 61, 206). Although resolving power has long been used for the quality assessment of optical instruments it is not satisfactory for the application to fluoroscopic systems, the function of which is normally to produce images of objects with relatively small contrasts. A much better method of quality assessment is the determination of the contrast response or modulation transfer function, which is now considered to be the best criterion for evaluating optical systems.

2.5.1. Transfer functions in image quality assessment

The optical transfer function gives the relation between the spectral distribution of the object and that of the image as a function of the spatial frequency of the light intensity distribution in the object plane.

The method is based on the optical transfer theory which states that in the case of a linear system the intensity distribution function in an image can be found from the convolution of the intensity distribution function of the object and the spread function (49). The spread function of an image forming system is defined as the intensity distribution obtained when an image is formed of an infinitely small spot or an infinitely narrow slit emitting light of unit intensity. This means that the Fourier transform of the intensity distribution function in an image can be found from the multiplication of the Fourier transform of the intensity distribution in the object and that of the spread function of the system. The Fourier transform is a complex function. When in a practical situation both amplitude and phase are considered the term optical transfer function is used. When only amplitude relationships are regarded, such as in this publication, the usual term is modulation transfer function (MTF).

In the quality assessment of optical systems sinusoidally varying light patterns are used, which are produced by means of special targets or Moiré-patterns. When the system is linear a sinusoidally light distribution is found in the image plane having the same spatial frequency but another amplitude and phase than the original. This method is analogous to the evaluation of electronic circuits by means of time-varying sinusoidal signals. The determination of transfer characteristics is in common use now for the description of optical and electronic systems and combinations of both (28, 104, 105, 107, 114, 156, 174, 180, 186, 187). When sinusoidally varying intensity patterns are used and the system is linear, it is even possible to derive the transfer function of a complete system from the multiplication of the transfer functions of the composing elements. It was examined how far this universal method can be applied to the image formation in radiology (3, 88, 112, 148, 149, 150, 155, 183, 189, 195, 202, 225). When sinusoidal x-ray intensity patterns are assumed it is possible to show the influence of the well known unsharpness factors due to focus size and movement blurring in the mathematical expression for the intensity distribution in the image. It is extremely difficult however to produce sinusoidal distributions of x-radiation, because monoenergetic radiation is never used and because of the great influence of stray radiation. In our measurements we have, therefore, made use of crenalite types of targets which yield an approximation to a square-wave spatial distribution of the intensity. The target consists of a thin metallic layer with groups of lines and spaces in regular patterns. The method is explained in fig. 2:

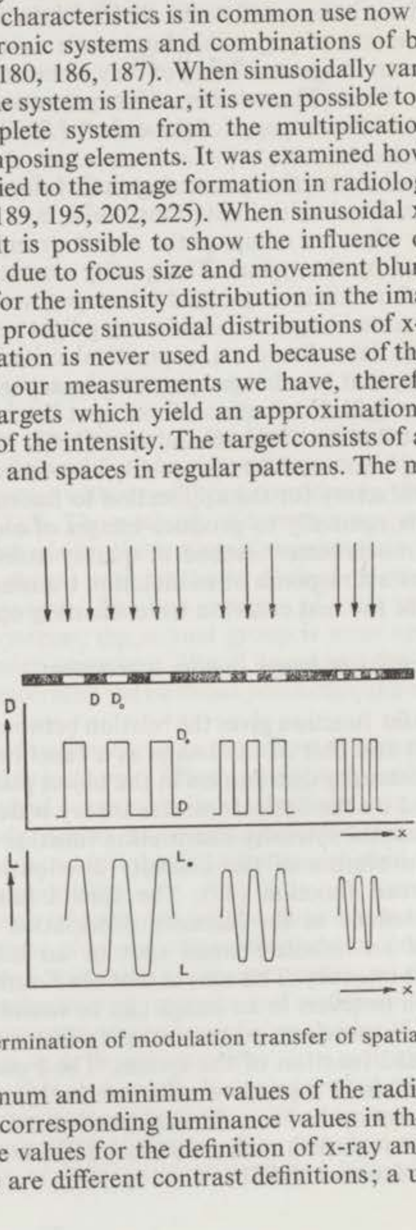


Fig. 2. Determination of modulation transfer of spatial frequencies.

When the maximum and minimum values of the radiation dose-rates are D_0 and D, and the corresponding luminance values in the final image L_0 and L, we can use these values for the definition of x-ray and light contrast and modulation. There are different contrast definitions; a usual definition is to define the contrast C as the brightness difference of the object and its background divided by the background brightness. For light objects on a dark background C varies from 0 to infinity, for dark objects on a light background C varies from 0 to 1. To avoid misunderstandings, it is preferable here to use the concept of modulation, M, which is the difference of two intensity values divided by the sum of these values. The range of M is from 0 to 1. The ratio of these modulation values which depends upon the space frequency, can be defined as the modulation transfer (MTF) for that particular spatial frequency. Modulation can be used for x-ray and light intensity patterns.

$$M_x = \frac{D_o - D}{D_o + D} \qquad M_L = \frac{L_o - L}{L_o + L} \qquad MTF = \frac{M_L}{M_x} \tag{11}$$

When the distribution of the radiant energy in the object plane O(x) and the spread function S(x) of a system are known, the energy distribution L(a) around a line in the image plane can, if certain mathematical and physical conditions are fulfilled, be calculated by convolution of the object and spread functions:

$$L(a) = \int_{-\infty}^{\infty} S(x)O(x-a)dx \tag{12}$$

We have carried out this integration for the simple case where the x-radiation passes through a slit of width w. The incident beam is assumed to be perpendicular to the object and image planes. We have calculated the energy in two lines in the image plane, one through the point P at the middle line of the slit, the other through Q, which lies at a distance w from the middle of the slit, thus at a distance $\frac{w}{2}$ parallel to the edge of the slit. It is assumed that:

$$O(x) = 1 \text{ for } \frac{w}{2} \geqslant x \geqslant -\frac{w}{2} \text{ and } O(x) = 0 \text{ for } x < -\frac{w}{2} \text{ and } x > \frac{w}{2}$$
$$S(x) = \frac{1}{2K} \exp\left(-\frac{|x|}{K}\right) \tag{13}$$

which is a generally accepted form for the spread function in fluorescent screens.

As a result of this calculation we find:

$$Lp = 1 - \exp\left(-\frac{w}{2K}\right), L_Q = \exp\left(-\frac{w}{2K}\right) - \exp\left(-\frac{3w}{2K}\right)$$
$$\text{and } MTF = \frac{1 - \frac{3}{2}\exp\left(-\frac{w}{2K}\right) + \frac{1}{2}\exp\left(-\frac{3w}{2K}\right)}{1 - \frac{1}{2}\exp\left(-\frac{w}{2K}\right) - \frac{1}{2}\exp\left(-\frac{3w}{2K}\right)} \tag{14}$$

There are a number of additional factors influencing the modulation transfer function e.g. the finite distance from focus to image plane (non-parallel beam), the focus size and often the movement of the object. The determination of modulation transfer functions of spatial frequencies (M_sTF) is a powerful method in the image quality assessment.
In many systems there is a certain time lag, which can be considered in an analogous manner, by determining the modulation transfer of temporal frequencies (M_tTF). In that case modulation is defined in the same way but the moments of maximum and minimum intensity occur at the same place but in succession.

2.6 Physical and technical factors in image formation.

Visual sensitivity and acuity are of utmost importance in fluoroscopic work; the conditions of observation can be much improved by the application of image intensifiers. A certain loss of contrast and definition is unavoidable in each apparatus, but this does not necessarily diminish the diagnostic value of the final image. A basic physical limit of fluoroscopic observation is set by the quantum fluctuations (162, 209). Formula 9 ,where this aspect of fluctuation theory is considered, can be used to estimate the liminal contrast and detail values.

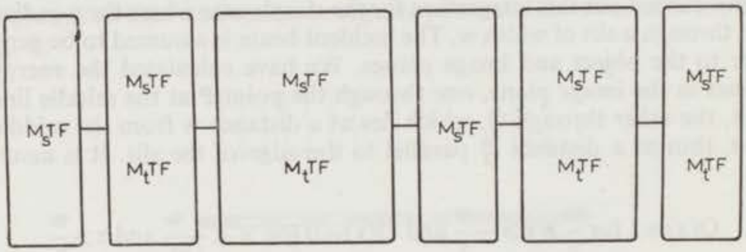


Fig. 3. Image deterioration in fluoroscopy.

A further step is the coupling of image intensifiers with closed circuit television systems, by which additional noise and loss of contrast are introduced. It is obvious that a television circuit introduces extra noise, mainly in the pick-up tube and in the first stages of the amplifier (40, 41, 42, 43, 58, 86, 120). As was shown by experiments there seems to be a good agreement between the subjective notion of sharpness in the television picture and the optical resolution (8). Deviations from the ideal detector, which are found back in the modulation transfer curves, are due to the technical components used in the construction of the system (e.g. scatter and grain size in screens, spherical aberrations of lenses and mirrors, characteristics of pick-up tubes and the electrical channel). The introduction of television involves the occurrence of flicker phenomena. It is necessary to work above the critical fusion frequency, which depends upon many factors. The main causes of image deterioration, apart from noise, are shown in fig. 3.

When television scanning mechanisms are used, the above mentioned concept of spatial frequence can be easily transformed into time frequency. When the television channel is assumed to extend from zero to a maximum video frequency f_v, the spatial frequency f_s can be found from the video frequency divided by the product of the line frequency f_l and the effective length of one scanning line l. The line frequency is the product of the frame frequency f_f and the number of scanning lines per frame N_l, so that

$$f_s = \frac{f_v}{f_l\, l} = \frac{f_v}{f_f N_l\, l} \tag{15}$$

This expression shows that a simple relation exists between the methods of quality assessment in optics and electronics. It must be remembered that due to the separate historical development of optics and electronics, there is a discrepancy between what is meant by the number of resolved lines in the two fields. In optics it is usual to count the number of dark (or light) lines of a grid target, whilst in video engineering both dark and white lines are counted.

In the television channel the frequency bandwidth is the most important limitation of the transmission; it is directly connected with the horizontal resolution. For a sharp reproduction of fine details a wide frequency band is necessary. When a small light spot on a dark background is scanned, this will result in a steep impulse of short duration at the input of the electrical channel (7, 145, 230). The frequency spectrum of this impulse can be found by means of the Fourier transform. This spectrum will be only partly transmitted because of the limited bandwidth of the channel. Assuming the duration of the impulse short enough that the assumption is justified that all frequencies in the bandwidth between zero and f_v have equal amplitudes A, the output signal V(t), can be calculated from:

$$V(t) = A \int_0^{f_v} \cos 2\pi ft \; df = \frac{A \sin 2\pi f_v t}{2\pi t} \tag{16}$$

This bandwidth limitation on time varying signals can be compared with the limitation in the spatial frequency spectrum in an optical medium; both phenomena can be treated mathematically in analogous ways.

The choice of technical parameters imposes certain restrictions on the television image. It is a common mistake to take the number of horizontal scanning lines equal to the vertical resolution R_v. The latter is diminished however by the loss of a number of lines during the image change (e.g. 5 per cent.) so that a vertical blanking factor (v.b.f.) of 0.95 is to be accepted. Another spoiling factor is introduced by the scanning line itself, the finite dimensions and light distribution of which lead to a certain loss of information in between two successive scanning lines. This loss is normally estimated to be 25 per cent, so that a scanning line factor (s.l.f.) of 0.75 is to be taken into account. The vertical resolution R_v is the product of the vertical blanking factor, the scanning line factor and the number of scanning lines per frame; thus with the assumptions made:

$$R_v = 0.95 \times 0.75 \times N_l \tag{17}$$

The horizontal resolution R_h is equal to twice the product of the maximum video frequency f_v and the time required for the display of a horizontal scanning line t_h. Without horizontal blanking this time would be equal to the reciprocal of the line frequency f_1. When we assume a horizontal blanking of 18 per cent, a correction factor 0.82, the horizontal blanking factor (h.b.f.), is to be added. This factor is placed in the numerator. With the assumptions made, we obtain.

$$R_h = 2f_v t_h = \frac{2 \times 0.82 \times f_v}{f_l} \tag{18}$$

We have calculated the values for R_v, R_h and f_l for two frame frequencies and five different values of line number. These data are collected in table I.

TABLE I

The limitations of picture resolution in television systems.

Number of lines N]	405	525	625	819	1025
$f_l(f_f=25c/sec)$	10125	13125	15625	20475	25625
$f_l(f_f=30c/sec)$	12150	15750	18750	24570	30750
R_v	289	374	445	584	730
$R_h(f_v=5Mc/sec; f_f=25c/sec)$	809	625	524	405	320
$R_h(f_v=5Mc/sec; f_f=30c/sec)$	675	521	437	334	267
f_v(in Mc/sec) for $R_v=R_h, f_f=25c/sec$	1.78	2.99	4.24	7.28	11.39
f_v(Mc/sec) for $R_v=R_h, f_f=30c/sec$	2.14	3.59	5.08	8.73	13.67

We have assumed a television picture of equal width and height, thus a picture ratio (p.a.r.) of 1: 1. which matches the round output screen of the image intensifier. An obvious requirement for a television image is that the horizontal and vertical resolutions are equal. We have calculated the video frequencies necessary to fulfill this requirement.

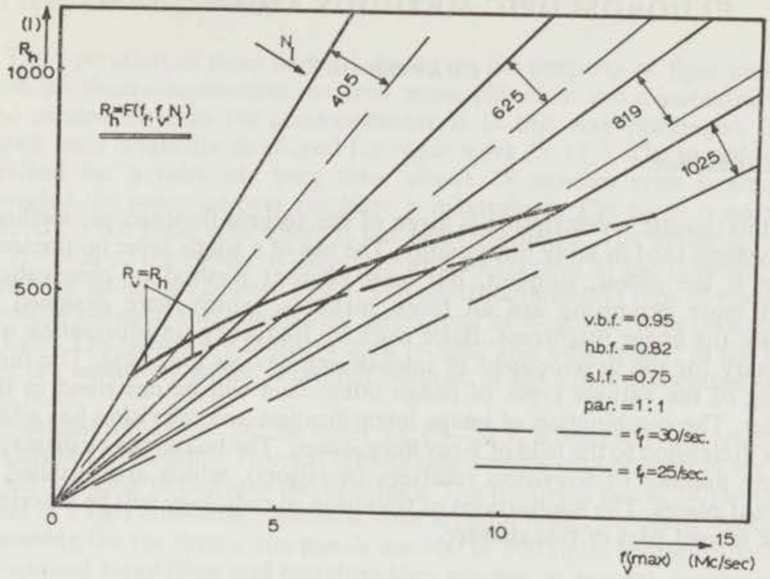


Fig. 4 Relations between resolution and bandwidth

Figure 4 shows the relationship between the horizontal resolution and the maximum video frequency for four values of N_l. It can be easily seen from this figure that the possible resolution increases with the video bandwidth. An increase in bandwidth means however an increase of noise in the television system, higher doses and more costy deflection units. It is pointless to use television circuits with much higher resolving power than the intensifying systems they are connected to.

FLUOROSCOPIC METHODS AND SYSTEMS

CHAPTER III

3.1 Introduction

In this chapter a description is given of the various fluoroscopic methods and systems used in x-ray fluoroscopy. The use of a single layer luminescent screen is the oldest, simplest, but least efficient method of observation. Much more promising are all those methods, which were designed to increase the image brightness. Basic work on frequency transformation was necessary for the development of intensifying devices (84, 115). The functioning of the various types of image intensifiers will be described in this chapter. The combination of image intensification and television has added a new dimension to the field of x-ray fluoroscopy. The image can be displayed on any number of television receivers (monitors), which are installed at different places. The applications of television in radiology will be described in the second part of this chapter.

3.2. The conventional fluoroscopic screen

In the early years, after the discovery of the x-radiation, barium platinumcyanide was used for the fluoroscopic screens. The main disadvantage of this material was its instability under the influence of the radiation. Although the conversion ratio was considerably good another disadvantage arose, as the screens emitted light with maximum energy at about 420 nm. This made the screens more attractive for photographic purposes, many films being blue-sensitive, than for direct observation with the dark adapted eye, which has its maximum sensitivity at about 510 nm. There was then a period of enormous technological research on luminescent screens; the best screens for fluoroscopy have their maximum responses in the yellowgreen parts of the light spectrum. Most screens are formed out of a mixture of zincsulfide (maximum light emission at about 470 nm) and zinc-cadmiumsulfide (maximum light emission at about 550 nm). The manufacture of fluoroscopic screens has become a special branch of technology with many developments (2, 67, 167). The light emission has also been studied extensively (126). The properties of the screen depend upon the characteristics of the basic materials and small amounts of heavier elements, such as iron or nickel which may change the characteristics (e.g. afterglow) enormously. Normally a dark-adaptation of at least 20 minutes is required before fluoroscopy. Screen exposure rates are normally between 10 and 100 mR/min, brightness is in the range between 0.3 and 0.003 asb. Between the screen and the observer a lead glass layer is placed, thus protecting the observer from the radiation passing through the screen. Both in the physical and in the physiological sense the single screen is a most inefficient fluoroscopic device.

3.3 *Image retaining panels*

The operation of these panels is based on the property of light emission from an electroluminescent material when placed in a d.c.-potential field. The excited state in the semiconductor is in this way prolonged. These panels were originally developed for radar work (5, 171). The image can be retained for a relatively long time, about 25 minutes after irradiation, provided the potential over the layer is maintained. The panel is normally viewed on the same side where it has been irradiated. The image is erased by removal of the potential difference and by reversal of the polarity, after which the panel can be used again. The electroluminescent type of phosphor is placed between two conducting layers, one of which must be transparent to light. The panels are sentitive both to light and x-radiation; in the latter case the sentitivity is not very high because of the small absorption in the thin layer.

A potential difference, of the order of 60-120 V is necessary to retain the image after irradiation. Normal intensifying screens may be used in the case of x-irradiation to increase the efficiency. The resolving power of the image panel is 2 to 3 lines/mm measured with a metal mesh test plate. Although promising for the future, the panels are 100 to 200 times less sensitive than the normal x-ray films and therefore they are not, at present, applicable in the field of medical radiology.

3.4 *Image intensifiers*

Image intensifiers are essentially converters of x-radiation or light of low intensity into light of high intensity. Four important types of brightness intensifiers are shown in fig. 5. They are discussed more in detail in the following sections.

3.4.1 *Electron optical image intensification*

The intensifying mechanism is based on the conversion of a low brightness image into a pattern of varying electron current density (Fig. 5A). The electrons are accelerated in an electric field and focused by means of an electron optical system on to a luminescent viewing screen. For industrial and medical purposes these amplifiers are in most frequent use. The x-rays are converted into light in a normal luminescent screen; this light then falls upon a photocathode. There are two different ways of realizing the optical coupling of the primary luminescent screen and the photocathode. The luminescent screen can be outside the vacuum tube containing the photocathode. The image is focused on the latter by means of a high aperture optical system, either a refractive one (a lens) or a reflecting one (a mirror system). Another way of bringing the light on to the photocathode is to mount the luminescent screen inside the vacuum tube and in close contact with the photocathode. This second method guarantees an efficient use of the light; on the other hand the x-ray flux, which has a much lower number

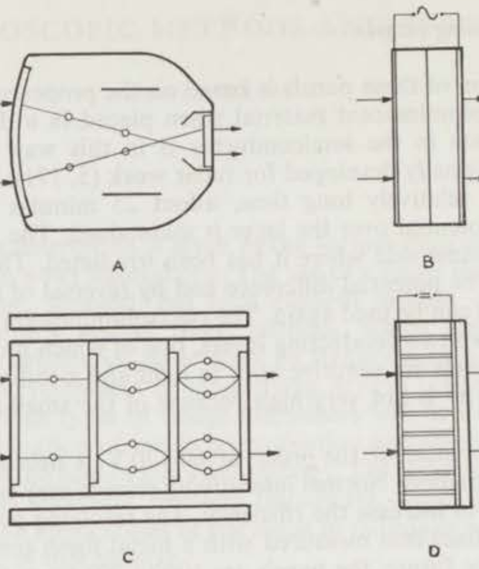


Fig. 5 Four types of image intensifier, *A*. Electronoptical image intensifier. *B*. Solid state image intensifier. *C*. Secondary emission image intensifier. *D*. Channelled image intensifier.

of incident photons than the light flux, has to pass through the wall of the vacuum tube. The maximum in the spectral response of the luminescent screen must be matched to the range where the photocathode has its maximum sensitivity. In this way a conversion ratio of 0.1 to 0.25 is obtainable; this means that on the average one photo-electron is liberated for every ten to four incident x-ray quanta.

In practice, the brightness intensification is obtained as a result of two causes; primarily the viewing screen is considerably smaller than the photocathode, and a certain amount of brightness enhancement is thus obtained by means of a geometrical reduction of the image surface. A second factor in the total gain is due to the acceleration of the photo-electrons in the electric field in the vacuum tube. The diameter of the first experimental intensifier tubes was 12 cm and the gain about 500 times. Newer developments brought image intensifiers having diameters between 15 and 33 cm. A discussion of the construction and the applications of the electron optical image intensifier and the limits of detail perceptibility as well as the properties of various types of frequency converters can be found in the literature (40, 84, 146, 159, 204, 207, 208, 212).

The thickness and graininess of the screen used in image intensifiers are important limiting factors for the image detail. With the present image intensifiers gains are possible up to about 10000 times compared with a good fluoroscopic screen. The contrast is diminished by an overall illumination of the secondary screen; this effect may be caused by different factors, such as the diffusion of x-radiation in the glass walls of the intensifier and the influence of spurious electrons, due to thermal and field emission, impinging upon the secondary screen.

Modern intensifiers have the possibility of electronoptical enlargement; in that case the central part of the input screen can be displayed on the output screen. There are also developments of cascaded types of intensifiers, which were constructed recently. The gain of these intensifiers, commonly used with infra-red and visible radiation, may amount to 10^5 times.

3.4.2 New developments in image intensification

Although electronoptical image intensifiers are in general use now, there are important and promising developments in image intensification: the solid state image intensifier and the secondary emission image intensifier. The solid state image intensifier is a relatively simple device. It consists of parallel semiconductor layers (Fig. 5B). One of these layers is a photoconductor, the resistance of which changes with the intensity of the incident radiation (e.g. x-rays or light). The second layer is electroluminescent and is electrically connected in series with the photoconductive layer. An alternating voltage is placed across the two layers in series. If radiation falls upon the photoconductor the lateral resistance diminishes and consequently a higher voltage is applied locally over the electroluminescent layer. The latter emits light. The intensity increases with the frequency and the amplitude of the voltage. In fact the photoconductor is the regulating element for the light emission from the electroluminescent layer. To prevent light feedback there is an opaque layer between the photoconducting and the electroluminescent layer. Various types of solid state image intensifiers have been described (47, 62, 68, 87). Normally cadmium sulphide is used as a photoconductor, whereas the electroluminescent layers consist of mixtures of zinc sulphide and selenide. (122, 123, 205). With the intensifiers described it was possible to obtain gains of about 400 times. In all solid state image intensifiers the main disadvantage up to now is the time-lag, caused by electron trapping in the photoconductor. Better results are expected from other materials such as cadmium telluride and certain ternary photoconductors such as cadmium-indium-sulphide; these are however less sensitive.

Other types of image intensifiers were developed recently. The underlying principle is that of secondary electron emission. Current gains of 10^9 times are possible by means of these intensifiers under favourable conditions (76). There are two types of constructions. In the first type the essential parts are a number of parallel placed dynodes, coated with a secondary emission material (Fig. 5C). The incoming light is converted by a photocathode into an electron current, which is multiplied in a succession of secondary emission processes. After the last stage the current impinges on a viewing phosphor.

Longitudal magnetic fields are used to keep the electron beams focused. Such an intensifier having a light gain of 10^5 times and combined with a 405 lines television system was described for medical purposes (34). In another construction a large number of small channels are formed, each of which is in principle a miniature photomultiplier (58). It will be clear that in the last case the resolving power of the intensifier is restricted mainly by the number and the dimensions of the composing chanelled miniature intensifiers. The focusing of the electron beams is not such a problem (Fig. 5D). Experimental intensifiers of this type look promising for radiological purposes (52, 53, 108, 197). Finally experimental constructions are to be mentioned in which an electronoptical and a secondary emission intensifier are cascaded (76). This combination seems to be specially suited for crystallography.

3.5 Television in x-ray fluoroscopy

The use of television has many advantages. The image can be observed at different places even outside the examination room and without the danger of scattered radiation; it can be used for demonstrations and the electric signal can be recorded. For medical examination use of a television system may also be advantageous because of the following reasons: dark adaptation is unnecessary; the radiation dose can normally be decreased; and the examination can be carried out in a moderately lit room. The radiological television has been introduced now in many modern hospitals (14, 15, 20, 48, 55, 63, 66, 69, 71, 73, 80, 81, 90, 97, 101, 102, 103, 117, 160, 167, 224). Instead of filming the image from an image intensifier it can now also be filmed from the monitor, thus using the brightness intensification and the regulation of brightness and contrast of the receivers (37, 72, 99, 100, 179, 180, 181).

In general the television camera receives the bright image from the viewing screen of an image intensifier. The devices are coupled by means of lens systems. Much can be expected from fiber optics. There exist also apparatus where the television pick-up tube is placed directly behind a fluoroscopic screen. Another possibility is to use an x-ray sensitive television pick-up tube; this has been done in industrial situations where the radiation dose delivered to the object was not important (116, 125). At the moment it is still rather difficult to make x-ray sensitive areas having a high sensitivity. Special x-ray sources with a moving focus have also been designed (78, 79, 146). As far as we know no installations used in practice are based on this idea, which can only be realized with many technological difficulties in the production of these special x-ray tubes and pine-hole collimators for the x-ray beam. Finally it is not expected that dose reductions may be obtained by flying spot x-ray sources.

A general diagram of a fluoroscopic television installation is shown in fig. 6. The final image of the intensifier can be directly photographed and filmed or picked up by a television camera. An optical image divider distributes the light from the viewing screen to the cameras. It will be clear that the contrast response of the final image is influenced by all links of the chain.
Although the quantum fluctuations in the x-ray beam and the properties of image intensifiers are important limiting factors, the characteristics of the television circuit also have their influence. The video bandwidth, which is normally between 5 and 8 Mc/s in professional systems, and the properties of the image pick-up tube are important in this respect.

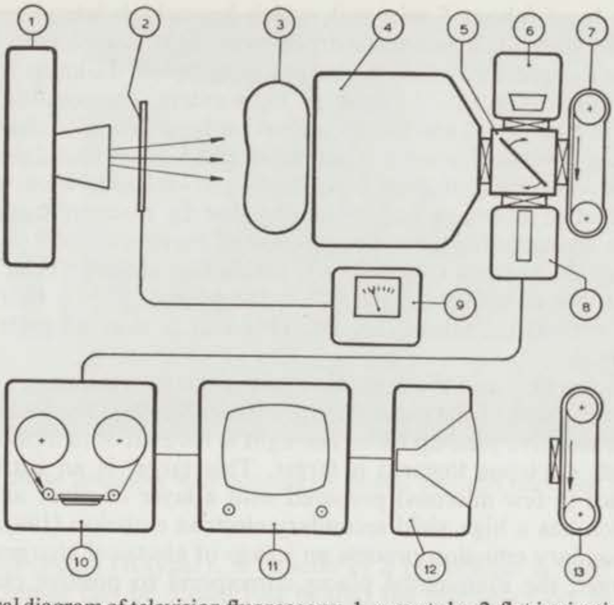


Fig. 6. General diagram of television fluoroscopy. 1. x-ray tube. 2. flat ionization chamber. 3. patient. 4 image intensfier. 5. image divider. 6. photographic camera. 7. film camera. 8. television camera. 9. measurement of incident radiation energy. 10. video recorder. 11. television monitor. 12. kinescope. 13. film camera.

3.5.1 Television pick-up tubes in fluoroscopy

Only a small group out of the many types of television pick-up tubes, come into consideration for use in fluoroscopy. Very fragile and bulky types of pick-up tubes can not be used. In the last few years two types of pick-up tubes have proved to be very useful for use in x-ray fluoroscopy: the vidicon and the image orthicon (98, 118, 120). Another type of tube, the c.p.s.-emitron was only seldom used in an experimental set-up (34, 74).
In all these tubes the two-dimensional optical image, which is changing with time, is converted into an electrical signal. The optical image influences the electrical properties of a sensitive layer, or target, which is an essential part of the pick-up tube. A thin electron beam scans the electrical image on the target point by point and line by line and is responsible for the coding into an electrical video signal. The spatial variations in brightness are thus converted into an electrical signal. In analogy to the existing definition of the gamma of the photographic process, a similar value can be defined for this conversion process (230). This gamma is defined as the slope of the plot of the video signal current against the logarithm of the photocathode illumination.

The first pick-up tube mentioned here is the vidicon type. The basic idea of this tube was suggested long before technology permitted its realization. Nowadays the tube is most frequently used in professional television (94, 98, 109, 136, 216, 223). The sensitive layer is an extremely thin photoconductive layer (about 5 microns), which has a high lateral resistance in complete darkness; this resistance drops when light is absorbed. In fact the layer forms a capacitor, which is charged in complete darkness by electrons from the scanning beam. As soon as light enters, the condition of good insulation is ended and the photoconductive layer loses its charge locally. The signal is generated when a scanning electron beam recharges the layer. In the first vidicons antimony trisulphide and - selenide were used in the photoconductive layer. A large time-lag due to electron trapping made these tubes unusable for x-ray fluoroscopy of moving objects (59, 95, 128). The lead oxide vidicon (plumbicon), which has recently been developed for the purpose of colour television has the advantage of a short restoring time after optical excitation (85, 86, 110) and is thus of great value for fluoroscopy.

The construction and the operation of the image orthicon are completely different from those of the vidicon (9, 69, 70, 90, 91, 92). The image orthicon is the most sensitive pick-up tube. The light is focused onto a photocathode, which emits electrons towards a target. This target is an extremely thin glass surface (a few microns) prepared with a layer of silver and calcium-oxide, which has a high yield secondary electron emission (199). By means of this secondary emission process an image of electrical charges is formed on the target, the illuminated places correspond to positive charges. The target is scanned by a beam of low velocity electrons (to avoid unwanted secondary emission). When the scanning beam passes positive spots there is a compensation of charges; at places where no secondary emission has occurred the scanning beam remains unchanged. The electron optical design of the tube is such that the scanning beam passes a number of multiplying stages before leaving the image orthicon. A serious disturbance of the image may occur in the form of halo-effects. The gamma of an image orthicon is 1, that of a vidicon between 0.6 and 0.9. An isocon, which was also used in some of our experiments, is a special type of image orthicon with an increased signal to noise ratio, developed for the use at low light levels.

3.5.2 Fluoroscopic television installations

The combination with television has enormously stimulated the use of image intensifiers. The first experimental set-up described made use of an image orthicon as a pick-up tube (147, 148). Many television systems have been developed by different industries. In our experiments we used Philips, Siemens and Old Delft installations. All systems tested use standard television channels having 625 lines per image, interlaced, and 25 images per second.

The Philips fluoroscopic systems used in our experiments had a 5-in, 9-in or a 9-5-in image intensifier (220). The intensification is obtained by the demagnification of the image dimensions from the input screen (15 or 23 cm respectively) to 2.3 cm at the output screen and by the acceleration of the electrons emitted by the photocathode. The intensifier anode screen and the sensitive layer of the television pick-up tube are coupled by a wide aperture

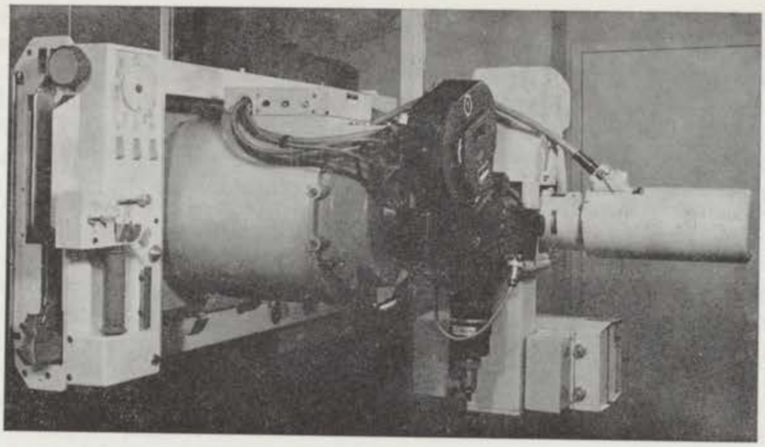


Fig. 8. Image intensifier with cameras for photo, cine and television pick-up.

tandem lens system (Rayxar). A vidicon or a plumbicon is used as pick-up tube. The image can be filmed just behind the intensifier on 70 or 35 mm film or on 16 mm film by means of a synchronous camera in front of a monitor (99, 100, 151, 168). The Siemens systems, which we were able to test, were a 7-in and a 10-6-in image intensifier respectively. Vidicons were used as television pick-up tubes and the optical coupling was by means of a Rodenstock system.

The Old Delft 12½-7-in systems, which we also used in our experiments, are known for their large field of observation (153). In these systems the fluoroscopic input screen and the light intensifier are separate. The intensifier has a round input screen, (diameter 8 cm) and a 1.6 cm output screen. Assuming a luminance gain of 100 to 140 times, we get a total gain of 2500 to 3500 times. The light emitted by the fluoroscopic input screen falls through a wide aperture (f/0.68) concentric system (25, 96, 137, 188). Spherical aberrations are corrected by a special meniscus lens. The optical coupling between the anode screen and the television pick-up tube (a 3-in image orthicon) consists of a Rayxar and a Deltamar lens. There are two types of installations: the Cinelix and the Delcalix. The Cinelix yields the possibility of directly filming from the anode screen with a specially developed 35 mm camera with a field of view of 270°. The Delcalix has almost the same lay-out. There is however no possibility for directly filming from the anode screen, but films can be made from a television monitor or a special kinescope.

3.5.3 Monitors and Memories

The television circuits used in x-ray fluoroscopy are standardized according to the CCIR recommendations. In our experiments we used professional

36 cm (Philips) and 43 cm (Fernseh and Siemens) monitors. The application of television made it also possible to store the visual information in semiconductor or magnetic layers. These methods have been used in radiology with success (79, 164, 165, 192). Magnetic recording is possible on a video tape (13, 75), on the surface of a drum (165, 191) or on a disk (82, 190). In our experiments we have made use of 1-in Magtronics, Old Delft and Philips recorders and $\frac{1}{2}$-in Sony and Shibaden video tape recorders.

CHAPTER IV

MEASUREMENTS OF IMAGE CHARACTERISTICS

4.1 Introduction

Three essential elements of an image, which can be measured physically, are brightness, contrast and size of detail. In this chapter an attempt is made to obtain an objective assessment of the brightness, which is directly related to the conversion of x-radiation into light, and the relationship between the contrast reproduction and the dimensions of the observed details, which relationship is studied here with the modulation transfer function of space frequencies. The physical measurements are chosen in such a way to suit as much as possible the physiological factors involved in fluoroscopic vision. The conversion function of fluoroscopic devices can be determined from exposure and luminance measurements which are described in the first part of this chapter. The relationship between contrast transfer and detail dimensions has been studied by determining the modulation transfer function of spatial frequencies (M_sTF). The time-lag is studied by means of the modulation transfer function of time-frequencies (M_tTF). A figure of merit for fluoroscopic systems is discussed.

4.2 Determination of the conversion factor

Measurements of the luminous output were carried out as recommended by the ICRU (157). The radiation used has to be filtered with 20 mm Al., which approximates a human abdomen. The standardized conversion factor is, however, only one point of the conversion function. This factor is to be measured so that the input exposurerate is 1 mR/sec and the h.v.l. of the incident radiation is 7 mm Al. It is to be noted here, that the radiant spectrum is not fully described by this simple indication of the first h.v.l. The focus screen distance has to be 70 cm. These conditions can be fulfilled with a Müller 1000 apparatus, six valves rectification and an 0-90 x-ray tube when the indicated tube voltage is about 75 kV. In our measurements the screen input exposure rates were determined by means of a Philips dosimeter (type 37470) and an E.I.L.-dosimeter (type 37A) with the appropriate ionization chambers. The radiation conversion is quoted in $cd.m^{-2}.mR^{-1}.sec$. To prevent the x-rays from impinging on the photocathode of the photomultiplier, a 1 cm thick lead glass was placed behind the screen. Corrections were made for the light absorption in the lead glass. The illuminated field on the screen was circular with a diameter of 12 cm. The photomultiplier was placed behind a circular window with a diameter of 2 cm. The distance between the leadglass and the photocathode was 18 cm. A metallic cone was used to prevent disturbances from erroneous light sources. The luminance levels were measured with a 50 AVP (Philips) photomultiplier which was matched to the characteristics of the human eye in daylight (photopic vision) by the addition of two glass filters (Schott 1 mm GG 20 and 2 mm GG 14).

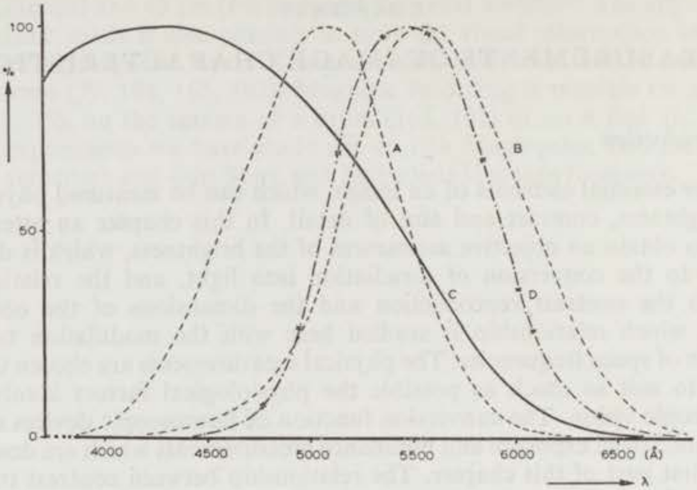


Fig. 8. Relative spectral sensitivities of the eye (CIE) and of the detector A. scotopic vision B. photopic vision C. photomultiplier D. photomultiplier with correction filters

The sensitivity of the detector has been determined photometrically (Fig. 8).

The photomultiplier was connected with a self built stabilised power supply unit. The output voltage of which could be regulated in steps of 100 V between 1200 and 1600V. (Fig. 9). Silicon rectifiers (Semikron SK 0.4/24 are used in a Graetz-circuit. The voltage is regulated by a Philips E130L in series. The reference voltage is derived from a group of ten neon tubes (83 A1) in series, which are placed in the cathode circuit of the amplifier tube (EF 80) of which the anode voltage variations are used as the control potential of the regulating tube (12). The fluctuations in the output voltage are within 0.1 per cent for mains fluctuations of 10 per cent. Long time drift is less than 0.01 per cent per hour. The current through the photomultiplier is measured with a galvanometer (Kipp A1 4). At room temperature the dark current is of the order of 0.5 μA; the light measurements were carried out so that the photomultiplier current was of the order of 100 μA. The current through the parallel resistors for the potential setting of the photomultiplier dynodes was derived from the same power supply and for reasons of stability this current was chosen to be about one hundred times the current through the photomultiplier.

The illumination of the photocathode of the photomultiplier can be regulated in steps by a set of grey filters (Schott NG3). There is a protection against overexposure of the photocathode (e.g. if the lights in the room are suddenly switched on) by means of a relay, which can react upon the photomultiplier current. The apparatus has been calibrated against a sub-standard, consisting of an incandescent lamp, which is mounted inside a closed black box. A green filter (Schott V.G.9) is placed in front of the window in the box. The substandard is regularly measured by a Schmidt and Haensch brightness meter (type 13714).

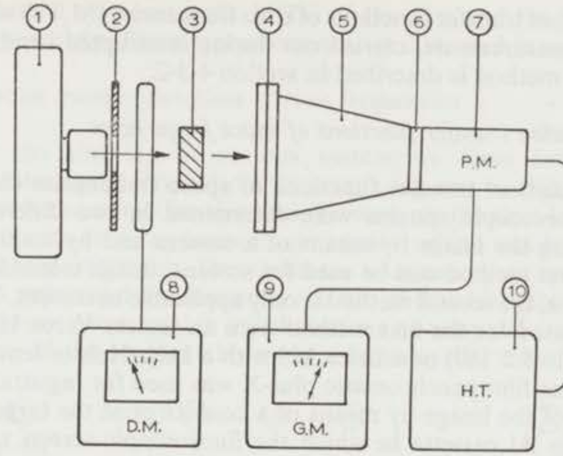


Fig. 9. Measurement of the conversion function.
1. x-ray source 2. diaphragm 3. extra filter 4. screen 5. black cone 6. light filters 7. photomultiplier 8. dosimeter 9. light measurement 10. high tension supply.

4.2.1 Measurements of the conversion factor

The measurements of luminous output of the different fluoroscopic systems were carried out as described in the preceding section. The results are shown in table II. We were also able to measure the luminous output of some image intensifiers. For two 9-in image intensifiers the conversion factors were 47 and 82 $cd.m^{-2}.mR^{-1}.sec$ respectively, and for a new type 5-in image intensifier this factor proved to be 65.

TABLE II

Conversion factors of fluoroscopic screens

Screen	Conversion factor ($cd.m^{-2}mR^{-1}$ sec)	Screen	Conversion factor ($cd.m^{-2}.mR^{-1}$. sec
Helia (Siemens)	192×10^{-4}	Kruppa 6D	146×10^{-4}
Kyokko	163×10^{-4}	Suprema (Streck)	133×10^{-4}
CAWO-62	153×10^{-4}	Lumofin (Goos)	161×10^{-4}
Dupont CB-2	127×10^{-4}	Levy West I	113×10^{-4}
Auer	156×10^{-4}	Levy West II	114×10^{-4}
Kruppa 9D	174×10^{-4}	Levy West III	56×10^{-4}

4.3 Determination of the modulation transfer functions

The modulation transfer functions of space frequencies (M_sTF) were all determined indirectly, by means of photographic registration of the image of a target. The M_sTF was calculated after measuring the blackening on the film and correcting for non-linearities in the photographic process. This is described in detail in section 4-3-1

The modulation transfer functions of time frequencies (M_tTF) were obtained from light measurements, carried out during interrupted irradiation of the systems; the method is described in section 4-3-2.

4.3.1 Modulation transfer functions of space frequencies

The modulation transfer functions of space frequencies (M_sTF) of the different fluoroscopic systems were determined in two different ways, by photographing the image by means of a camera and by making a contact print. The first method can be used for screens, image intensifiers and television systems, the second method is only applicable to screens. The cameras, which were used for the first method were an Exacta Varex II with a Telemegor lens (1 : 5.5/180) or a Leica M3 with a Leitz Hektor lens (1 : 2.5/125). Kodak 35 mm film panchromatic plus-X was used for registration. For the registration of the image by means of a contact print the target was placed on a 0.3 mm Al cassette in which the fluoroscopic screen was placed in direct contact with an industrial no-screen film.

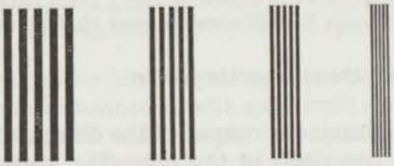


Fig. 10. Target for the measurement of the modulation transfer function of space frequencies.

The target was made on a 10 micron thick copper foil by an electrolytic process (manufactured by Veeko), the lead equivalent thickness of the target is 50 microns. The slits are arranged in groups of five. Together six groups with space frequencies of 1, 3, 5, 8, 12 and 20 line pairs per cm. The slits which have a height of 20 mm are open and separated by bars which have the same width. In fig. 10 part of the target is shown. For measuring the modulation transfer between 20 and 50 line pairs per cm which was done on x-ray films, a Schott target of the same thickness was used containing these high space frequencies. All measurements were done with the target directly on the screen or system and a focus-target distance of 70 cm.

The measurements of the film blackening were carried out on a microdensitometer (Kipp 224). Because of the gamma of the film and the nonlinearities in the photographic process, corrections were made, by determining the density of the film behind a reference block with six different known attenuating steps, which was recorded on the same film. These corrections were always made in the two photographic methods.

Finally the influences of the two methods were studied. The modulation transfer of the telelens was determined separately by photographing the target hanging in front of a frosted glass plate before a light source. It is not necessary to make corrections for the lens, the M_sTF of the lens, being much better than that of fluoroscopic devices. As far as the second photographic method is concerned the M_sTF of the film and the camera were determined separately. These measurements are discussed in section 4-3-3.

4.3.2 Modulation transfer functions of time frequencies

To study the time-lag of various system we have determined the reactions to interrupted irradiation. This time-lag can be disturbing when fast moving structures must be observed. To measure the time-lag the system was irradiated with an x-ray beam (3 cm square) which was interrupted by a 2 mm thick lead obturator. The obturator is driven by an electric motor. The radiation pulses and the time intervals are of equal length. The number of radiation pulses per second is called the time or temporal frequency. The time variation of the incident beam approximates the rectangular form.

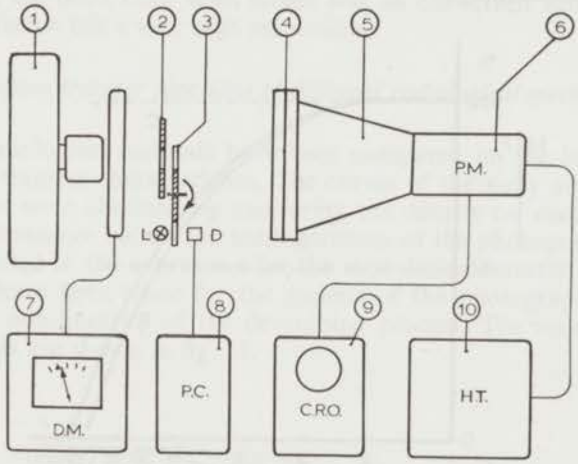


Fig. 11. Diagram for the measurement of the modulation transfer function of time frequencies.
1. x-ray source 2. lead diaphragm 3. chopper 4. luminescent screen and lead glass 5. black cone 6. photomultiplier 7. dosimeter 8. electronic pulse counter 9. cathode ray oscilloscope 10. high tension supply.

To obtain an accurate measurement of the time frequency the obturator was also used to interrupt a light beam, which was directed on to a photocathode connected to an electronic counter (v. d. Heem, type 9908). A diagram of this setup is shown in fig. 11. The modulation transfer function of time frequencies (M_tTF) was determined for various fluoroscopic devices; the results of these measurements are shown in the section 4-3-8.
The maximum and minimum values of the luminescence were measured on the screen of an oscilloscope (Tektronix type 502) which was connected to a resistance in series with the photomultiplier.

4.3.3 Comparison of the photographic methods of measurement

The modulation transfer functions of space frequencies (M_sTF) were in the case of the fluoroscopic screens, determined in two different ways, by photographing and by making a contact print of the image on the screen. These two methods are discussed in section 4-3-1. The target was placed directly on the fluoroscopic screen and corrections were made for the non-linearity of the photographic process. When making the contact print there is a slight influence of the x-radiation directly acting upon the photographic layer. We have determined the film blackening due to this direct action by making photographs with the same exposure times and using the fluoroscopic screen in the other direction, that is as a filter in the x-ray beam. The blackening due to this direct action of the x-radiation was about 4 per cent of the total blackening.

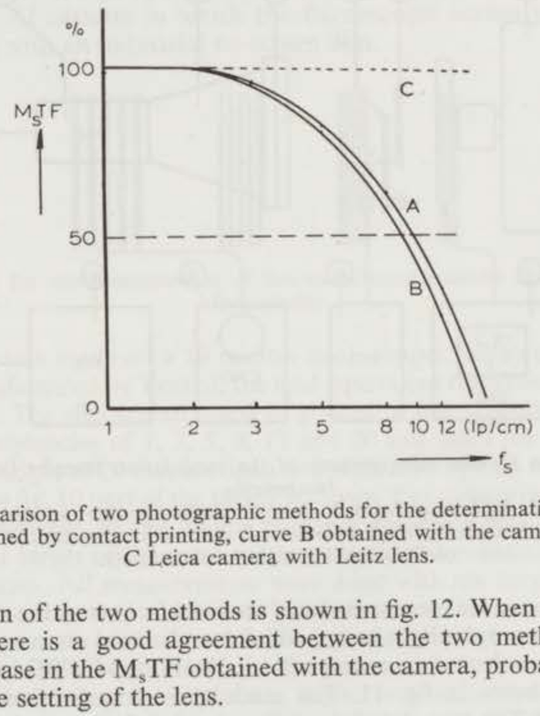


Fig. 12. Comparison of two photographic methods for the determination of the M_sTF. Curve A obtained by contact printing, curve B obtained with the camera, dotted curve C Leica camera with Leitz lens.

A comparison of the two methods is shown in fig. 12. When all corrections are made there is a good agreement between the two methods. There is a slight decrease in the M_sTF obtained with the camera, probably due to the MTF and the setting of the lens.

4.3.4 Modulation transfer functions of the fluoroscopic screens

The photographic methods were used to determine the M_sTF for different fluoroscopic screens. The modulation transfer was set 100 per cent by definition for a space frequency of 1 lp/cm. We have given in table III the space frequencies in lp/cm for which the M_sTF were reduced to respectively 70, 50, 30 and 10 per cent of the maximum value.

TABLE III

M_sTF of different fluoroscopic screens

% M_sTF	70	50	30	10	% M_sTF	70	50	30	10
Helia	5.2	7.1	9.8	16.2	Kruppa 6D	7.8	11.1	15.7	24.0
Kyokko	6.8	8.6	10.6	14.8	Suprema(Streck)	5.7	8.2	11.7	18.2
Cawo-62	7.4	10.3	14.4	23.6	Lumofin (Goos)	7.0	9.7	13.0	23.0
Dupont CB2	5.6	7.6	10.6	16.1	Levy West I	5.5	8.2	11.0	18.1
Auer	5.9	8.3	11.8	18.2	Levy West II	5.0	6.6	8.8	11.1
Kruppa 9D	6.4	8.7	11.9	18.2	Levy West III	8.9	12.0	16.2	24.5

These data show that there are only relatively small differences in the transfer functions for various screens. New screens have been used for these experiments. Only the third Levy West screen was an old screen with rather low conversion factor but a very high resolution.

4.3.5 Modulation transfer functions of different radiological methods

Different radiological methods have been compared on the basis of their modulation transfer characteristics. The curves of the x-ray and cinematographic films were obtained by measuring the density on each film itself; instead of luminance values the antilogarithms of the photographic density were substituted in the expression for the modulation transfer. In all cases corrections have been made for the gamma of the photographic material and for the non-linearity of the developing process. The results of these measurements are shown in fig. 13.

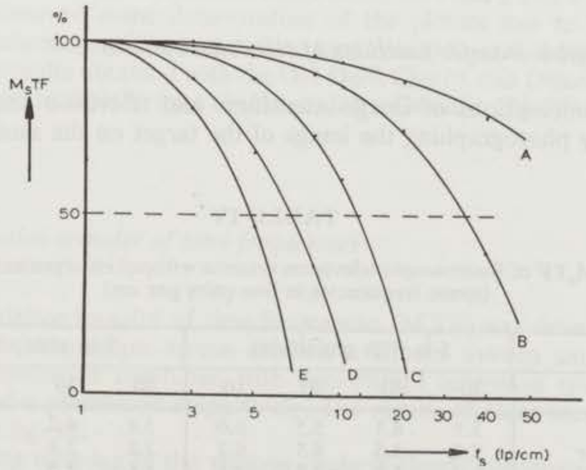


Fig. 13. M_sTF for different photographic methods.
A. no-screen film; *B*. x-ray film with intensifying screens; *C*. screen photography *D*. 35 mm cine film; *E*. 16 mm film taken from television monitor.

4.3.6 Modulation transfer functions of image intensifiers

To compare the modulation transfer functions of various image-intensifiers, we have photographed the image of the target on the anode screen of the following intensifiers: An old type Philips 5-in intensifier (A); a Siemens 7-in image intensifier (B), a Philips 9-in image-intensifier (C) and the combination of the mirror optics and electronic light intensifier of a 12½-in Delcalix system (D). The results of these measurements are given in fig. 14.

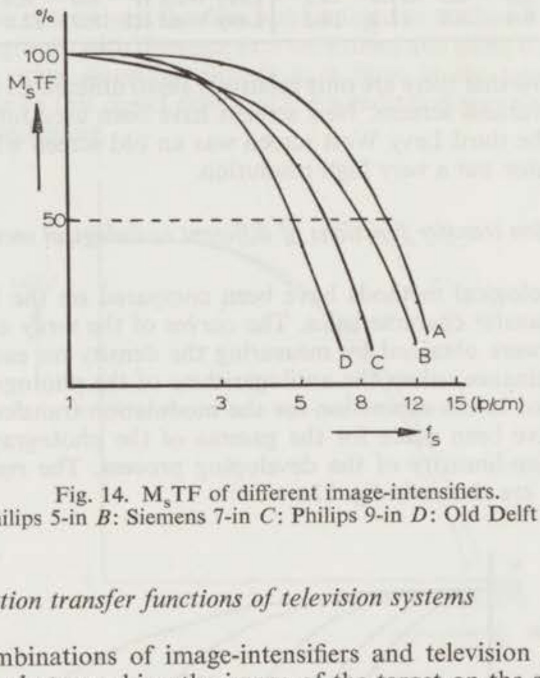


Fig. 14. M_sTF of different image-intensifiers.
A: Philips 5-in *B*: Siemens 7-in *C*: Philips 9-in *D*: Old Delft 12½-in.

4.3.7 Modulation transfer functions of television systems

Different combinations of image-intensifiers and television channels were examined by photographing the image of the target on the same television

TABLE IV

M_sTF of fluoroscopic television systems without enlargement
(space frequencies in line pairs per cm)

System	5-in with plumbicon				9-in with plumbicon			
% M_sTF	70	50	30	10	70	50	30	10
direct	3.5	4.3	5.5	8.0	3.4	4.2	5.0	6.0
ODX recorder	2.7	3.6	4.5	6.2	2.2	2.8	3.7	5.1
Sony recorder	1.9	2.3	2.7	3.1	1.6	1.9	2.4	4.0
Magtronics rec.	3.2	4.3	5.4	6.0	2.7	3.9	4.7	5.5
Shibaden rec.	2.0	2.8	3.8	5.2	3.8	4.1	4.9	5.7
Philips rec.	2.7	3.6	4.5	6.2	1.8	2.1	2.5	3.6

TABLE V

M_sTF of fluoroscopic television systems with enlargement (space frequencies in line pairs per cm)

System	12½-7-in with image orthicon				10-6-in with vidicon				9-5-in with plumbicon			
% M_sTF	70	50	30	10	70	50	30	10	70	50	30	10
normal	4.0	4.4	4.7	5.4	5.5	6.6	7.4	9.2	3.8	4.7	5.7	7.8
ODX recorder	2.2	2.7	3.8	4.6	3.1	4.1	5.2	6.3	2.9	3.7	4.8	5.0
Sony recorder	2.2	2.7	3.3	4.4	2.3	2.3	3.6	4.8	2.2	2.6	2.9	4.1
Magtronics rec.	2.2	2.6	3.2	4.7	4.5	4.8	5.6	6.3	2.7	3.2	4.0	4.8
Shibaden rec.	1.7	2.0	2.5	3.5	2.7	3.4	3.9	5.4	2.4	3.1	4.3	4.7
Philips rec.	1.8	2.2	2.7	3.6	2.5	3.4	4.5	5.5	1.9	2.4	3.6	4.5
enlarged	4.3	5.0	6.1	7.5	9.3	11.0	12.5	14.3	4.5	5.4	7.0	9.6
ODX recorder	2.7	4.0	5.6	7.0	4.5	5.5	7.5	9.3	2.9	4.0	5.8	8.2
Sony recorder	2.4	3.4	3.9	4.8	3.6	5.1	5.8	7.5	3.4	4.2	4.8	5.8
Magtronics rec.	3.3	4.4	5.4	6.0	5.3	6.7	8.1	9.3	4.0	5.1	6.5	8.5
Shibaden rec.	2.7	3.4	3.9	5.4	3.4	4.4	5.5	8.5	4.2	5.1	5.8	8.5
Philips rec.	2.1	3.0	4.2	5.8	3.9	4.6	7.0	9.0	3.0	4.5	5.5	6.0

monitor. In the same way the image was examined after recording on each of the five video recorders mentioned in chapter III. The results are shown in table IV and table V. When we compare these spatial transfer functions with those of image intensifiers, we observe a certain loss of modulation due to the optical coupling, the television circuit and the magnetic recorder. The video recorders have a limited bandwidth, between 2 and 4 Mc/sec; we have also observed some deterioration of the picture due to mechanical causes and inhomogeneities in the video tape. We did not find big differences between the results obtained with the Old Delft Cinelix and Delcalix systems. The date given in table V were obtained with a Delcalix 12½-7-in with image orthicon.

4.3.8 Modulation transfer of time frequencies

The modulation transfer of time frequencies (M_tTF) was determined of a conventional fluoroscopic screen (Helia), a Cinelix system and a Philips 9-in image intensifier combined with two Philips television systems, with a vidicon and a plumbicon respectively. The results of these measurements are shown in fig. 15.
The disturbing time-lag in the vidicon chain is clearly demonstrated in the modulation transfer. We have found that this transfer function may vary considerably with the input exposure rate. These results were obtained with an input exposure rate of 25 μR/sec.

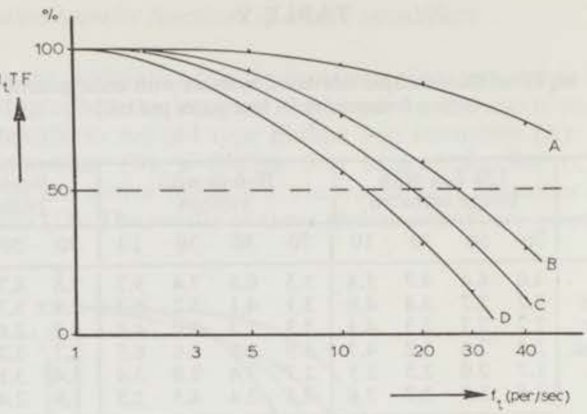


Fig. 15. Modulation transfer functions of time frequencies.
A. Conventional screen; *B*. Cinelix system with image-orthicon; *C*. Philips 9-in with plumbicon; *D*. Philips 9-in with vidicon.

4.4 Discussion

With regard to the measurements described in this chapter we can say that the conversion factor of a fluoroscopic system is of utmost importance. For the fluoroscopic screens which were measured we found conversion factors between 20×10^{-3} and 5×10^{-3} cd.m.$^{-2}$.mR^{-1} sec. For electronoptical image intensifiers, this factor is normally several thousands times greater, which has made possible fluoroscopy with cone vision. The subjective impression that the observation is much better when intensifying systems are used, is to be attributed in the first place to the conversion factor and not at all to the reproduction of contrasts. An explanation for this phenomenon is to be sought in the properties of the eye in dark- and light adaptation. A rough estimate of the performance of a particular screen can be obtained from the product of the conversion factor and the effective spatial bandwidth. This latter may be defined as that range of spatial frequencies where the modulation transfer is 50 per cent or greater (178). In this way, an analogy is obtained with the concept of the gain-bandwidth product such as used in communication theory and in the theory of photoconductivity. To a certain extent, this conversion-bandwidth product is also applicable to the intercomparison of image intensifiers. The temporal response of both screens and image intensifiers is generally to be neglected in regard to that of the eye.

When more photoelectronic devices are used in series (e.g. image intensifiers and television pick-up tubes with a certain time-lag) it is far more difficult to express the systems' performances by means of a singular figure. Theoretical considerations derived from signal theory have led to the definition of the concept of noise contrast, to combine the essential system parameters: the effective spatial and temporal bandwidth and the number of incident photons (150). We have been able to find correlations between this noise contrast and the results of observation experiments (106).

There is a remarkable difference in modulation transfer of the conventional photographic methods (no-screen films and normal films with intensifying screens) and all those methods based on the registration behind intensifying systems. This would be in favour of general application of large format roentgenograms, if other factors such as the need to study movements, and to keep the radiation doses low did not play a role. Losses in modulation transfer are caused by image intensifiers and magnetic recorders. The worst results are obtained in kinescopy, which can be seen from Fig. 13E. It is therefore unnecessary to make films on 35 mm from the television receivers; the picture quality is such that 16 mm film is good enough. From table IV and V it becomes clear that magnetic recording of the television signal shows a considerable reduction due to the limitated bandwidth of the recording system. The method of videotape recording is quite useful. This does not mean that there should be no place for kinescopy, with or without magnetic recording. Kinescopic films are obtained with very low radiation doses and they are in many cases good enough for certain clinical purposes. The determination of the modulation transfer of time frequencies (fig. 14) illustrates the disadvantages of the vidicon as a pick-up tube when fast moving structures are studied. We find that in the evaluation of television systems much more attention should be paid to the transfer of temporal frequencies.

CHAPTER V

MEASUREMENTS OF IMAGE QUALITY

5.1 Introduction

In the process of visual observation there are aspects which cannot be determined only from physical measurements of the image characteristics. Although the brightness and the relationship between the modulation transfer and the dimensions of the transferred details are essential, there is a considerable influence of the observer himself, caused by e.g. the way he observes an image and his experience with a particular type of image. In this chapter two test methods are described for the subjective perception of the fluoroscopic image. The first method makes use of the well known target after Cobb, which is also used in optics. It has the disadvantage of many perception tests, namely that the pattern of the target is known by the subject and that no attention is paid to movement.
In addition a second test method is described which approaches as near as possible the actual situation occurring in fluoroscopic examinations. A special phantom has been constructed to estimate the degree of observation in the use of different fluoroscopic systems. At the same time an attempt is made to find a correlation to the test methods, which were developed for the assessment of film projectors and television circuits (6, 130). No special skill is required from the subjects joining in the test. In this way an attempt is made to imitate the activity of the medical examiner, who tries to detect structural deviations, normally of relatively small dimensions and with low contrast and being located in a way unknown to the observer.

5.2 Quality assessment with a non-moving target

The target which we used was originally designed by Cobb for visual perception tests. It consists of a regular pattern which is repeated 45 times. In each group there are four equivalent sections of two lines. The dimensions of the sections diminish from 1.9 to 16.7 line pairs per cm. A particular group was regarded to be detectable when the observer could perceive at least three out of the four sections in that group. The target is shown in fig. 16. A copy of this test pattern was made electrolytically in lead on a 10 micron thick layer of copper foil. The effective lead thicknesses of the targets were about 20, 50 and 100 microns respectively, but most of the measurements were done with the so-called 50 micron target. The results of these statical experiments are given in the fourth section of this chapter.

5.3. Quality assessment with moving objects

The test method is based on the detection of small objects, which move in an unpredictible way in a test field. The field brightness as well as the

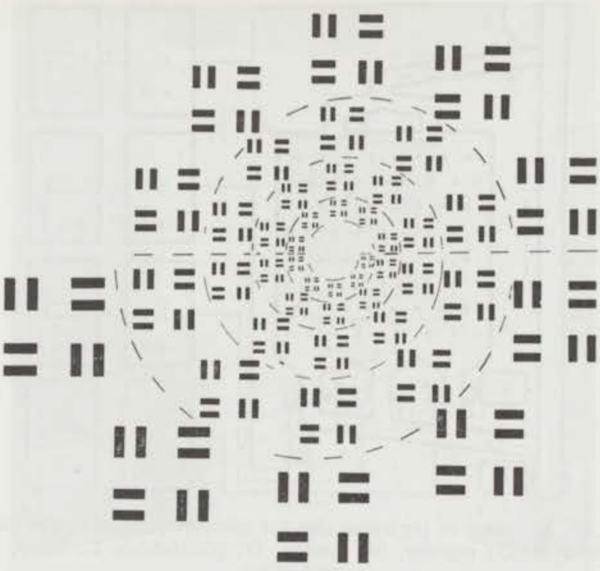


Fig. 16. Target used for image quality tests.

dimensions of the objects and their contrast against the background can be varied. The scene itself is an imitation of the image of a thorax in fluoroscopy.

The test field consists of a 10×10 cm^2 plexiglass plate on which obstacles are placed in a regular pattern. The obstacles are plastic straws of an outer diameter of 2 mm, a length of 8 mm and a wall thickness of about 0.1 mm. This test field is placed in the x-ray beam, between the x-ray tube and the fluoroscopic screen or system. The contrast of the plastic obstacles to the plexiglass background under fluoroscopy is so low that the straws are not seen. The objects to be observed are normally wooden or plastic balls of an outer diameter of about 5 mm. The test can however also be carried out with objects of much smaller dimensions (e.g. diameters of 1 and 2 mm) mounted inside a thin hollow spherical plastic pearl (outer diameter 5 mm) which serves as a vehicle for the small object. The objects pass the test field in a far from uniform and jumping motion. The mean passing time is of the order of 4 sec. and the mean length of the path is approximately 14 cm. We did not find big differences in the behaviour of objects of slightly differing weights, due to the various compositions. A diagram of the apparatus is shown in fig. 17.

The objects enter the vertically mounted test field on the upper side; there are two entries, one of them situated 2 cm from the centre of the upper side of the field to the right, the other the same distance to the left. When the objects enter the test field and fall downwards they meet the obstacles, where they have each time theoretically the same chances of going left or right. In this way the course of an object in the test field is not predictible. The spatial distributions of the falling objects approach that of a combination of

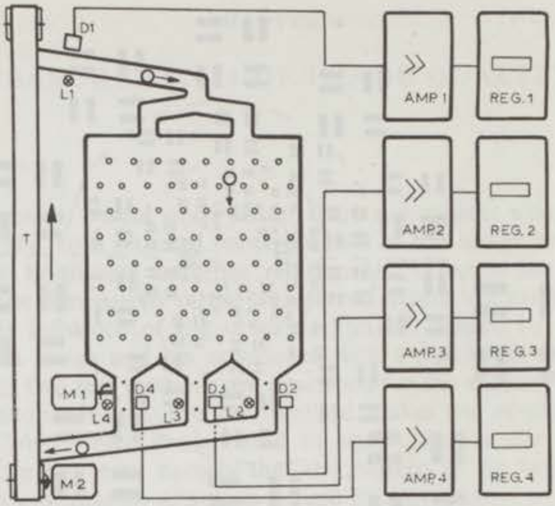
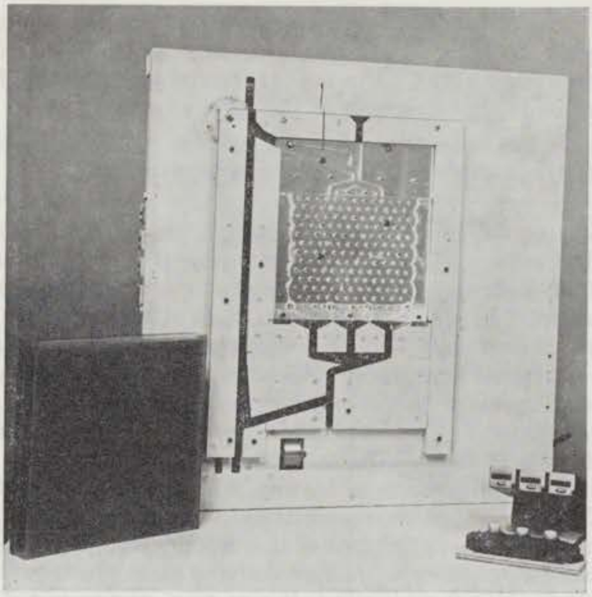


Fig. 17. Diagram of the apparatus for measurement of image quality.
AMP: amplifier REG: register, M: motor, D: photodiode L: lamp, T: transport mechanism

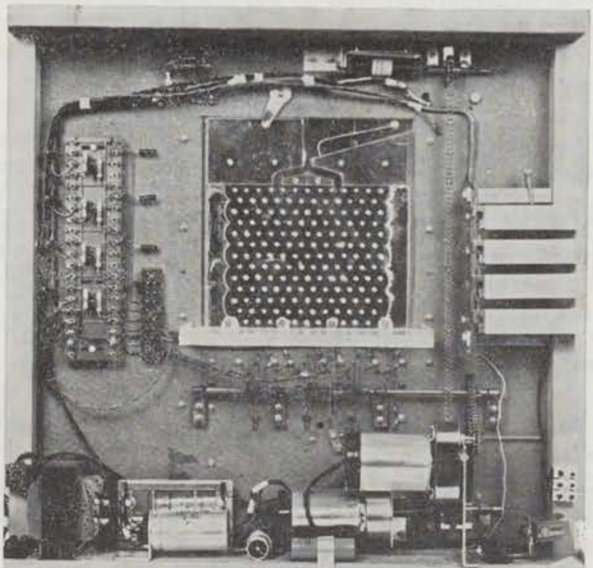
two probability curves, the tops of the curves being under the entries of the object in the upper side of the field. At the bottom of the test field there are three marked channels through which the objects can leave the field in the centre, on the right and on the left. In front of the observer there is a little switchboard with three buttons, corresponding to the three channels through which the objects can disappear. When he sees an object passing through one of the channels he pushes the corresponding button, thus recording his observation. When leaving the test field each of the objects interrupts a light beam which is concentrated on a photodiode; this current pulse is amplified in a two stage transistor amplifier and then fed to a digital register. In the diagram the amplifiers and registers are marked respectively with AMP and REG. The number of objects leaving each of the exit channels as well as the total number is registered. All objects pass lamp L_1 which is opposite to the photodiode D_1. In the exit channels there are lamps L_2, L_3 and L_4 respectively opposite to the photodiodes D_2, D_3 and D_4. A mechanical sluice system, which is driven by motor M_1 avoids a too fast succession of the objects. A transport system T, driven by motor M_2 conveys the objects again to the upper side of the test field.

The assumption is made that the quality of the image is related to the ratio of the number of observed objects and the total number of objects used in the test. For the percentage of objects detected in a series we have coined the term observability. To make the test situation as realistic as possible, the test field is placed between blocks of wax, with ribs molten into them. The wax blocks had a thickness of 3 cm each and 7 slices of 1 cm plexiglass were added to get an approximation of an average human thorax.

In the tests described two types of objects having high and low contrasts



front view of the apparatus



back view of the apparatus
power supply and amplifiers on the left registers on the right

Fig. 18. Apparatus for subjective quality assessment

were used. The contrasts were approximately 40 and 8 per cent measured in a 2 mm round opening in the centre of the objects. When not indicated otherwise there was no grid in front of the screen or systems and low contrast objects were used. A photograph of the apparatus is shown in fig. 18.

5.4.1 Results of measurements with a non-moving target

The statical test was used in a comparison of the perception in screen and television fluoroscopy. The 50 μ lead equivalent target was seen by two observers. The observation on the screens was after at least 20 minutes of dark adaptation. The eye of the observers was at a distance of 10 to 25 cm during screen fluoroscopy and at a distance of 100 to 130 cm from the monitor in television fluoroscopy. All screens and systems were examined without grid. The image on the monitor was seen without dark adaptation. For the investigation of the screens the target was observed with x-radiation from a O-90 tube at 70 kV. The target was at a distance of 1 m from the focal spot having a dimension of 1.2 mm. The exposure rates at the screens were 50, 200 and 500 μR/sec respectively. Due to the target the exposure rate was diminished to 40 per cent of its value. A second group of observations was carried out using a f /2.5 magnifying glass which gave a considerable improvement in the visibility. It was thus demonstrated that in the conventional fluoroscopic observation the human eye is the limiting factor and that the observation improves when more light is thrown on the retina. The results of the observations with the Cobb target are shown in table VI.

TABLE VI

Visibility of discrete space frequencies (in 1p/cm) on different fluoroscopic screens.

screen exposure rate (μR/sec)	with unaided eye			with magnifying glass		
	50	200	500	50	200	500
Levy West III	5.0	6.1	8.3	5.7	6.7	9.5
Kruppa 6D	6.1	7.4	8.7	7.2	8.3	10.5
Kruppa 9D	5.7	7.4	8.3	6.7	8.3	10.0
Dupont	5.6	6.7	7.7	6.5	8.3	9.5
Suprema (Streck)	5.3	6.7	7.7	6.5	8.3	10.0
Cawo	5.7	7.2	8.3	6.7	8.3	10.5
Auer	5.6	7.2	8.3	7.2	8.7	10.0
Helia	6.1	7.7	8.3	7.4	8.7	10.0

By means of photography we were able to affirm that all groups of the target were present in the image which is in agreement with the modulation transfer functions of these screens given in table III, chapter IV.
The same target was used for the evaluation of the image produced by different television systems and magnetic recorders. The x-ray source used in these experiments was a mobile unit Utilis (Enraf) used at a voltage setting of 70 kV. The image conditions during observation were chosen thus that there was no disturbing influence of x-ray quantum fluctuations. On the

other hand overirradiation was avoided. The input exposure rate was of the order of 50 μR/sec. The results of these measurements are shown in table VII.

TABLE VII

Visibility of discrete spatial frequencies measured on television and magnetic recoding systems

System	12½-7-in with image orthicon (Delcalix)	10-6-in with vidicon (Siemens)	9-5-in with plumbicon (Philips)
normal	8.3	10.7	7.7
ODX recorder	6.7	10.5	7.4
Sony recorder	4.7	4.8	5.0
Magtronics rec.	6.5	9.5	7.4
Shibaden rec.	6.0	*u*8.3	4.8
Philips rec.	6.1	8.3	7.2
enlarged	10.5	15.4	10.5
ODX recorder	9.1	14.5	10.0
Sony recorder	6.5	8.7	6.5
Magtronics rec.	8.7	14.5	10.0
Shibaden rec.	8.3	11.8	7.7
Philips rec.	8.7	12.5	9.5

Comparing the observation with television and screen fluoroscopy we see that with television finer details can be detected, although the modulation transfer in television systems is in general worse than that of screens (c.f. Tables III and V in chapter IV.)

5.4.2 Results of measurements with moving objects

The test method with moving objects was originally developed to determine the observability in screen fluoroscopy and to compare screen and electronically-aided fluoroscopy. The first group of experiments was carried out by one observer, using only two fluoroscopic screens, one screen with a very high conversion factor and the other with a very low conversion factor. (Helia and Levy West III). The properties of these screens are given in chapter IV. The experiment was repeated on five different days. Each screen was examined with fully dark adapted eyes at exposure rates of 100, 200, 500 and 1000 μR/sec respectively. At each exposure rate every day six series of one hundred falling objects were observed; three series with high contrast objects and three with low contrast objects. These experiments were carried out with a Müller DA 1000 x-ray machine using a 0-90 tube. The voltage on the tube was equal to that normally used in examinations of the thorax (90 kV, h.v.l. 4.5 mm Al). The results of these measurements are shown in fig. 19).

From these results it becomes clear that there is a gradual increase in the observability with increasing exposure rates, thus with increasing brightness. The observability is, of course, much better in the case of objects with high contrast and for the screen with the high conversion factor. These results

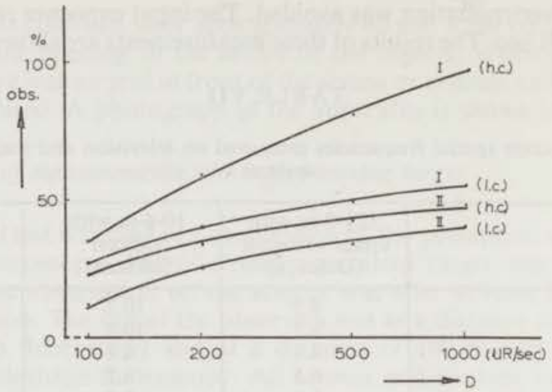


Fig. 19. Observability measured on two fluoroscopic screens.
Screen I: Helia; Screen II: Levy West III; h.c. = high contrast; l.c. = low contrast

are in accordance with expected values based on formulae 9 and 10 in chapter II.

For the second group of experiments the test was repeated during 20 days. The test was carried out each of these days at the same time, by the same observer using the same x-ray machine mentioned above. The comparison was made between a conventional screen (Levy West Sirius) and a Philips 9-in image intensifier with a television circuit (plumbicon camera).

The tests with the screen were carried out after at least 30 minutes dark adaptation, those with the television channel without previous adaptation. For practical reasons the test with the screen was done first and that with television thereafter. The test with the screen was done at four different exposure rates and with the television with six different exposure rates. For each exposure rate three times after each other. The tube voltage during these measurements also was equal to that normally used in thorax examinations 90 kV (h.v.l. 4.5 mmAl).

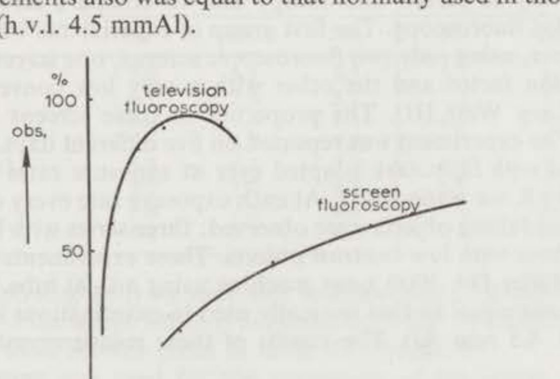


Fig. 20. Comparison of direct screen and television fluoroscopy.

Only the low contrast objects were used. The test apparatus was close to the screen. The screen was at a distance of 70 cm from the tube's focus. Exposure rates was measured behind the phantom. It will be clear that each day 12 series were done with the screen followed by 18 series with television. The choice of the exposure rates was taken at random. The results of these measurements are shown in fig. 20.
The third group of experiments with the same apparature and under the same conditions was done by a group of five subjects. They were all familiar with the observation of fluoroscopic images (doctors and radiographers). They were asked to join the test for three days. Three exposure rates were chosen in screen fluoroscopy and two in television fluoroscopy. For each exposure rate two series of 100 objects were to be observed immediately after each other. The results of these experiments are shown in table VIII.

TABLE VIII

average percentage of moving objects seen by five observers

Method	screen fluoroscopy			television fluoroscopy	
exposure rate at table top (mR/sec)	0,5	1,0	1,5	0,2	0,5
observer A	14	40	73	41	80
observer B	22	52	85	47	73
observer C	18	60	83	51	92
observer D	16	45	78	38	79
observer E	28	55	80	43	84

The fourth group of experiments was a comparison of four television systems, Philips 9-in with plumbicon, Delcalix 12½-in with image orthicon, Delcalix 12½-in with isocon and Siemens 10-in with vidicon. The same mobile x-ray tube (Enraf-Utilis) was used during all these measurements at a voltage setting of 70 kV (h.v.l. 3.2 mmAl). As there was no regulation of the tube current, the various exposure rates were changed by means of extra filtration of the beam with aluminium filters. Due to the considerable initial filtration the h.v.l. does not change much. All tests were carried out by one observer. Each series of hundred objects was repeated three times. The results are shown in table IX.

TABLE IX

Comparison of fluoroscopic television systems
The observability is indicated in per cents

Exposure rate at phantoms output (μR/sec)	100	50	25	15
Philips 9-in with plumbicon	94	93	81	42
Siemens 10-in with vidicon	67	46	15	—
Delcalix 12½-in with image orthicon	86	60	52	28
Delcalix 12½-in with isocon	94	61	50	44

In regard of these results we can evaluate that the relatively small score obtained with the Siemens installation might be ascribed to the time-lag in the pick-up tube. In chapter IV it became clear that this apparatus has a very good transfer of space frequencies: it has also a high conversion factor. The somewhat lower scores obtained with the Delcalix with image orthicon may be due to a lesser sentisivity of this apparatus, which is to be expected because of its big diameter. Delcalix with isocon gives an increase in observability due to the very high sensitivity of the isocon.

5.5 Image deterioration due to scatter and noise

The observation experiments with moving objects are now being continued in two directions. In the first place the observability is determined in the case of biplane irradiation. This method is coming into use in cardiac examinations.
Provisional results point to an enormous decrease of image quality. When the thorax is normally irradiated in the p.a.-direction, there is now a considerable influence due to the sideways scattered radiation from the lateral x-ray tube. The image deterioration is worst at the side of this tube and it is difficult to find optimal grids for this purpose.
Secondly the observability is being studied in connection with the noise. We feel that in television systems the observability is directly related to the ratio of the signal voltage to the noise power, the latter consisting of quantum noise and system noise. At present we are not able to measure the total noise power correctly. We have done a number of experiments determining the observability in the presence of extra noise. A wideband noise generator (Rohde und Schwarz) was used. We observed a marked decrease in observability as a function of the effective noise voltage, and dependent on its bandwidth.

5.6 Discussion

In the subjective assessment of image quality there are important influences of the observer's ability and conditions, e.g. the depth of adaptation and concentration and his familiarity with the observation of fluoroscopic images.
As far as the observation of non-moving images is concerned the results obtained with the non-moving target and the measurements of the modulation transfer function, which were described in chapter IV, agree for a good deal. The dark adapted eye is not able to detect the very fine structures although they are in the image as shown by means of the modulation transfer function. In fact the dark adapted eye cannot see the finest details on a screen. The visibility could be increased by means of a magnifying glass. The observation of high contrasts is easier than that of low ones. The most important limitations are due to the properties of the eye, the conversion and graininess of the screen. Because of the laziness of the eye no fluctuation in the x-ray

quantum noise are observed in screen fluoroscopy. On the television monitor small details might be missed due to the loss of modulation transfer, which is related with the bandwidth of the system. Magnetic recording proved to introduce extra loss of resolution and visibility.

The practice of fluoroscopic examination was simulated in the test with moving details, of which the contrast was relatively low. The test makes it possible to introduce an element of unpredictibility. This test method was originally used to compare screen and television fluoroscopy. The much better results with television fluoroscopy can be explained from the much higher light levels. A limitation for low exposure rates is set by the quantum noise; a drop in the scores was also found for high exposure rates. This is caused by the reaction of the automatic brightness control in the television circuit, which has to protect the pick-up tube against overirradiation. The same detail test has been used to compare various fluoroscopic television systems, with different intensifyers and pick-up tubes. An explanation of the results of these measurements is found in the different time-lags and sensitivities of the systems. The test seems to be also useful for the evaluation of image deterioration due to scatter and noise. The procedure of the moving detail test proved to be easy to learn, which makes it possible to use the test for groups of observers.

CHAPTER VI

RADIATION MEASUREMENTS

6.1 Introduction

In chapter II we have outlined the general methods of measuring x-ray doses, based on ionization. The ionization of air makes possible a quantitative determination of radiation doses in practical situations. In this way it becomes possible to study the merits of different fluoroscopic procedures and to compare the older conventional fluoroscopic methods with the modern ones which make extensive use of image intensification and television. The need for critical consideration of fluoroscopic procedures and methods is felt more strongly because the United Nations reports (213) have revealed that, in the more developed countries of the world, the highest contribution to the man-made genetically significant radiation dose must be ascribed to medical diagnostics.

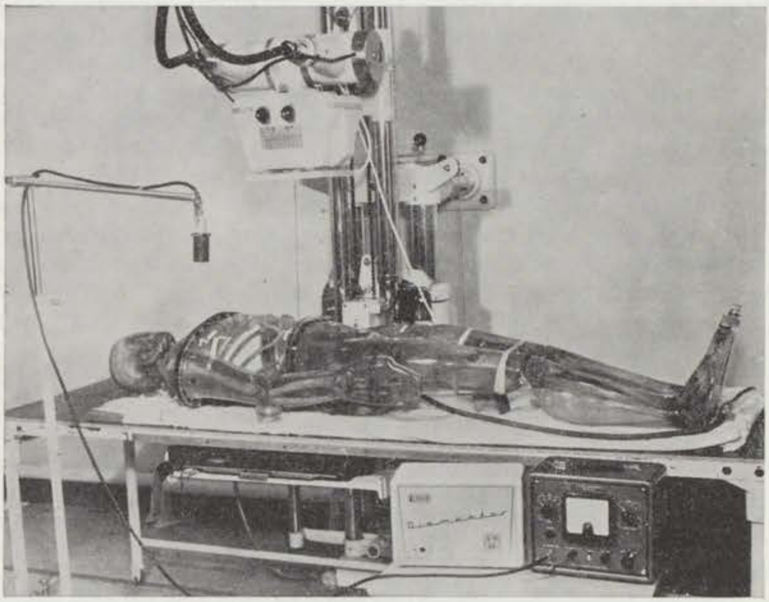


Fig. 21. Phantom used for radiation measurements.

It will be shown that the doses can be greatly reduced when television is used. Many of the radiation measurements described in this chapter were carried out during routine examinations of patients. In principle, this was done only when the routine did not have to be changed in any way. We were thus able to study what actually happens without giving the patient any extra doses.

In situations where stray radiation is determined, it is impossible to carry out the measurements during irradiation of a living body. In such cases a phantom was used, which reproduces as closely as possible the actual situation during an examination. For those measurements we have used two phantoms. A plastic cylinder filled with water and a phantom of the human body, built by Beekman and Weber (11, 221). This body phantom, which has the format of a standard male, was built using data derived from a statistical study for the benefit of the clothing industry. The body phantom, which is shown in a photograph, Fig. 21, is made out of transparent plastic walls, thickness approx. 4 mm and contains a complete male skeleton. The density of the lungs is simulated by filling the pulmonary region with a mixture of sawdust and polystryrene grains. By means of measurements on this body phantom we were able to study a number of fluoroscopic procedures with special attention to details concerning radiation protection. We have studied the relationship between the position of the x-ray source with regard to the phantom and the gonadal dose, as well as the stray radiation in the environment of the irradiated body and the dose reduction due to the use of round instead of square x-ray beams. With regard to the phantom a comparison is made between the stray radiation caused by the phantom, by a cylinder filled with water and that caused by a dead body under the same conditions.

TABLE X

Radiant energy inciding on patients during a routine chest fluoroscopy

method	screen fluoroscopy				television fluoroscopy			
Radiologist	number of examinations	incident energy (mWsec)			number of examinations	incident energy (mWsec)		
		mean value	max. value	min. value		mean value	max. value	min. value
A	59	29	57	11	—	—	—	—
B	54	15	45	5	50	6	16	4
C	49	16	26	7	81	9	27	4
D	39	13	20	9	56	6	13	3
E	35	9	25	3	51	6	12	4
F	27	11	23	7	—	—	—	—
G	26	15	27	9	14	8	12	5
H	25	28	45	14	18	11	45	5
I	—	—	—	—	45	9	36	2
J	17	15	22	9	—	—	—	—
K	13	29	45	18	14	10	19	7
L	3	15	19	11	3	8	6	5
Total	347	18	57	3	332	8	45	2

6.2 Incident energy in chest fluoroscopy

These measurements have been carried out with a Reinsma integral dosemeter during routine clinical examinations. The flat ionization chamber was mounted in the x-ray beam. We have measured the incident radiation; the results are given in mWsec. The diagnostic dosemeter actually measures the surface integral of the exposure ($Rxcm^2$). This value must be multiplied by a proportionality factor dependent on the radiation spectrum. The results of these measurements are very interesting because incident energies can be compared, as given by different doctors during the same type of examination. It is also possible to compare the conventional method and modern television fluoroscopy. We have determined the incident energy in a big number of chest examinations, which were carried out by a group of doctors with a conventional screen (Levy West Sirius) and with a television channel (Philips 9-in with vidicon). These data are collected in table X. All examinations were carried out with the same x-ray machine and with the same tube voltage. Recent data obtained with a new 9-in image intensifier with a plumbicon camera point to still higher dose reductions.

6.3 Comparison of conventional and modern fluoroscopy

Comparative measurements of the incident radiant energy have been made during a large number of normal routine examinations which were carried out both with television and in the conventional way without any image intensification. All these examinations of each type were carried out by the same radiologist with a Müller DA 1000. A Levy West Sirius screen was used whereas the system was a Philips 9-inch image intensifier combined with television (vidicon camera). The incident energy was determined with a diagnostic monitor developed by Reinsma (172). Some of the results are shown in fig. 22 in which the percentage of 100 represents the energy delivered with conventional methods.

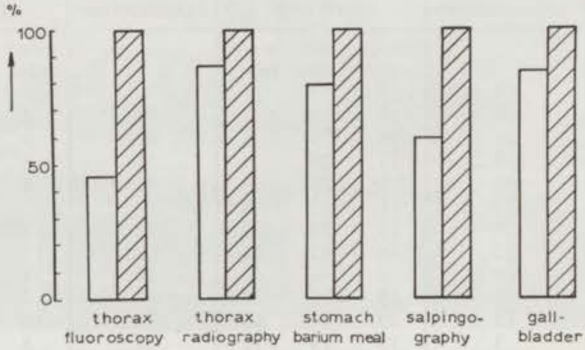


Fig. 22. Comparison of incident energies without (hatched) and with television fluoroscopy.

The great reduction in incident energy is of course found in cases where no roentgenograms are made. The image intensifier had an amplification of about 4000 times. Greater dose reductions might be expected when the amplification was still higher. However, there is a certain tendency to work with somewhat larger fields and for longer times when fluoroscopy is done with image-intensifying devices. Nevertheless, we can remark that the use of image intensifiers with television gives, apart from an improvement in observation, a definite reduction of the radiation energies delivered to the patient and the examiner.

6.4 The influence of the position of the x-ray tube on the gonadal dose

Modern x-ray fluoroscopy has given a greater freedom with regard to the place of the x-ray source in the installation. When television is used, a separation can be made between the places where the image originates and where it is displayed on a television receiver (73, 97). A choice can be made between the two arrangements shown in fig. 23.

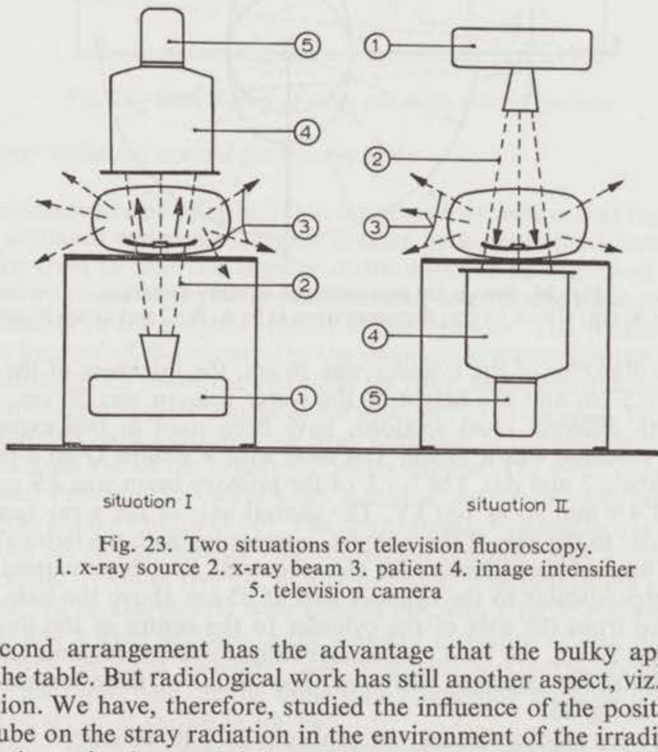


Fig. 23. Two situations for television fluoroscopy.
1. x-ray source 2. x-ray beam 3. patient 4. image intensifier
5. television camera

The second arrangement has the advantage that the bulky apparatus is under the table. But radiological work has still another aspect, viz. radiation protection. We have, therefore, studied the influence of the position of the x-ray tube on the stray radiation in the environment of the irradiated body and on the patient's gonadal dose. The results of the measurements, which were carried out with phantoms, are described in the following sections.

6.4.1 Measurements of stray radiation

As far as radiation scatter is concerned there are many implications in x-ray fluoroscopy. The scattered radiation causes a certain deterioration of the image; this influence can be diminished by the use of suitable grids. The scattered radiation gives also rise to many protection problems. Sensitive tissues of the irradiated body outside the primary beam are liable to receive a certain stray radiation dose and there is also a marked exposure in the surroundings. Theoretical expressions exist for the angular distribution of the scattered energy, but difficulties arise in the application of these expressions to practical situations. The intensity of scattered radiation outside the irradiated body increases in general with the voltage, unless this quantity is very large, and the beam size. This is illustrated by the measurements which we have carried out on a volume of water in a cylindrical plastic container, and on the body phantom. The set-up for these measurements is shown in fig. 24.

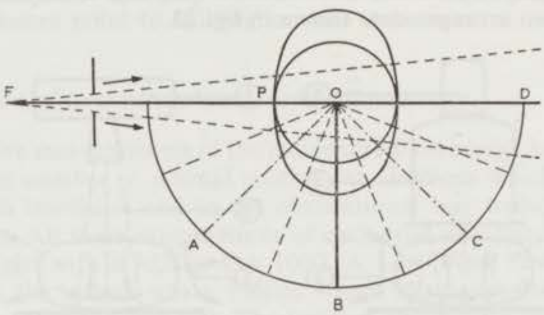


Fig. 24. Set-up for measurement of stray radiation.
FP = 50 cm; OP = 13 cm; distances from O to A, B, C and D are 50 cm.

The inside diameter of the cylinder was 26 cm, the thickness of the plastic walls was 0.5 cm and the height of the water column was 50 cm. Square beams, with different cross sections, have been used in this experiment. The x-ray machine was a Müller DA 1000 with a Philips O-90 x-ray tube (extra filtration 2 mm Al). The h.v.l. of the primary beam was 2.9 mmAl at 70 kV and 4.9 mm Al at 100 kV. The central axis of the x-ray beam was perpendicular to the axis of the cylinder, intersecting with the latter at 25 cm above the base of the cylinder. All measurements have been carried out in a plane perpendicular to the cylinder axis at 25 cm above the base, whilst the distance from the axis of the cylinder to the centre of the ionization chamber was 50 cm. An E.I.L. dosemeter (Electronic Instruments Ltd) with its 35 cc ionization chamber was used. The results of these measurements are shown in fig. 25.

All values were standardized at an exposure of 1 R, measured in free air at the place of the centre of the plane of incidence (Point P in Fig. 22). The smallest focus-to surface distance was 50 cm. There is a good agreement with the results of similar measurements (19, 102). We may note (cf. Table XI) that there is an increase in the stray radiation at the higher tube voltages and for increasing beam cross sections. In addition, the last mentioned factor is responsible for a decrease of the surrounding non-directly irradiated part of the volume, which acts as an attenuator for the scattered radiation.

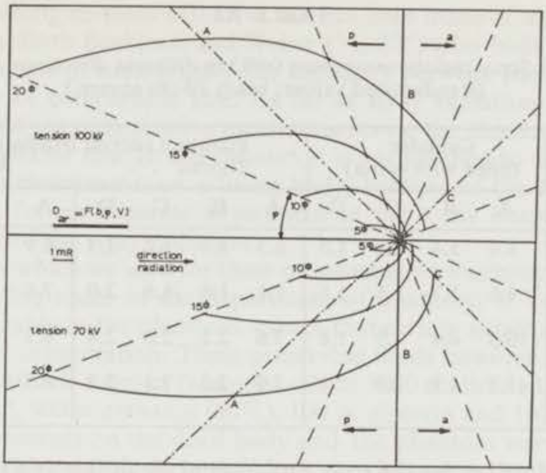


Fig. 25. Distribution of stray radiation around cylinder.

6.4.2 Stray radiation around the human body

It was demonstrated (cf. Fig. 25) in the preceding section that the exposure rate of scattered radiation is much greater backwards than forwards. We have also tried to find the angular distribution of the scattered radiation in the environment of the body phantom and to compare these results with measurements in the neighbourhood of the cylinder. The results could be different because of the material in the phantom representing the lungs and the skeleton, which make the phantom far from homogeneous and because of its shape—,it is approximately 46 cm wide and 23 cm deep—, by no means cylindrical. We have measured the stray radiation in the environment of the body phantom and of the cylindrical water volume. The x-ray machine used was a Smit Provisor (full wave x-ray machine, with four valve rectification and a x-ray source Philips O-90). The stray radiation exposure was measured again with an EIL-dosemeter; the ionization chamber was mounted on a photographic tripod in free air, in a large room, thus preventing extra stray radiation. All measurements were carried out with a focus-surface distance of 55 cm and a fixed field size in the plane of incidence of 20×20 cm^2. The plane where the stray radiation was measured was perpendicular to the plane of the input field, at the same time containing the axis of the x-ray beam. The set-up is shown in fig. 24.

The stray radiation exposure was measured n A (backwards about 45°), in B (sideways) and in C (forwards about 45°). For comparison the radiation exposure was also measured in D, on the beam axis; this is a mixture of penetrated and scattered radiation. In the centre of the phantom (or cylinder) on the beam axis, a point O was chosen. The distances from A, B, C and D to O were all 50 cm. The results of these stray radiation measurements are given in table XI; all values are standardized on an exposure of 1 R, measured in point P in free air.

TABLE XI

Stray radiation exposure (mR) in different directions
(standardized values; beam 20 cm square.)

Tube voltage (h.v.l.)	Cylinder (filled with water)				Phantom (dorsal irradiation) Thorax				Abdomen			
Localisation	A	B	C	D	A	B	C	D	A	B	C	D
70 kV (2.3 mm Al)	8.6	3.4	1.2	1.0	6.3	1.3	1.2	1.3	6.9	1.7	0.9	0.7
90 kV (2.9 mm Al)	9.6	3.7	1.5	1.5	7.1	1.8	1.6	2.0	7.6	2.1	1.1	1.2
110 kV (3.4 mm Al)	10.6	4.4	1.9	1.8	7.6	2.1	2.0	2.4	8.2	2.4	1.4	1.7
125 kV (3.9 mm Al)	11.1	4.5	2.0	2.1	7.9	2.2	2.1	2.9	8.5	2.8	1.6	2.0

The measured values for the stray radiation in air shown as a function of the x-ray tube voltage in the curves of fig. 26. The curves for the scattering by the thorax, the abdomen and the water volume are marked t, a and w, respectively. We note that the exposure of the backwards scattered radiation is for every tube voltage more intense than that scattered forwards. The ratio of the exposures of the radiation scattered backwards and forwards decreases with increasing tube voltage; this has been shown by the dotted lines in figure 26.

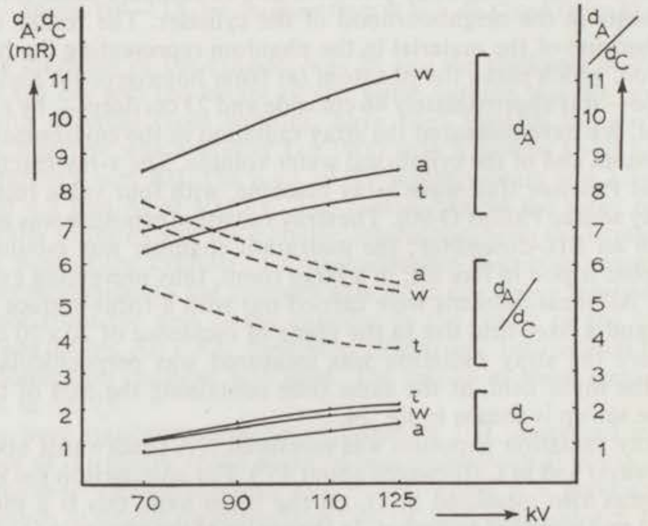


Fig. 26. Stray radiation around the phantom and the water volume

These results, which are in good accordance with those described in the literature (20) stress the high amount of backscatter.

In the preceding sections extensive use has been made of a phantom of a standard man. Both Beekman and Weber (11, 221) who built this phantom showed, by means of radiography the similarity between the phantom and a living body of comparable size. As far as stray radiation is concerned, we have carried out comparative measurements on the phantom and a dead body of comparable size. In our opinion it is not justified to carry out these comparative measurements on a living body, because of the relatively long time required for an accurate adjustment of the x-ray beam and for the determination of the stray radiation.
The dead body which we used for these measurements was intact, as prepared for the dissecting-room of the department of anatomy. It had a size and weight comparable to the phantom, except that certain substances had been added to it for conservation. These preserving fluids however are mainly of relatively low atomic number (amongst others 1000 cc distilled water, 750 cc formalin (40%), 500 cc aethanol (90%), 100 cc glycerin and 100 cc phenol).

The measurements on the dead body and the phantom were carried out under comparable conditions; both objects were lying on a 1 cm thick wooden table and the same x-ray machine (Enraf-Utilis, half-wave rectification, extra filtration 1 mm Al) was used. The irradiation of the thorax and the abdomen was in both cases from behind. The stray radiation measure ments were carried out with a EIL-dosemeter in three parallel planes: the plane of the supporting table, the plane of incidence of the radiation and a third plane 20 cm above the plane of incidence. The results of these comparative measurements were in good agreement (within 15 per cent) for a tube voltage of 80 kV. In all cases there was a little more stray radiation from the dead body than from the phantom. This may be due to small differences in size and to the addition of the preserving fluids. We have, for technical reasons, not repeated these measurements with higher energy radiation. These would probably have shown still better agreement.

6.5 Measurements of gonadal exposure

We have, also, studied the influence of the position of the x-ray tube on the gonadal exposure. We have used the above mentioned human-equivalent phantom when the thoracic and abdominal regions were irradiated. In these experiments we used again the Smit-Provisor with a Philips O-90 tube and a filtration of 2 mm Al. The focus-skin distance was 55 cm. The male gonadal exposure was measured by means of the EIL-dosemeter, the female gonadal exposure by means of a special ionization chamber for under water purposes which was designed and constructed for similar dose measurements by Weber. This ionization chamber in connection with a Carry vibrating reed electrometer, had been calibrated to an x-ray standard. We have chosen the input fields so that the axis of the x-ray beam passed through the tenth thoracic vertebra and the first lumbal vertebra respectively. For the localization of the gonads we have kept to the same places as indicated by Beekman (11). The male gonadal exposure was measured by placing the ionization chamber between the phantom's legs, 8 cm below the symphysis.

The female gonadal exposure was measured in the abdominal volume, $2\frac{1}{2}$ cm above the symphysis, $2\frac{1}{2}$ cm to the left, and 9 cm under the skin of the abdomen. The results of these measurements are collected in table XII. These measurements were carried out with an entrance field of 20 cm square. All values are standardized on an exposure in free air, at the table top, of 1 roentgen.
The normalized gonadal exposures increase with increasing voltage. The gonadal exposures are highest when the radiation is incident on the ventral side of the phantom.
From the measurements of the gonadal dose and the stray radiation an important conclusion can be drawn. During most of the radiological examinations the patient is generally lying in supine position. For this reason the x-ray source should be mounted under the examination table.

TABLE XII

Gonadal exposure (mR) due to irradiation
(standardized values)

field size 20 × 20 cm²	thoracal region				abdominal region			
direction of irradiation	dorsal		ventral		dorsal		ventral	
tube voltage (h.v.l.)	female	male	female	male	female	male	female	male
70 kV (2.3 mm Al)	0.21	0.03	0.43	0.67	50.2	0.66	148	10.5
90 kV (2.9 mm Al)	0.65	0.05	0.78	0.74	64.2	1.18	173	12.4
110 kV (3.4 mm Al)	1.14	0.08	1.33	0.77	98.1	1.83	205	14.3
125 kV (3.9 mm Al)	1.52	0.09	1.72	0.80	101.3	2.16	215	16.0

6.6 The influence of the form of the x-ray beam cross section

The image intensifying devices have round input screens and a reduction of both integral absorbed dose and gonadal dose can therefore be expected when a beam with a round cross section is used instead of the usual square or rectangular beams. The gonadal doses were measured with varying tube voltages and for square and round x-ray beams. In our case the size of the input field of the square beams was 10×10 cm² and the diameter of the round beam was 10 cm. The gonadal doses were determined in the way described in section 6-5 of this chapter. An x-ray machine (Müller DA 1000) with six valve rectification was used. There was an extra filtration 2 mm Al and the focus-surface distance was 50 cm. The body phantom was laid on the table top, in supine position, thus in the same position as patients during most of the examinations. The results of these measurements are shown in table XIII all data are standardized on an input exposure of 1 R, measured at the table top in air without other scattering.

The results show an increase of the gonadal dose with increasing tube tension, which can be explained by the relatively high absorption of the softer radiations and the increasing scatter of higher energy radiation. They also show a marked influence of the radiation scatter due to the relatively small body volume that is outside the round beam but inside the square beam. This argues for the application of round beam cross-sections where possible.

TABLE XIII

Gonadal exposures (in mR) for x-ray beams with square and round cross-sections (standardized values)

Anatomical region	upper abdomen (L_1)				lower abdomen (L_5)			
Beam form	square		round		square		round	
Gonadal exposures	female	male	female	male	female	male	female	male
50 kV (1.9 mm Al)	1.17	0.01	0.66	0.01	34.1	0.33	27.4	0.26
70 kV (2.6 mm Al)	4.38	0.08	1.78	0.04	62.8	0.88	52.0	0.76
90 kV (3.4 mm Al)	7.53	0.15	3.62	0.10	84.2	1.36	73.2	1.19
125 kV (4.8 mm Al)	11.72	0.33	5.31	0.17	100.5	1.82	94.7	1.48
Anatomical region	femural joint				femur, 20 cm from femural joint			
Gonadal exposures	female	male	female	male	female	male	female	male
50 kV (1.9 mm Al)	0.61	0.82	0.47	0.45	0.11	3.02	0.07	1.83
70 kV (2.6 mm Al)	0.94	1.81	0.68	1.06	0.29	6.35	0.34	3.31
90 kV (3.4 mm Al)	1.53	2.60	0.98	1.57	0.46	8.08	0.43	4.26
125 kV (4.8 mm Al)	2.14	3.92	1.85	2.52	0.79	9.98	0.60	5.94

6.7 Discussion

From the results collected in this chapter some general conclusions can be made. The use of television gives a considerable dose reduction, which should be much greater if all pictures were made from the intensifier output screen (57, 179). As explained in chapter IV this type of image formation is however liable to considerable losses in modulation transfer, so that these techniques are usable only for certain types of examination.
The incident energies delivered during one type of examination show a wide range of values. This is due to the great variety in the patient material and to the different procedures used by the examiners. It might be interesting

to consider the influence of automatic control of incident radiation as used in modern x-ray machines. As far as the construction of television installations is concerned the x-ray source should preferably be mounted under the table top and round instead of square diaphragms should be used in fluoroscopy.

CHAPTER VII

CONCLUDING REMARKS AND RECOMMENDATIONS

We have seen that modern radiology possesses a large arsenal of technical devices. The aim of this study was to find quantitative criteria for the assessment of the image quality and the radiation burden in x-ray fluoroscopy. When we review the experiments which were carried out, we are led to the following conclusions and recommendations.

1. Both modern and conventional radiological techniques are accessible to investigation by physical methods, such as the determination of the radiation dose, the conversion factor, the picture resolution and the transfer functions of space and time frequencies.

2. It is the luminous output of a screen or system that mainly determines the external conditions of observation. The conversion factor, the only well-defined factor in this field, yields only a restricted information concerning the conversion properties of the system. For screens we found conversion factors between 5×10^{-3} and 20×10^{-3} $cd.m^{-2}.mR^{-1}.sec$ and for electron optical image intensifiers between 47 and 82 $cd.m^{-2}.mR^{-1}.sec$. The methods for determining this factor need to be and can be further improved. The influence of radiation quality, the exposure rate and the properties of the pick-up device should be taken into account.

3. The modulation transfer function of space frequencies reveals many of the characteristics connected with the reproduction of the contrast of various picture details. The knowledge of this function yields a much better assessment than the one based on picture resolution only. It became clear that the best modulation transfer is found with conventional photographic methods (large size films, with and without intensifying screens). All methods of image registration through intensifying media are characterized by a marked loss of resolution (up to 10 times) and considerable dose reduction (up to 25 times). These methods are, therefore, appropriate for the formation of images which are less sharp but can be made with lower doses and normally in large numbers per unit of time (fast series photography, cine films, magnetic recording). The loss of resolution was considerably more when the image was recorded magnetically. The best results were obtained with 1-in video tape. The modulation transfer function does not take into account the question of x-ray photon noise, which is an important disturbing factor in fluoroscopy. The human eye does not exploit the relatively good modulation transfer of a conventional fluoroscopic screen to the full because visual acuity is considerably lowered at low brightness levels.

4. From the results of the measurements of the modulation transfer function of time frequencies it became clear that the various fluoroscopic systems differ over a wide range. Time-lag in pick-up tubes may lead to loss of information. It might be advantageous to use tubes with little time-lag for special purposes (e.g. for cardiac examinations).

5. An estimate of the quality of a fluoroscopic screen can be obtained by taking the product of its conversion factor and the effective spatial band-

width. For television systems the effective temporal bandwidth is also to be considered. We think the noise contrast gives a good general impression of the systems' performances.

6. The physical measurements of image properties were complemented by subjective tests based on observation of non-moving details and objects moving unpredictibly through a thorax-like test field. From these measurements an explanation on a quantitative basis was found for the better observation in television fluoroscopy as compared with screen fluoroscopy. The best observability was obtained with a combination of an image intensifier and a plumbicon used in the television camera. The observability was less when mirror systems were used and also with television pick-up with a vidicon.

7. At low exposure levels at the entrance of the fluoroscopic systems television pick-up tubes with little time-lag and low noise should be used to observe moving structures. Both the plumbicon and the isocon appear to be quite suitable for this purpose.

8. An impression of the radiation burden delivered during the various procedures and methods was obtained by measuring the radiation incident on the body and also by determining the doses from phantom measurements. From these measurements of the incident radiation it was concluded that there is a marked dose reduction of at least 50 per cent when television is used in fluoroscopy. As far as the construction of modern installations is concerned it was found that in general the radiation source should be mounted behind (or under) the examination table. Circular radiation fields should be preferred if the full area of the image intensifier is used.

GLOSSARY

Absorbed dose: The amount of energy imparted by ionizing particles and photons per unit of mass.

Blanking factor: The factor indicating the information loss in a television display due to the interruption in the succession of pictures or lines.

Contrast: The difference in brightness of an object (or its pictural representation) and the background divided by the brightness of the background.

Conversion factor: The ratio of output image brightness and the exposure rate at the input of a screen or system.

Effective bandwidth: The range of spatial or temporal frequencies where the modulation transfer is fifty per cent or greater.

Exposure: The sum of the electrical charges of either sign produced in an air volume due to x- or gamma radiation divided by the mass of that air volume, which is assumed to be in electronic equilibrium.

Focal spot or focus: The orthogonal projection of the bombarded area on the anode of the x-ray tube in the direction of the beam axis.

Half value layer: The thickness of a layer of a certain substance, which is necessary to reduce by its attenuation the original x-ray exposure rate to half its value.

Integral absorbed dose: The volume integral of the product of the absorbed dose and the density.

Modulation: The difference of the maximum and minimum radiation intensity in a regular test pattern divided by the sum of these values.

Observability: The percentage of objects observed in a test series with unpredictibly moving details.

Phantom: A radio-opaque model of the human body imitating the physical behaviour of such with respect to x-radiation.

Resolution: Number of lines resolved per unit of length, per picture height or per picture width.

Spread function: The intensity distribution of an infinitely small spot or an infinitely narrow slit emitting radiation of unit intensity.

Target: Thin metal plate used for the assessment of the image quality. The same term is often used for the layer in an image orthicon or an isocon on which the electrostatic image is formed. The use of the term target for the focal spot of an x-ray tube has been avoided deliberately in this publication.

Visibility: The power of the human eye to discriminate fine structures in a fluoroscopic image.

REFERENCES

1. AIRY G. B., On the diffraction of an object glass with circular aperture, Trans. Cambr. Phil. Soc. 5, 1835, 283-290
2. ALBRECHT C., W. J. OOSTERKAMP, C. V. OSENBRUGGE, X-ray screens with reduced information losses, Medica Mundi 5, 1959, 80-84
3. ALBRECHT C., W. J. OOSTERKAMP, The evaluation of x-ray image forming systems, Medica Mundi 8, 1962, 106-115
4. ARDRAN G. M., H. E. CROOKS, Routine dose recording in diagnostic radiology, Brit. J. Radiology 36, 1963, 689-694
5. ARDRAN G. M., H. E. CROOKS, P. W. RAMBY, The Thorn electroluminescent panel, Brit. J. Radiology 36, 1963, 927-931
6. ARP F., Statistische Betrachtungen zu den Messungen über die Seheigenschaften des menschlichen Auges, Z. angew. Physik 10, 1958, 317-320
7. ARP F., Das Ausschöpfen des Informationsgehaltes von Bildvorlagen mittels fernsehtechnischen Abtastverfahren, Optik 23, 1965, 83-87
8. BALDWIN M. W., The subjective sharpness of simulated television images, Proc. Inst. Radio Eng. 28, 1940, 458-468
9. BANKS G. B., Television pick-up tubes for x-ray screen intensification, Brit. J. Radiology 31, 1958, 619-625
10. BARENDSEN G. W., Dose survival curves of human cells in tissue cultures irradiated with alpha, beta, 20 kV and 200 kV x-radiation, Nature 193, 1962, 1153-1155
11. BEEKMAN Z. M., Genetically significant dose from diagnostic roentgenology, Thesis Leiden 1962
12. BENSON F. H., Voltage stabilized supplies, Macdonald London 1957
13. BERCI G., A. J. SEYLER, An x-ray television image storing apparatus, Am. J. Roentgenology 90, 1963, 1290-1300
14. BIRKEN H., Bildverstärkung und Röntgen-Fernsehen, Der Radiologe 4, 1964, 111-116
15. BISCHOFF K., Die Bedeutung des Röntgenfernsehens für die Erweiterung des Durchleuchtungseinsatzes in der medizinischen Diagnostik, Fortschritte Röntgenstrahlen 95, 1961, 104-123
16. BLACKWELL H. R., Contrast thresholds of the human eye, J. Opt. Soc. Am. 36, 1946, 624-642
17. BLANC-LAPIERRE A., Comparaison entre la transmission de l'information en optique et en radioélectricité, Optica Acta 2, 1955, 1-5
18. BOHEEMEN G. V., Het meten van de dosis bij de röntgencinematografie, Thesis Leiden 1963
19. BOMFORD C. K., T. E. BURLIN, The angular distribution of radiation scattered from a phantom exposed to 100-300 kVp x-rays, Brit. J. Radiology 36, 1963, 436-439
20. BOTDEN P. J. M., Some remarks on intensification, contrast, detail in x-ray image intensifiers, Medica Mundi 8, 1962, 59-63
21. BOUMAN M. A., On the quanta explanation of vision, Thesis Utrecht 1949
22. BOUMAN M. A., J. TEN DOESSCHATE, Nervous and photochemical components in visual adaption, Opthalmologica 126, 1953, 222-230
23. BOUMAN M. A., Visual thresholds for line-shaped targets, J. Opt. Soc. Am. 43, 1953, 209-211
24. BOUMAN M. A., Quantenbiologie des Auges, Studium Generale 13, 1960, 141-157
25. BOUWERS A., Achievements inoptics, North Holland Publ. 1, 1946
26. BOUWERS A., Information content of x-ray pictures made with the various techniques, Acta 9th Int. Congress Radiology II, 1466-1471
27. BOUWERS A., Der Informationsinhalt des Röntgenbildes, Röntgenblätter 15, 1962, 81-87
28. BOUWERS A., Quailitätsprüfungen bei elektronischen Übertragungssystemen, Röntgenblätter 16, 1963, 81-84
29. BRINK G. V. D., Retinal summation and the visibility of moving objects, Thesis Utrecht 1957
30. BRONKHORST W., Kontrast und Schärfe im Röntgenbild, Thieme 1927
31. BURGER G. C. E., B. VAN DIJK, Zur Bestimmung der kleinst wahrnehmbaren Objekt-

grösze bei der Durchleuchtung, Fortschritte Röntgenstrahlen 58, 1938, 382-385
32. BURGER G. C. E., Fantoomproeven met röntgenstralen, Philips T. T. 11, 1949, 295-302
33. CARLSSON C., Determination of integral absorbed dose from exposure measurements, Acta Radiologica 1, 1963, 433-458
34. CATCHPOLE C. E., X-ray image intensification using multistage image intensifiers, Adv. in Electronics and Electron Physics 16, 1962, 567-579
35. CHAMBERLAIN W. E., Fluoroscopes and fluoroscopy, Radiology 38, 1942, 383-413
36. CHANTRAINE H., P. PROFITLICH, Über die Bedeutung von Schärfe und Kontrast für die Mindestdicke von erkennbaren Einzelheiten, Fortschritte Röntgenstrahlen 47, 1933, 437-447
37. CHERIGÉ E., A. JUTRAS, Le téléradiodiagnostic en pathologie digestive, Ann. de Radiologie 4, 1960, 503-513
38. CLAUS W. D., The concept of permissible dose in: Radiation biology and medicine, Addison Wesley 1958
39. COBB P. W., F. K. MOSS, The four variables of the visual threshold, J. Franklin Inst. 205, 1928, 831-847
40. COLTMAN J. W., Fluoroscopic image brightening by electric means, Radiology 51, 1948, 359-367
41. COLTMAN J. W., Scintillation limitations to resolving power in imaging devices, J. Opt. Soc. Am. 44, 1954, 234-237
42. COLTMAN J. W., The specifications of imaging properties by response to a sine wave input, J. Opt. Soc. Am. 44, 1954, 468-471
43. COLTMAN J. W., A. E. ANDERSON, Noise limitations to resolving power in electronic imaging, Proc. Inst. Radio Eng. 48, 1960, 858-865
44. COMBEE B., P. J. M. BOTDEN, W. KÜHL, Progress in image intensification, Medica Mundi 8, 1962, 101-105
45. COPE A., A. ROSE, X-ray noise observation using a photoconductive pick-up tube, J. Appl. Physics 25, 1954, 240-242
46. COURT BROWN W. M., R. DOLL, Leukaemia and aplastic anaemia in patients irradiated for ankylosing spondylitis, Med. Red. Council Special Report 295, 1957
47. DIEMER G., H. A. KLASENS, J. G. VAN SANTEN, Solid State image intensifiers, Philips Res. Rep. 10, 1955, 401-424
48. DU BOULEY G. H. D. G. HALEY, Clinical use of a 12½-in-image intensifier, Proc. 3rd Int. Conf. Medical Electronics London 1960, 475-479
49. DUFFIEUX P. M., L'intégral de Fourier et ses applications à l'optique, Rennes 1946
50. DUGGAN H. E., G. L. OLDE, Radiation dose to the skin and the gonads from diagnostic x-ray procedures, Canad. Med. Ass. J. 89, 1963, 1144-1147
51. EDISON TH. A., Communication to Lord Kelvin, Nature 53. 1896, p. 470
52. EMBERSON D. L., A. TODKILL, W. L. WILCOCK, Further work on image intensifiers with transmitted secondary electron multiplication, Adv. in Electronics and Electron Physics 16, 1962, 567-579
53. EMBERSON D. L., The further development of a transmission type image intensifier, Trans. Inst. Radio Eng. N.S. 9, 1962, 107-114
54. EPP, E. R., Measurements of bone marrow and gonadal doses from x-ray examinations of the pelvis, hip and spine, Britt. J. Radiology 36, 1963, 247-265
55. FASSBENDER C. W., S. BAYINDIR, Bildqualität und Dosisleistung am Systemeingang beim Röntgenfernsehen im Vergleich zum elektronenoptischen Bildverstärker, Fortschritte Röntgenstrahlen 104, 1966, 560-566
56. FEDDEMA J., W. J. OOSTERKAMP, Volume doses in diagnostic radiology, Modern trends in diagnostic radiology, 1953, 35-42
57. FEDDEMA J., The quantitative ratio of requisite radiation to available information in different radiodiagnostic techniques, Medica Mundi 8, 1962, 116-121
58. FLINN E. A., Progress report on a channelled image intensifier, Advances in Electronics and Electron Physics 16, 1962, 155-162
59. FORQUE S. V., R. R. GOODRICH, A. D. COPE, Properties of some photoconductors, principally antimony trisulphide, R.C.A.-Review 12, 1951, 335-349
60. FORTUIN G., Light and vision, Medica Mundi 7, 1961, 3-13
61. FOUCAULT L., Mémoire sur la construction des téléscopes en verre argenté, Ann. de l'Observatoire Impériale de Paris 5, 1859, 197-237

62. FOWLER J. F., Solid state image intensifiers, Brit. J. Radiology 32, 1959, 455-463
63. FRANSEN J., Automation in x-ray diagnostics, Medica Mundi 5, 1959, 68-72
64. FRANZEN J., Die Strahlenexposition des Knochenmarkes bei Thoraxaufnahmen unter Berücksichtigung der Zellmarkverteilung, Fortschritte Röntgenstrahlen 99, 1963, 393-405
65. FRIK W., Detailerkennbarkeit und Dosis bei der Röntgendurchleuchgung, Hüthig Verlag, Heidelberg 1959
66. FRIK W., Röntgenfernsehen und Strahlenbelastung, Der Radiologe 5, 1964, 146-153
67. FROST D., Über die Bildunschärfe der Verstärkerfolien und Leuchtschirme, Röntgenblätter 10, 1957, 193-200, 234-254
68. GARLICK G. F. J., Recent developments in solid state image amplifiers, Adv. in Electronics and Electron Physics 16, 1962, 607-612
69. GARTHWAITE E., D. G. HALE, An x-ray image amplifier using an image orthicon camera tube, J. Brit. Inst. Radio Eng. 19, 1959, 615-522
70. GARTHWAITE E., X-ray image intensifiers using image orthicon tubes, Adv. in Electronics and Electron Physics, 12, 1960, 379-387
71. GARTHWAITE E., D. G. HALSEY, R. L. BEURLE, Television x-ray intensifier sensitivity, Proc. Inst. El. Eng. 110, 1963, 1975-1978
72. GARTHWAITE G. W., Ancillary equipment for use with image intensifiers, Brit. J. Radiology 34, 1961, 741-743
73. GEBAUER A., J. LISSNER, Das Röntgenfernsehen bei der Thorax- und Magen-Darm-Untersuchung, Der Radiologe 4, 1964, 116-121
74. GIBBONS D. J., The tri-alkali stabilized emitron, a new television camera tube of high sensitivity, Adv. in Electronics and Electron Physics 12, 1960, 203-218
75. GIRDANY B. R., E. S. GAITHER, Televex-tape-kinescopy and cineradiography, Radiology 79, 1962, 752-754
76. GOETZE G. W., A. TAYLOR, Recent applications of transmission secondary amplification, Adv. in Electronics and Electron Physics 16, 1962, 557-566
77. GRAND Y. LE, Les yeux et la vision, Dunod Paris 1960
78. GREATOREX C. A., Image intensification using a flying spot x-ray tube, Adv. in Electronics and Electron Physics 12, 190, 327-344
79. GREATOREX C. A., Image storing techniques applied to diagnostic radiology, Adv. in Electronics and Electron Physics 16, 1962, 593-600
80. GREATOREX C. A., Television techniques in diagnostic radiology, Phys. in Med. and Biol. 9, 1964, 1-24
81. GREGORIO G., Sull'intensificazione dell' imagine radiologia, La Radiologia Medica 49, 1963, 3-12
82. GUENTHER W. H., Aufzeichnung und Wiedergabe von Standbildern mit Folienspeichern, Rundfunkt. Mitt. 6, 1962, 106-110
83. GUNZ F. W., H. R. ATKINSON, Leukemia following irradiation, Radiology 82, 1964, 1067-1071
84. GUYOT L. F., Derniers développements sur les intensificateurs d'image, Adv. in Electronics and Electron Physics 16, 1962, 91-97
85. HAAN E. F. DE, Signal to noise ratio of image devices, Adv. in Electronics and Electron Physics 12, 1960, 291-306
86. HAAN E. F. DE, A. V. D. DRIFT, P. P. M. SCHAMPERS, Het plumblicon, een nieuwe televisie-opneembuis, Philips T.T., 25, 1963, 277-295
87. HADLEY C. P., R. W. CHRITSENSEN, Solid state image intensifiers under dynamic operation, R.C.A.-Review 20, 1959, 670-681
88. HALMSHAW R., Photographic aspects of the definition attainable in radiographs, J. of Photographic Science 12, 1964, 110-118
89. HAMMER-JACOBSON E., Radiation protection of personnel and patients in x-ray diagnostic departments, Radiography 27, 1961, 210-217
90. HAY G. A., X-ray image intensification using optical television methods, Adv. in Electronics and Electron Physics 12, 1960, 363-377
91. HAY G. A., The image orthicon in diagnostic radiology, Adv. in Electronics and Electron Physics 16, 1962, 581-591
92. HAY G. A., A physical assessment of the Cinelix 12-in electro-optical image intensifier in television fluoroscopy, Radiology 83, 1964, 86-91
93. HECHT S., The quantum relation of vision, J. Opt Soc. Am. 32 1942, 42-49

94. HEIMANN W., Fernseh-Bildaufnahmeröhren mit Widerstandsphotoschichten, Arch. d. elektr. Übertragung 9, 1955, 13-19
95. HEIMANN W., Möglichkeiten zur Verringerung der Nachwirkungserscheinungen bei Kameraröhren vom Typ Vidikon, Arch. d. elektr. Übertragung 13, 1959, 221-225
96. HEKKER F., On concentric optical systems, Thesis Delft 1947
97. HERSTEL W., Some experiences with x-ray image intensifiers and television channels, Adv. in Electronics and Electron Physics 16, 1962, 601-606
98. HERSTEL W., l'Analyse de l'image en radiodiagnostic télévisé, J. B. de Radiologie 46, 1963, 279-285
99. HERSTEL W., M. B. ROST VAN TONNINGEN, C. T. RUYGROK, La kinescopie en radiodiagnostic télévisé, J. B. de Radiologie 46, 1963, 1-7
100. HERSTEL W., Electronica ancilla medicinae, J. B. de Radiologie 46, 1963, 544-546
101. HERSTEL W., Vision and television in modern radiology, Radiography 34, 1968, 51-54
102. HERSTEL W., l'Influence de la position du tube de rayons-x sur la dose gonades et le rayonnement diffusé, Ann. de Radiologie 8, 1965, 87-91
103. HERSTEL W, Les extensions techniques de la vision humaine, J. B. de Radiologie 49, 1966, 107-109
104. HERSTEL W., Quelques aspects numériques de la formation de l'image en radiodiagnostic, Ann. de Radiologie 9, 1966, 391-395
105. HERSTEL W., The assessment of image quality in medical fluoroscopy, Adv. in Electronics and Electron Physics, 9, 1966, 363-368
106. HERSTEL W., Die Auswertung des Durchleuchtungsbildes mit bewegten Objekten, Röntgenblätter, -to be published
107. HERSTEL W., Neue Verfahren zur Beurteilung der Güte des Durchleuchtungsbildes, Fortschritte Röntgenstrahlen 104, 1966, 556-560
108. HERSTEL W., The observation of moving structures with x-ray image intensifiers, Adv. in Electronics and Electron Physics 1969, in press.
109. HEYNE L., P. SCHAGEN, H. BRUINING, Een experimentele opneembuis voor televisie met toepassing van fotogeleiding, Philips T.T. 16, 1954, 43-45
110. HEYNE L., The lead oxide vidicon, Acta Electronica 2, 1957, 124-131
111. HINE G. J., BROWNELL G. L., Radiation dosimetry, Academic Press 1963
112. HÖFERT M., Messung der Kontrastübertragungsfunktion von Röntgenverstärkerfolien, Acta Radiologica 1, 1963, 1111-1112
113. HOLLAENDER A., G. E. STAPLETON, Ionizing radiation and the living cell, Scientific American 203, 1959, 95-100
114. HOLM, T., Some aspects of radiographic information, Radiology 83, 1964, 319-327
115. HOLST G., J. H. DE BOER, M. C. TEVES, C. F. VEENEMANS, Transformation, of light of long wavelength into light of short wavelength, Physica 1, 1934, 297-305
116. JACOBS J. E., H. BERGER, Large area photoconductive x-ray pick-up tube performance, Electrical Engineering 75, 1956, 158-161
117. JANKER R., Die praktische und wissenschaftliche Verwendung der elektronischen Bildverstärkung und des Röntgenfernsehens, Fortschritte Röntgenstrahlen 88, 1958, 377-385
118. JANKER R., A. STANGEN, Kritische Überlegungen zum Röntgenfersehen mit dem Image-Orthikon und dem Vidikon, Fortschritte Röntgenstrahlen 96, 1962, 630-636
119. JOHANNSEN D. E., P. I. MCBRIDE, J. W. WULFECK, Studies on dark adaptation, J. Opt. Soc. Am. 46, 1956, 67-71, 266-269
120. JONES R. C., On the detective quantum efficiency of television camera tubes, J. Soc. Mot. Pict. and Television Eng. 68, 1959, 462-466
121. JONES R. C., Quantum efficiency of human vision, J. Opt. Soc. Am. 49, 1959, 645-653
122. KAZAN B., F. H. NICHOLL, Electroluminescent light-amplifying picture panel, Proc. Inst. Radio Eng. 43, 1955, 1888-1897
123. KAZAN B., E. W. GODFREY, Experimental results with the panel x-ray amplifier, Radiology 72, 1959, 855-862
124. KEANE B. E., G. SPIEGLER, Assessment of the dose to the gonads outside the diagnostic x-ray beam, Brit. J. Radiol. 34, 1961, 362-367
125. KELLER M., M. PLOKE, Sichtbarmachung von Röntgenbildern einer auf Röntgenstrahlen ansprechenden Fernsehaufnahmeröhre, Z. angew. Physik 7, 1955, 562-571

126. KLASENS H. A., The light emission from fluorescent screens irradiated by x-rays, Philips Res. Rep. 2, 1947, 68-78
127. KÜHL W., Durchleuchtung und Bildgüte, Bildgüte in der Radiologie, Fischer Verlag Stuttgart, 1966, 191-203
128. KUNZE W., Zur Frage der Trägheitserscheinungen in Fernsehaufnahmeröhren vom Vidikontyp, Hochfrequenztechnik und Elektroakustik 66, 1957, 84-89
129. KRAMERS H. A., On the theory of x-ray absorption and of the continuous x-ray spectrum, Phil. Mag. 46, 1923, 836-871
130. KROEBEL W., F. BELOW, Zum Problem der Bildgütecharakterisierung insbesondere von Fernsehbildern, Rundfunkt. Mitt. 1, 1957, 2-6
131. LANGENDORF H., M. A. REUSS, Über die Wirkung von Röntgenstrahlen verschiedener Wellenlänge auf biologische Objekte, Strahlentherapie 41, 1933, 655-662
132. LASNITZKI I., D. E. LEA, Variation with wavelength of the biological effect of radiation, Brit. J. Radiology 13, 1940, 149-161
133. LAWRENCE J. S., A. H. DOWDY, W. N. VALENTINE, Effects of radiation on hemopoiesis, Radiology 51, 1948, 400-413
134. LEUCUTIA T., Leukemogenic and cancerogenic effects of radiation, Am. J. Roentgenology 85, 1961, 989-994
135. LINFOOT E. H., Information theory and photographic images, J. of Photographic Science 7, 1959, 148-156
136. LUBZYNSKY H. G., S. TAYLOR. J. WARDLEY, Some aspects of vidicon performance, J. Brit. Inst. Radio Eng. 20, 1960, 323-334
137. MAKSUTOR D. D., New catadioptric meniscus systems, J. Opt. Soc. Am. 34, 1944, 270-284
138. MAYNEORD W. V., Radiation carcinogenesis, Brit. J. Radiology 41, 1968, 241-250
139. MASSENTI S., Il problema della dose somministra al paziente nella scopia televisica e nella roentgencinematografia, La Radiologica Medica 49, 1963, 449-453
140. MEDICAL RESEARCH COUNCIL, The hazards to man of nuclear and allied radiations, Special reports 1956 and 1960
141. MELLINK J. H., H. VERHOEF, Beschouwingen over de stralenbelasting van de patient bij röntgenonderzoek, Ned. T. v. Gen. 103, 1959, 1989-1998
142. MELLINK J. H., W. HERSTEL, Some measurements of integral absorbed dose in diagnostic radiology, Xth Int. Congress Radiology 1962
143. MELLINK J. H. De ontwikkeling van de dosimetrie der ioniserende straling, Inaugural Lecture, Leiden 1964
144. MELLINK J. H. Estimation of integral absorbed doses in diagnostic radiology, Radiologica Clinica (in press)
145. MERTZ P., T. GRAY, The theory of scanning and its relation to the characteristics of the transmitting signal in telephotography and television, Bell System Techn. J. 13, 1934, 464-515
146. MOON R. J., Fluoroscopic image amplification by means of a scanning x-ray tube, Science 112, 1950, 389-395
147. MORGAN R. H., R. E. STURM, The John Hopkins fluoroscopic screen intensfier, Radiology 57, 1951, 556-560
148. MORGAN R. H., The frequency response function, Am. J. Roentgenology 88, 1962, 175-186
149. MORGAN R. H., L. M. BATES, The frequency response characteristics of x-ray films and screens, Am. J. Roentgenology 92, 1964, 426-440
150. MORGAN R. H., Visual perception in fluoroscopy and radiography, Radiology 86, 1966, 403-416
151. MORTON C. A., J. E. RUEDY, C. L. KRIEGER, The brightness intensifier, R.C.A.-Review 9, 1948, 419-432
152. MOSELEY R. D., J. H. RUET, The reduction of patient dose by diagnostic radiologic instrumentation, Thomas Illinois 1964
153. MULDER J. D., Der elektro-optische Bildverstärker "Cinelix 12½" in der Praxis einer Universitätsklinik, Acta Medicotechnica 11, 1963, 147-150
154. MULLER H. J., Radiation and human mutation, Scient. Am. 193, 1955, 58-68
155. NAWIJN A., Kontrastübertragung und Qualität der Spiegelkamera für Röntgenschirmbildphotographie, Röntgenblätter 16, 1963, 227-231

156. NAWIJN A., Contrastoverdracht van optische systemen, Ned. Tijdschrift v. Natuurkunde 30, 1964, 183-193
157. NATIONAL BUREAU OF STANDARDS, Handbook 87, 1963, Clinical dosimetry (ICRU-report 10d)
158. NATIONAL BUREAU OF STANDARDS, Handbook 89, 1963. Methods of evaluating radiological equipment and materials (ICRU-report 10f)
159. NEMET A., W. F. COX, Intensification of the x-ray image in industrial radiology, Proc. Inst. El. Eng. 103 (B), 1956, 345-355
160. NOIX M., La télévision radiologique, Doin et Cie 1962
161. OLDE G. L., H. E. DUGGAN, Radiation dose to the skin and to the gonads from diagnostic x-ray procedures, Canad. Med. Ass. J. 89. 1963, 1144-1147
162. OOSTERKAMP W. J., T. TOL, Prinzipielle und praktische Grenzen der Detailerkennbarkeit bei verschiedenen röntgenologischen Betrachtungsmethoden insbesondere bei Verwendung der Bildverstärkerröhre, Fortschritte Röntgenstrahlen 81, 1954, 381-392
163. OOSTERKAMP W. J., The concept of absorbed dose and its measurement, Symposium quantities and units, Rome 1958
164. OOSTERKAMP W. J., Möglichkeiten zur Steigerung der Detailerkennbarkeit im Röntgenbild, Ärztliche Forschung 16, 1962, 122-129
165. OOSTERKAMP W. J., TH. G. SCHUT, Magnetische Speicherung von Röntgenbildern Elektromedizin 6, 1961, 147-152
166. PERUTZ M. F., Proteins and nucleic acids, Elsevier Publ. Cie 1962
167. PFAHNL A. P., Über Röntgenleuchtschirme und Verstärkerfolien, Röntgenblätter 10, 1957, 7-15, 52-57, 107-116, 135-146
168. PICCHIO C., Sul problema della riduzione della dose in roentgendiagnostica, La Radiologia Medica 49, 1963, 2-16
169. PIRENNE M. H., E. J. DENTON, Quanta and visual thresholds, J. Opt. Soc. Am. 41, 1951, 426-427
170. PIRENNE M. H., F. H. C. MARRIOTT, E. F. O'DOHERTY, Individual differences in the night-vision efficiency, Med. Res. Council, Special Report 294, 1957
171. RANBY P. W., An electroluminescent image retaining panel, Electrical Review, 112, 1964, 1-6
172. REINSMA K., Dosismeters voor het bepalen van de integrale dosis in de medische röntgendiagnostiek, Thesis Eindhoven 1960
173. RIEBEL F. A., Use of the eyes in x-ray diagnosis, Radiology 70, 1958, 252-258
174. RÖHLER R., Zur Messung der Kontrastübertragungsfunktion mit Rechteckgittern und anderen periodischen Lichtverteilungen, Optik 19, 1962, 487-497
175. RÖHLER R., Erklärung der Sehschärfe und der Kontrastschwellen für kleine Objekte aus den optischen Abbildungseigenschaften der Augenmedien, Optik 19, 1962, 519-534
176. RONNEN J. R. V., Over radiologie en radioloog, een waarschuwend woord en een pleidooi, Inaugural address Leiden 1956
177. RONNEN J. R. V., J. H. MELLINK, Röntgenstralen en vruchtbeschadiging, Ned. T. v. Gen. 107, 1963, 1412-1414
178. RONNEN J. R. V., Grenzen und Anwendungsbereiche der konventionellen Durchleuchtung, Bildgüte in der Radiologie, Fisher Verlag Stuttgart 1966, 313-321
179. RONNEN J. R. V., P. VIJLBRIEF, Our experiences with the rapid 70 mm filmcamera mounted on a 9-ich image intensifier, Medica Mundi 12, 1967, 9-18
180. RONNEN J. R. V., Toepassing van beeldversterking in de röntgendiagnostiek, Ned. T. v. Geneeskunde 110, 1966, 2168-2171
181. RONNEN J. R. V., Bewegungsstudien mit Röntgenstrahlen, die verschiedenen Methoden der Durchleuchtung. Communication: Symposion über Bildgüte in der Radiologie, Herrenchiemsee 1967
182. ROSE A., Quantum efficiency and human vision, Adv. in Biol. and Med. Physics 5, 1957, 211-242
183. ROSSMANN K., G. LUBBERTS, H. M. CLEARE, Measurements of the line spread function of radiographic systems containing fluorescent screens, J. Opt. Soc. Am. 54, 1964, 187-190
184. SANCHES H., Het meten van de integrale dosis in de röntgendiagnostiek, Thesis Leiden 1961

185. SCHAAL A., Messungen der Integraldosis bei Diagnostikspannungen, Fortschritte Röntgenstrahlen 99, 1963, 406-410
186. SCHADE O. H., Electro-optical characteristics of television systems, R.C.A.-Review 9, 1948, 5-37
187. SCHADE O. H., Image gradation, graininess and sharpness in television and motion picture systems, J. Soc. Motion Picture and T.V. Eng. 56, 1951, 137-177; 58, 1952, 181-222; 61, 1953, 97-164; 64, 1955, 593-617
188. SCHMIDT B., Ein lichtstarkes komafreies Spiegelsystem, Mitt. d. Hamburger Sternwarte 7, 1932, 15-17
189. SCHOTT O., Bildqualität und Dosisprobleme beim Röntgen-Fersehen, Röntgenblätter 15, 1962, 181-190
190. SCHOTT O., Der Folienspeicher für Röntgen-Fernsehdiagnostik, Röntgenblätter 16, 1963, 65-72
191. SCHUT TH. G., W. J. OOSTERKAMP, The application of electronic memories in radiology, Medica Mundi 5, 1959, 85-88
192. SEYLER A. J., An x-ray television system with image storage and automatic exposure release, J. Brit. Inst. Radio Eng. 24, 1962, 229-240
193. SCHOBER H., Untersuchungen über die Verwendbarkeit des Landoltschen Ringes als Normzeichen bei der Sehschärfebestimmung, Optik 9, 1952, 277-290
194. SCHOBER H., Informationstheorie in Optik und Fernsehen, Optik 13, 1956, 350-364
195. SCHOBER H., M. HÖFERT, Die Anwendbarkeit der in der Optik gebräuchlichen Kontrastübertragungs- und Informationstheorie auf die Abbildung mit Röntgenstrahlen, Acta Radiologica, 1, 1963, 1179-1188
196. SHANNON C. E., W. WEAVER, The mathematical theory of communication, Univ. Illinois Press 1949
197. SLARK N. A., A. J. WOOLGAS, Transmission secondary image intensifiers, Trans. Inst. Eng. N.S. 9, 1962, 107-114
198. SOBELS F. H., De betekenis van de stralengenetica in de tegenwoordige samenleving, Ned. T. v. Gen. 46, 1963, 2151-2158
199. SOMMER A. H., New photo-emissive cathodes of high sensitivity, Rev. Scient. Instr. 26, 1955, 725-725
200. SOUTHALL P. C., Introduction to physiological optics, Dover Editions 1961
201. SPIERS F. W., Measurements of the gonadal dose in the medical use of x-rays, Physics in Med. and Biol. 2, 1967, 152-156
202. STAHNKE I., H. HEINRICH, Die Modulations-Übertragungs-Funktion einer elektronenoptischen Röntgen-Bildverstärker-Röhre, Optik 23, 1966, 251-267
203. STEWART A., W. PENNYBACKER, R. BARBER, Adult leukemias and diagnostic x-rays, Brit. Med. J. 2, 1962, 882-890
204. STURM R. E., R. H. MORGAN, Screen intensification systems and their limitations, Am. J. Roentgenology 62, 1949, 617-634
205. STÜRMER W., Some applications of solid state image converters, Adv. in Electronics and Electron Physics 16, 1962, 613-619
206. STRUTT J. W., (Lord Rayleigh) Investigations in optics, with special reference to the spectroscope, Scientific Papers Cambridge University Press 1, 1899, 415-459
207. TEVES M. C., T. TOL, Elektronische versterking van röntgenbeelden, Philips T.T. 14, 1952, 65-92
208. TEVES M. C. e.a., Toepassingen van röntgenbeeldversterking, Philips T.T. 17, 1955, 65-100
209. TOL T., W. J. OOSTERKAMP, J. PROPER, Limits of detail perceptibility in radiology particularly when using the image intensifier, Philips Res. Rep. 10, 1955, 141-157
210. TUDDENHAM W. J., The visual physiology of roentgen diagnosis, Am. J. Roentgenology 78, 1957, 116-123
211. TREWIN R. B., Ionizing radiation as an industrial health problem, Canad. Med. Ass. J. 90, 1964, 20-23
212. TUUK J. H. V.D., W. KÜHL, A new x-ray image intensifier with 9-in screen, Medica Mundi 5, 1959, 47-51
213. UNITED NATIONS, Reports of the Scientific Committee on the effects of atomic radiation, New York 1958 and 1962
214. VELDEN H. A. V.D., The number of quanta necessary for the perception of light of the human eye, Opthalmologica 111, 1946, 231-331

215. VENDRIK A. J. H., E. EYKMAN, Toepassing van de detectietheorie op zintuiglijke waarneming, Ned. T. v. Natuurk. 29, 1963, 269-286
216. VINE B. H., R. B. JANES, F. S. VEITH, Performance of the vidicon television camera tube, R.C.A.-Review 7, 1951, 3-10
217. VOS J. J., A. LAZET, M. A. BOUMAN, Visual contrast in practical problems, J. Opt. Soc. Am. 46, 1956, 1065-1068
218. VRIES H. de, The quantum character of light and its bearing upon threshold of vision, differential sensitivity and visual acuity of the eye, Physica 10, 1943, 553-564
219. VRIES H. de, Light quanta and vision, Revue d'Optique 28, 1949, 101-104
220. VIJVERBERG G., Fluoroscopy and recording via an x-ray image intensifier providing detail enlargment, Medica Mundi 11, 1966, 106-109
221. WEBER J., Beenmergdosis tengevolge van de röntgendiagnostiek, Thesis Leiden 1964
222. WEBSTER E. W., R. WIPFELDER, Limitations of combined image amplifier-television systems for medical fluoroscopy, Trans. Inst. Radio Eng. BME 9, 1962, 150-155
223. WEIMER P. K., S. V. FORQUE, R. R. GOODRICH, The vidicon, a photoconductive camera tube, Electronics 23, 1950-70-73
224. WEISS J. H., Large field cineradiography and image intensification using the TVX-system, Radiology 76, 1961, 264-266
225. WINTER H. G. de, Zur Optimalisierung der Kontrastübertragung des Schirmbildes, Röntgenblätter 16, 1963, 1-4
226. WISE M. E., The latent period and its variation in human leukaemia induced by x-rays, Health Physics 4, 1961, 250-266
227. WISE M. E., Human radiation hazards, Rendiconti Soc. Ital. di Fisica 1961, 450-492
228. WOLFSON J. L., C. GARRETT, Gonadal exposure to adults in diagnostic radiography, J. Canad. Ass. Radiologists 10, 1959, 60-66
229. ZIELER E., Untersuchungen zur Bestimmung der Integraldosis in der Röntgendiagnostik, Fortschritte Röntgenstrahlen 94, 1961, 248-260
230. ZWORYKIN V. K., G. A. MORTON, Television, the electronics of image transmission in color and monochrome, Wiley New York 1954, 236-265

SAMENVATTING

Bij de röntgendoorlichting wordt steeds gezocht naar een compromis tussen de kwaliteit van het beeld en de stralingsdosis die nodig is om dat beeld te verkrijgen. De samenhang tussen deze grootheden is hier numeriek bestudeerd met hulpmiddelen, die ontleend zijn aan de elektronica en de optica. Deze samenhang wordt niet slechts beinvloed door technische factoren, maar ook door natuurlijke beperkingen zoals de quantenfluctuaties van röntgenstraling en de eigenschappen van het oog. Verschillende methoden van röntgendoorlichting worden besproken, waarbij speciaal aandacht wordt geschonken aan de toepassing van beeldversterking en televisie bij de doorlichting. De bepaling van de beeldkwaliteit berust op metingen van de conversie-factor, de modulatie-overdracht van ruimte-en tijdfrequenties en de visuele waarneming van kleine objecten, die op een niet te voorspellen wijze bewegen. Aan de hand van eenvoudige metingen wordt de vervorming van de modulatie-overdrachtsfunctie gedemonstreerd. De resultaten van een groot aantal stralingsmetingen, verricht tijdens radiologische onderzoeken, worden vermeld. Metingen van de strooistraling werden uitgevoerd aan een fantoom, aan het levende en het dode lichaam. Ten slotte worden er aanbevelingen gegeven om een optimale beeldinformatie te verkrijgen bij minimale stralingsdoses.

ZUSAMMENFASSUNG

Bei der Röntgendurchleuchtung sucht man immer nach einem Kompromiss zwischen der Qualität des Bildes und der dazu erforderlichen Strahlendosis. Hier wird der Zusammenhang dieser zwei Gröszen untersucht und zahlmässig angegeben. Die Messmethoden entsprechen gebräuchlichen Methoden der Elektronik und der Optik. Der Zusammenhang ist nicht nur durch technische Faktoren alleine gegeben, sondern zusätzlich auch durch die Quantenfluktuation der Röntgenstrahlung und die Eigenschaften des menschlichen Auges bedingt. Es wird ein Überblick gegeben über die üblichen Durchleuchtungsmethoden. Im speziellen wird die Anwendbarkeit der Bildverstärkung und des Fernsehens in der Röntgendurchleuchtung betrachtet. Die Bildgüte wird aus der Modulations-Übertragungs-Funktion von Raum-und Zeitfrequenzen und der Konversions-Funktion bestimmt und auch aus der visuellen Beobachtung von Details, die sich in einer unvorhersehbaren Weise bewegen. An der Hand einfacher Messungen wird gezeigt, wie die Modulations-Übertragung durch technische Faktoren vermindert wird. Es werden die Resultate von in praktischen Situationen ausgeführten Dosismessungen mitgeteilt. Streustrahlungsmessungen wurden an einem Phantom und am lebenden und toten Körper durchgeführt. Es werden Empfehlungen zur Erzielung einer optimalen Bildinformation bei kleinstmöglichen Strahlendosen gegeben.

SUMMARY

In x-ray fluoroscopy a compromise is always sought between the quality of the image and the radiation dose required to obtain that image. The relationship between these two quantities is examined here on a numerical basis by methods derived from electronics and optics. This relationship is not only influenced by technical factors, but also by natural limits such as the quantum fluctuations of the x-radiation and the properties of the human eye. The usual methods of x-ray fluoroscopy are reviewed. Special attention is paid to the application of image intensification and of television in fluoroscopy. The determination of the image quality is based on the measurement of the conversion function, the modulation transfer function of space and time frequencies and the visual perception of small objects which move in an unpredictible way. The deterioration of the modulation transfer curve due to technical factors is shown in a simple geometric model. The results are given of a great number of dose measurements in practical situations. Measurements of stray radiation have been carried out on a phantom, on the living and the dead body. Recommendations are given for the achievement of optimal information at minimal radiation doses.

RÉSUMÉ

Dans la radioscopie on cherche toujours un compromis entre la qualité de l'image et la dose de radiation, qui est nécessaire pour obtenir cette image. La relation entre ces deux quantités est examinée ici et exprimée d'une façon numérique, en utilisant des méthodes dérivées de l'électronique et de l'optique. Cette relation n'est pas seulement influencée par des facteurs techniques, il y a d'autres facteurs imposant des limites importantes comme la fluctuation quantique de la radiation-x et les caractéristiques de l'oeil humain. Un aperçu est donné des méthodes radioscopiques. L'application de l'amplification de de brillance et de la télévision est considerée tout particulièrement. La qualité de l'image est determinée ici par la mesure de la fonction de conversion et le transfert de la modulation de fréquences spatiales et temporaires et par la perception visuelle de détails, dont le mouvement est imprévisible. On montre la détérioration du transfert de la modulation causée par des facteurs techniques dans une géométrie simple. On donne les résultats d'un grand nombre de mesures de la dose de radiation dans des applications pratiques. Des mesures de la radiation ambiente sont faites sur un fantôme et sur le corps humain vivant ou non. Des récommandations sont données pour obtenir une image d'information optima pour des doses minima.

CURRICULUM VITAE

In accordance with the wishes of the Faculty of Mathematics and Science of the University of Leiden, a short account here is given of the author's education and career.
He was born in Eindhoven in 1929 where he grew up, and attended the Municipal Grammar School obtaining the diploma in 1947 and later the Technical College obtaining the diploma in 1950. During the next two years he fulfilled his national service where he attended the Reserve Officer's Training College of the Corps of Signals and worked in a telecommunications section.
From October 1952 until January 1957 he studied at the Technological University at Delft. He passed the propaedeutics examinations in 1953, the candidate's examination in 1955 and the doctoral examination in electrical engineering in 1957. The final research work for the diploma was done under the guidance of Prof. Dr. Ir. G. H. Bast on data transmission in carrier frequency channels.
Because of his special interest in the applications of physics and engineering to biology and medicine, he followed some of the basic courses in the Faculty of Medicine at the University of Leiden in the period between 1957 and 1959.
From 1957 until 1959 he worked at the Electronics Laboratory at Delft as an assistent of the University Research Fund and under the supervision of Prof. Ir. L. H. M. Huydts, on the application of semiconductors in medical electronics.
Since June 1959 the author has been working at the Institute of Radiopathology and Radiation Protection in Leiden. In this connection he works under the direction of Prof. Dr. J. R. von Ronnen and Dr. J. H. Mellink in the Department of Radiology of the University Hospital. His main involvement besides teaching is the research and development of methods in radiation protection and medical radiology.
This study, on the limitations of fluoroscopy due to physical and technical causes, arose from practical problems concerning image-dose relationships in radiology.

Stellingen bij het proefschrift

van W. Herstel, 1968

I

Het door Lord Rayleigh aangegeven kriterium voor het oplossend vermogen dient niet te worden gebruikt voor de evaluatie van radiologische systemen.

J. W. Strutt, Scientific Papers 1899, 415

II

De circulaire polarisatie van gammastraling kan worden gemeten met een analysator van het transmissietype. Het door Steffen en Frauenfelder gepubliceerde rendement van een dergelijke analysator is onjuist.

R. H. Steffen e.a., Gamma Ray Spectroscopy, 1965, 1459
M. Goldhaber e.a., Phys. Rev. 1957, 826

III

Bij juridische geschillen tussen werkgever en werknemer inzake stralingsschade dient de bewijslast te drukken op de eerstgenoemde. Het is hiertoe mede noodzakelijk, dat de dosimetrische stralingseenheden een internationaal wettelijk gefundeerde basis krijgen.

IV

Het door McCracken en Maple gekozen mechanisme ter verklaring van de door hen berekende diffusiecoëfficiënt van waterstof in molybdeen is onjuist.

G. M. McCracken e.a. Brit. J. Appl. Phys. 1967, 919
L. H. James e.a., Brit. J. Appl. Phys. 1964, 681

V

Als oorzaak van de vermindering der gezichtsscherpte bij verlaging van de beeldhelderheid moet het toenemen van de onwillekeurige oogbewegingen mede worden aangemerkt.

J. L. Brown, J. Opt. Soc. Am. 1953, 197; 1954, 48

VI

Het is onjuist om personen bloot te stellen aan röntgenstraling alleen met de bedoeling de kwaliteit van het beeldvormende systeem te beoordelen.

VII

Om in een bundel-plasma systeem instabiliteiten met frequenties in de buurt van de ionenplasmafrequentie te bestuderen, heeft het voordelen een systeem te gebruiken met kleine radiale afmetingen.

A. Vermeer, T. Matitti, H. J. Hopman,
J. Kistemaker, Plasma Phys. 1967, 241

VIII

Snelheidsmeters in voer- en vaartuigen dienen geijkt te zijn in meter per seconde.

IX

Het niet nauwkeurig definiëren van het begrip lijnbreedte kan leiden tot verwarring bij het vergelijken van door middel van spectrografie verkregen meetresultaten.

R. W. Pohl, Optik und Atomphysik, 1963
C. P. Poole, Electron spin resonance, 1967
F. M. Johnson, Phys. Review 1959, 705

X

Het is onjuist de fysische beperkingen van ten behoeve van thermografie gebruikte of te gebruiken infrarood-detectoren slechts te baseren op het met de ruis equivalente vermogen.

J. Houghton, S. D. Smith, Infrared Physics 1966

XI

Samenwerking tussen universitaire en industriële laboratoria, waar gewerkt wordt op het gebied van de medische fysica en/of de medische techniek, dient te worden bevorderd met erkenning van het eigen karakter van elk dezer instellingen.

XII

De door Finean en Vandenheuvel gepostuleerde structuurmodellen voor de opbouw van biomembranen kunnen wellicht beide hun waarde behouden. Het model van Finean past meer bij membranen opgebouwd uit lipiden met kortere vetzuren met veel dubbele bindingen en dat van Vandenheuvel sluit beter aan bij een membraanopbouw, waarin vetzuren voorkomen met langere en meer verzadigde ketens.

J. B. Finean, Circulation, 1962, 1151
F. A. Vandenheuvel, J. Am. O. Chem. Soc. 1963, 455

XIII

Het is misleidend de veiligheid van het luchtverkeer te illustreren aan de hand van de verhouding van het aantal in een bepaalde periode per vliegtuig verongelukten en de som van de gedurende dezelfde tijd door de lucht afgelegde afstanden.

XIV

Aan het roemruchte verhaal van heer Bommel zijn nog veel meer stellingen voor proefschriften te ontlenen.

W. J. Berger, Proefschrift Nijmegen 1968, st. 15
C. C. Veerman, Proefschrift Delft 1968, st. 6
H. H. Frese, Openbare Les Leiden 1968, 18, 19

[illegible]
mogen dient niet te worden gebruikt voor de evaluatie van radiologische systemen.

[illegible] 1968, [illegible]

De circulaire polarisatie [illegible] kan worden gemeten met een analysator [illegible] Steffen en Frauenfelder gepubliceerde [illegible] is gegeven.

R. H. Steffen e.a., [illegible] 1965, [illegible]
M. Goldhaber e.a., Phys. Rev. 1958, 109

Bij juridische geschillen tussen werkgever en werknemer inzake stralingsschade dient de bewijslast te [illegible] op de [illegible]. Het is hiertoe mede noodzakelijk, dat de dosimetrische stralingsstandaarden een internationaal wettelijk gefundeerde basis krijgen.

Het door McCracken en Maple gegeven mechanisme ter verklaring van de door hen berekende diffusiecoëfficiënt van waterstof in molybdeen is onjuist.

[illegible] beschikbaarheid moet het toestaan [illegible]
mede worden [illegible]

[illegible]

Om in een bundel-plasma systeem instabiliteiten met frequenties in de [illegible]
van systeem te gebruiken met kleine [illegible]

[illegible] H. J. Hopman, [illegible]
[illegible] 1967, [illegible]