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EXPLORING DEPENDENCE OF THE PATINTS' RADIATION DOSE ON THE FORM OF POWER SUPPLY VOLTAGE OF X-RAY TUBE

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Описано методику та результати дослідження впливу форми напруги живлення рентгенівського випромінювача на загальну дозу опромінення пацієнтів під час виконання медичних обстежень. Надано результати експериментальних вимірів, описано алгоритм розрахунку дози опромінення, проведено порівняльний аналіз дозового навантаження на пацієнтів при використанні різних видів джерел живлення та аналіз ефективності модернізації існуючого рентгенівського обладнання

Ключові слова: чисельне моделювання, еквівалентна доза опромінення, медичні рентгенівські обстеження, джерела живлення

Описаны методика и результаты исследования влияния формы напряжения питания рентгеновского излучателя на общую дозу облучения пациентов во время выполнения медицинских обследований. Приведены результаты экспериментальных измерений, описан алгоритм расчета дозы облучения, выполнен сравнительный анализ дозовой нагрузки на пациентов при использовании различных видов источников питания и анализ эффективности модернизации существующего рентгеновского оборудования

Ключевые слова: численное моделирование, эквивалентная доза облучения, медицинские рентгеновские исследования, источники питания

1. Introduction

In modern medicine, one of the most common and important methods of diagnosis is the X-ray study. According to experts' estimations, establishing of more than 80 % of the diagnoses that require serious medical intervention is performed using X-ray images, results of roentgenoscopy and X-ray tomography. X-ray images are the main tool for the

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diagnosis and control of the process of treatment in traumatology. But in addition to the urgent practical examinations, in Ukraine there are also preventive X-ray examinations, conducted with the aim of timely detection of diseases of the respiratory system (active tuberculosis and its residual changes, malignant neoplasms, as well as non–specific lung diseases), mediastinum, skeleton of the chest cavity [1]. Preventive screening is nowadays one of the most effective and widely used tools as part of the measures for combating tuberculosis in Ukraine, which is one of the priority directions of the state policy in the sphere of health and social development [2]. With high informativeness of X-ray studies, they have an essential shortcoming: establishment of diagnosis is impossible without radiation impact on the patient. X-ray tube is the source of artificial ionizing gamma-radiation and thus the X-ray diagnostic methods always increase the probability of the patient's body damage because of radiation exposure.

According to experts, from 40 % to 60 % of the total dose of ionizing radiation is received by the Earth's population annually during medical diagnostic tests and therapeutic procedures that are performed with the use of ionizing radiation sources and their share continues to grow [3]. Therefore, there exist relevant problems of finding ways to reduce the radiation dose of population from artificial sources of radiation used in medicine [4].

A big share of radiodiagnosis in the formation of collective dose of radiation of population from artificial sources of ionizing radiation is about 75 % [5]. Along with the increase in the sensitivity of devices for registration of X-ray image, the reduction in these indicators is promoted by the use of modern X-ray devices with high-frequency power supply units because in the spectral structure of radiation in this case, the content of low-energy X-ray radiation substantially reduces, which is mostly absorbed by the body of a patient and does not provide valuable diagnostic information.

2. Literature review and problem statement

The problem of reducing specific weight of medical radiodiagnosis in the formation of collective radiation dose of the population due to artificial sources of ionizing radiation has been actively examined by both scientific and research and medical institutions and individual scientists. X-ray methods imply an appropriate choice of operating parameters as a function from the characteristics of patients in order to ensure minimum dose at adequate quality of the image that meets the purpose of examination and has a good signal/noise ratio [6]. To denote the optimization of X-ray doses, it is accepted to use the acronym ALARA that stands for "As Low As Reasonably Achievable" but the most relevant in radiology is the acronym ALADA – "As Low As Diagnostically Acceptable" [7]. There are different approaches to address this issue. Thus, for example, there are continuous efforts to design algorithms and programs for processing digital images that provide the capability to separate noises and improve quality of the images [8]. But a large segment of research is devoted to preliminary calculation, account and measurement of radiation doses received when using already available X-ray equipment and tools of the image processing. For example, there was proposed a design of new universal radiation metrics that could be used just as easily as the uniform metrics of length or temperature. The work is underway on developing biological indicators of radiation doses and standards of biological dosimetry [9]. In addition, there were proposals to use, as an alternative to physical metrics of a dose, tools and techniques, adapted for fast and reliable assessment of the quality of X-ray images [10] to prevent ineffective increase in the dose. Much attention is paid to the transition from the measured empirically [11, 12] or calculated by numerical methods [13, 14] dose of representative homogeneous [15, 16] and anthropomorphic [17, 18] phantom to the dose of a particular patient. In addition to the design and application of the systems for tracking the history of radiation exposure of a patient [19], optimization of other technical and clinical factors also significantly reduces the patients' and medical staff dose [20]. Thus, lower patients radiation doses can be achieved by implementation of the programs of quality control of dose-forming parameters of X-ray devices and technology of radiographic procedures. Optimization of modes of research and timely elimination of identified deviations in technical parameters from nominal values will contribute to lowering the doses of radiation while maintaining required quality of the diagnostic information [11]. But the difficulty of establishing norms is that the incoming surface dose at the same type of research substantially varies depending on the type of the medical device, its technical condition, geometrical parameters of particular patient and exposure options that the staff set according to their professional skills. But in addition to the state regulation of quality control, development of normative and methodical documents, systems of account of the received doses by each patient and improvement in the qualifications of medical personnel [21, 22], to ensure the desired level of radiation safety in medical X-ray diagnosis of Ukraine, it is necessary to pay more attention to the acceleration of the process of modernization of available X-ray devices to the modern level and the introduction of digital technologies with the ultra-low levels of patients' dose (in particular, scanning, using the lines of semiconductor sensors of ionizing radiation) [23].

The prospects of introduction in the practice of X-ray diagnosis units of "high voltage equipment" during radiographic examination of organs of the chest and the possibility of reducing the patients' radiation dose in this way is discussed in papers [24, 25].

One of possible cost-effective ways of solving the problem of quality of X-ray images, as well as reducing patients' and medical staff equivalent dose, is the application of methods to power X-ray emitters, which provide high stability of parameters and improved form of power voltage [26]. Improving operational parameters of the outdated X-ray equipment is possible through its modernization under condition of preservation and further use of the most expensive high-voltage part of the devices. For Ukraine such an approach is fairly relevant. According to the Committee on Nuclear Regulation of Ukraine, medical establishments use more than 72 % of the obsolete therapeutic and diagnostic equipment [27, 28], which cannot warrant stability of the parameters of irradiation. General condition of the entire X-ray equipment has not improved in recent years, much to our regret.

The X-ray equipment that is used to conduct medical examinations of the population includes power units of X-ray emitters. They differ from each other by the principle of operation and the form of output voltage. When using each of these devices, there is a particular spectrum of X-ray radiation formed that directly affects the patient's equivalent dose. To assess the expediency and prospects of modernization of the outdated equipment, it is necessary to conduct analysis of the influence of the form of power voltage of X-ray emitter on the dose of radiation of patient under condition of obtaining X-ray images of the same (maximum close) quality. Unfortunately, Authors of the article failed to find systematized results of such studies.

3. Aim and tasks of the study

The purpose of this study was to determine the influence of the form of output voltage of power units on the equivalent dose of radiation that the patient receives, under condition of creating X-ray images with the same degree of image quality when applying power units that are most often used in medical practice.

To accomplish the set goal, it was necessary to solve the following tasks:

– experimental clarification of emission characteristics of X-ray tube and construction of volt-ampere characteristics with the purpose of their further use for the calculation of operating modes of the emitter at different values of the anode voltage;

– construction of experimentally tested dependency of the rate of exposure dose of radiation in direct beam on the level of high voltage, normalized by the magnitude of the anode current of X-ray tube, with regard to the scattered radiation and all geometrical and physical parameters of X-ray device;

– removal of dependence of the optical output of X-ray converting screen on the operating parameters of X-ray emitter;

– construction of mathematical model for the process of X-ray exposure execution for different types of power sources of X-ray emitter;

– calculation of exposure characteristics of the emitter when using different types of power sources for further comparative analysis of patient's equivalent dose.

4. Materials and methods of research into effect of the form of power voltage on a patients' equivalent dose of radiation

One of the most important conditions for obtaining quality and informative X-ray image is the provision of exposure dose, which corresponds to the dynamic range of X-ray image recorder. Thus, for example, when producing radiography on photographic film, it is necessary to provide such minimum level of blackening of the photographic emulsion so that against the general background of the picture there were clearly distinguishable bright shadow zones that are created by the absorption of X-ray radiation by the more dense tissues of the patient's organism. There are similar requirements in relation to modern digital receivers of X-ray images. It should be noted that in both the first and the second cases, initial image is formed due to the fluorescent glow of X-ray converting screen, which is placed behind the object of study.

The basis of comparative analysis is the calculation of integral exposure dose, acting on the patient's body when using different power supply units of X-ray emitter, under condition of obtaining the same integral optical output of light energy from X-ray converting screen that is located in the input plane of the image recorder.

For the construction of mathematical model and conducting calculations, we require a number of characteristics, on the basis of which we will calculate the operating modes of the emitter in an arbitrary point in time.

To minimize an instrument error and to simplify further calculations, it is advisable to perform all measurements for the comparative analysis using the same equipment, namely:

– X-ray radiation recording device;

– the X-ray emitter;

– design elements of the device that directly affect the level of scattered radiation as it also contributes to the formation of total dose.

4. 1. Clarification of volt-ampere characteristics of X-ray tube

Using power supply units of different types, the formation of voltage on the electrodes of the X-ray tube occurs since the power devices are primarily the voltage sources. Current that flows through the X-ray tube is the result of cathode thermal emission, and its instantaneous value depends both on the instantaneous value of voltage between anode and cathode and the temperature of the cathode. Emission capacity of cathode and anode, and, accordingly, the anode current value, is regulated by changing current of cathode filament. The higher is the current flowing through the cathode filament, the higher the temperature of the cathode is, and the higher current will pass in the anode circle of X-ray tube. The time constant of thermal processes of the cathode is a few tenths of a second, so with fixed current of filament, temperature of the cathode can be considered unchanged over the entire time of X-ray exposure regardless of the form of power voltage of both the X-ray tube and the cathode filament itself. But to compute the instantaneous and the current values of the anode current, it is necessary to have the families of emission or volt-ampere characteristics of the X-ray tube. The former are provided in a standard form in the passport of the tube, but only for the working range of voltages from 40 to 150 kV that do not make it possible to perform calculation of the operating modes of emitter when decreasing the voltage below the level of 40 kV, for example, in the case of power supply from pulse voltage of low frequency. That is why the first objective of the study was practical clarification of characteristics of the X-ray tube that was used in subsequent experiments.

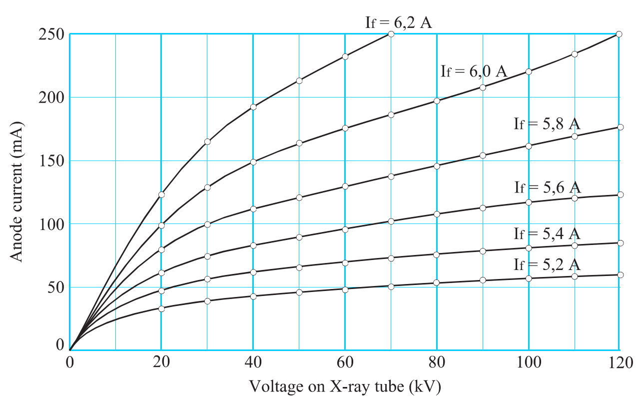

Fig. 1. Family of volt-ampere characteristics of X-ray tube

Fig. 1 demonstrates a family of volt-ampere characteristics of X-ray tube 20-50BD22-150 that operates with the cathode of small focus. In the range of voltages from 20 to 120 kV the curves are built based on experimentally obtained data for different values of current of the cathode filament. For lower voltages, characteristics are extrapolated randomly since the low energy X-ray radiation generated in this range is almost completely absorbed by the output aluminum filter of the emitter and, therefore, errors of extrapolation will not affect both the calculation of the total exposure dose and integral brightness of the screen.

4. 2. Other experimental data used in calculation

For consequent modeling and calculation of integral radiation dose, it is necessary to have a dependence of exposure dose power on the level of voltage at the emitter in the plane of the patient's location, normalized per unit value of the anode current of X-ray tube. Performing the calculation of such a dependence is quite difficult because the formation of total exposure dose is affected not only by the level of anode voltage but by spectral composition of radiation that depends on the voltage and by the intensity and spectral characteristics of scattered irradiation, which also depend on the voltage and geometry of location of the design elements of X-ray device.

In addition, for estimation of response of the converting screen of receiver of X-ray image to the stream of X-rays that has passed through the body of the patient, it is necessary to have characteristic of its sensitivity that would meet the criteria of real conditions of medical examination.

The required characteristics were obtained experimentally using high-frequency power supply unit IEC-F7, 12 kW power [29]. Measurements were carried out at different levels of voltage at the anode current of 100 Ma and exposure duration of 0.1 second. Simulation of the patient's body was performed by a water phantom with a layer of water of 150 mm, behind which a fragment of the X-ray sensitive converting screen was placed with a specially designed electronic recorder, which with the help of highly sensitive photodiode registered brightness of the flash of the screen. Before the experiment, we conducted a number of additional studies that confirmed the linearity and conformity of the recorder's sensitivity with the range of exposure power in the course of performing main measurements. We also calculated the magnitude of relative error, which does not exceed 2 %.

The obtained experimental data were averaged by the results of four measurements in order to reduce the influence of random errors, and approximated by means of linear functions. The coefficients of approximating straight lines were calculated by the criterion of minimizing the standard deviation, which in the final results did not exceed 1.6 %. The overall form of the obtained dependences is represented in Fig. 2, 3.

At the values of voltage 120 kV, simultaneously we carried out measurements of exposure dose, on the basis of which we built dependence, which is also fairly well approximated by a straight line (dotted line in Fig, 2). The measurement of exposure dose was carried out with the help of the dosimeter of X-ray range DKR-04M, whose detector was installed at a distance of 400 mm from the output window of emitter in the zone of phantom's location.

The linearity of the obtained characteristics and dynamic parameters of signals, registered by oscilloscope, demonstrated the possibility to use a photo recorder for measuring the integral light reaction of the converting screen on the X-ray radiation at different forms of supply voltage and the values of the anode current.

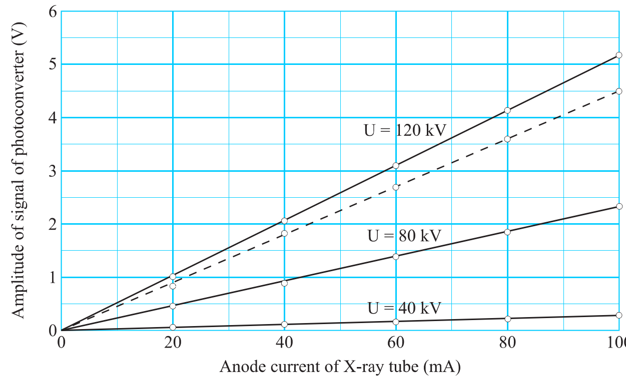

Fig. 2. Dependence of amplitude of the output signal of photo recorder on the anode current at different values of voltage on X-ray tube

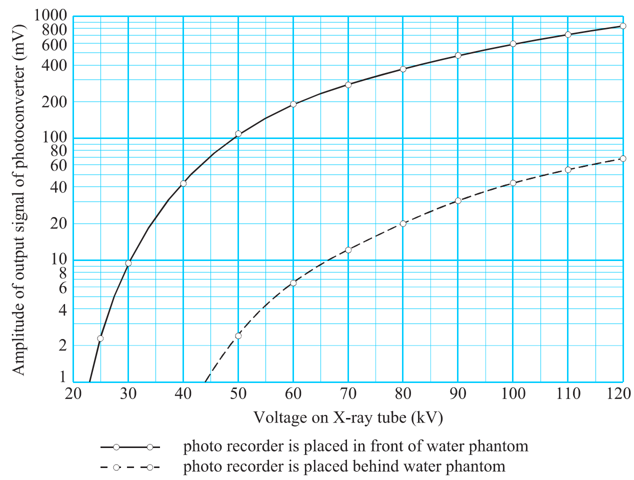

Fig. 3. Dependence of amplitude of output signal of photo recorder on the voltage on X-ray tube at its various positions

Dotted line in Fig. 3 shows dependence of the amplitude of signal of photo recorder, which is located in the input plane of receiver of X-ray image on the level of high voltage. It characterizes brightness of the flash of luminescent coating and is the base for calculation of the integral light response of the screen for the duration of exposure at various methods of power supply to the emitter.

4. 3. Numerical simulation

The basis of numerical analysis is the series of experimentally-derived dependences.

First, these are the emission characteristics of X-ray tube that are refined and expanded in the zone of low voltages by means of conducting additional experiments, and the families of volt-ampere characteristics of the X-ray tube constructed on their base.

Second, the calculations are based on the experimental dependence of exposure dose power in a direct beam of radiation on the level of high voltage supplied to the tube.

Third, in the course of calculations we use dependence of brightness of the glow of converting screen, which is one of the main structural elements of digital receivers of X-ray images, on the high voltage level on X-ray tube.

The analysis was conducted for four types of X-ray power supply sources, which differ by the operating principle and the form of output voltage that is applied to the tube (Fig. 4). Along with constant voltage, the calculations were carried out for a sinusoidal voltage, which is widely used in single-phase power sources, as well as for two forms of modified sinusoidal voltage used in the fluorographic X-ray devices 12F7 and "INDIARS", also widely represented in the Ukrainian fleet of X-ray equipment.

The calculations were performed using the MATLAB mathematical package in the range of amplitude values of voltages, most commonly used in medical examinations, namely, from 40 to 120 kV. Comparison of exposure efficiency and equivalent dose rate that a patient receives during examination was conducted by calculating the corresponding values for each half-cycle of low-frequency supply voltage (10 ms), because during longer exposures the values of estimated parameters will increase in proportion to the number of half-cycles.

For each type of power source we conducted simulation of dependence of instantaneous value of current of the tube on the applied voltage U(t) at the set current of the cathode filament. The calculation was carried out using experimentally derived volt-ampere characteristics of the X-ray tube.

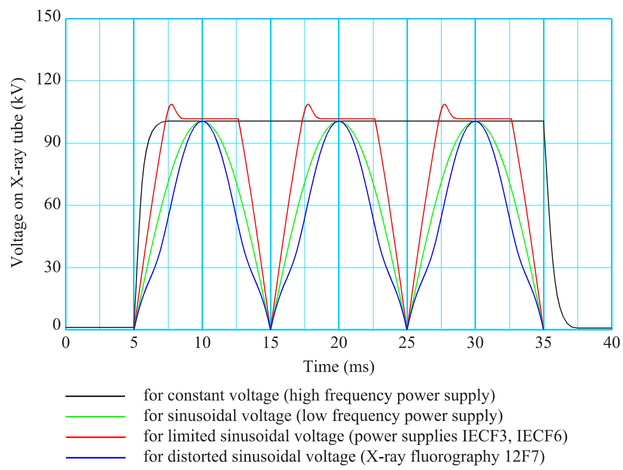

Fig. 4. Form of voltage on the X-ray tube when using different types of power sources

Since the resistive voltage control scheme used in the X-ray fluorographic devices 12F7 does not allow setting the required value of voltage at random current, the modeling of dependence U(t) was conducted by the selection of values of the current of fialment that provides necessary amplitudes of voltage.

Throughout the entire range with discreteness in 5 kV for all forms of voltage, the values of the following magnitudes were obtained by numerical methods.

1. Integral current I for the amplitude of voltage U_0 in one half-cycle of duration T_p:

$$I(U_0)=\int_0^{Tp} I(U(t))dt, \tag{1}$$

where I(U(t)) is the dependence of current of the tube on the applied voltage U(t) at a given current of the cathode filament. By the duration of half-cycle T_p we implied the time interval of 10 ms, which is determined by the frequency of industrial network power supply at 50 Hz.

2. The mean integral brightness of the glow of converting screen B for the amplitude of voltage U_0 in one half-cycle of duration T_p, normalized to current of the X-ray tube 100 mA:

$$B(U_0)=\frac{1}{I(U_0)}\int_0^{Tp} B(U(t))\cdot\frac{I(U(t))}{100}dt, \tag{2}$$

where B(U(t)) is the brightness of the converting screen at the voltage value U(t).

3. The rate of equivalent dose D for the amplitude of voltage U_0 in one half-cycle T_p, normalized to current of the X-ray tube 100 mA:

$$D(U_0)=\frac{1}{I(U_0)}\int_0^{Tp} D(U(t))\cdot\frac{I(U(t))}{100}dt, \tag{3}$$

where D(U(t)) is the equivalent dose rate at the value of voltage U(t).

Simulation for constant and sinusoidal voltage and the voltage in the form of limited by the amplitude sine was conducted at the same value of filament current value, in contrast to the fourth type of voltage, which is functionally related to the value of the anode current. Results of the calculation are displayed in Fig. 5.

For the possibility of comparing the equivalent dose, the results of calculations were recalculated for the time of exposure in one second. Fig. 6 displays dependences of equivalent dose rate for the current of tube 1 mA on the amplitude value of voltage for different types of power supply units.

Fig. 7 displays dependences of value of the mean integral brightness of the glow of the converting screen on the amplitude value of voltage for different types of power supply units, which are normalized by the value of current of X-ray tube of 1 mA.

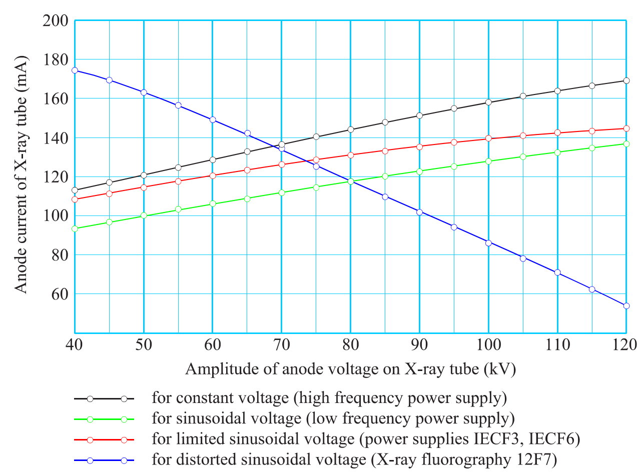

Fig. 5. Dependences of integral anode current of X-ray tube on the amplitude of applied voltage

To receive comparative characteristics of patient's equivalent dose with the same degree of image processing when applying different types of power supply units, we will assume that the degree of blackening of X-ray film (or the brightness of the resulting digital X-ray image) must meet the parameters of the fluorographic exposure for a patient of medium fullness when taking a radiography with voltage of 80 kV, exposure time 0.07 sec and current of the X-ray tube 100 mA. The degree of blackening of X-ray film is proportional to the product of the brightness of the glow of the screen by the duration of exposure.

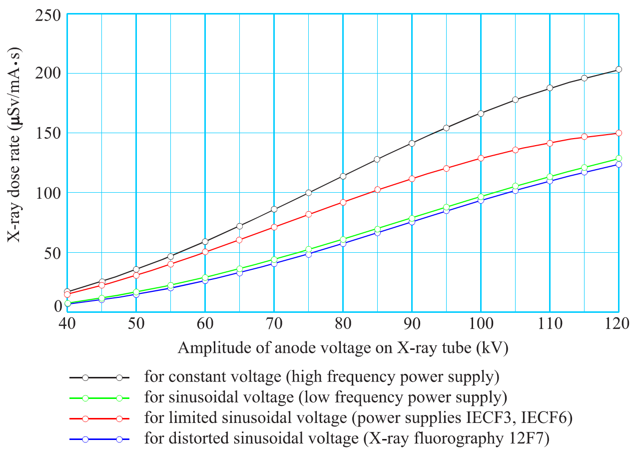

Fig. 6. Dependences of equivalent dose rate on the amplitude of applied voltage for the anode current 1 mA

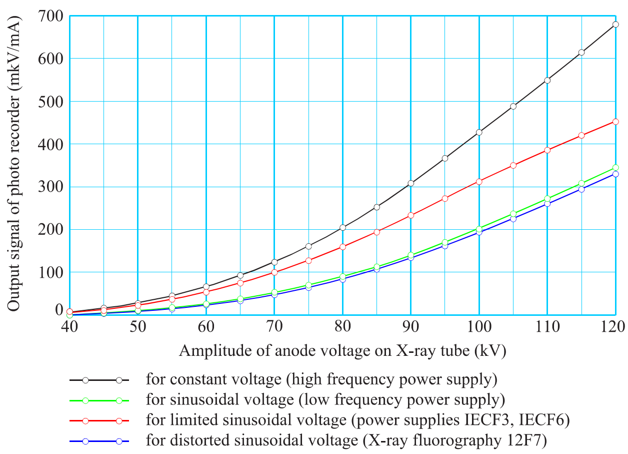

Fig. 7. Dependences of value of the mean integral brightness of the glow of the converting screen on the amplitude of applied voltage

As the quality criterion of the brightness of the glow of converting screen contains photometric converter's output voltage that is measured in millivolts, then for the above mentioned parameters of exposure, the dose of optical radiation in the visible spectral range roughly corresponds to the value B0=1.4 mV*s. With regard to this, we obtain:

$$D_B(U_0)=D(U_0)\cdot\frac{B_0}{B(U_0)}, \qquad (4)$$

where DB(U0) is the power of equivalent dose for the amplitude of voltage U0 normalized on the ratio of magnitude B0 and the mean integral brightness of the glow of the converting screen B(U0) at the appropriate amplitudes of voltage.

5. Results of research into influence of a form of supply voltage of X-ray emitter on the dose radiation a patient receives

Numerical simulation that is performed based on the experimentally obtained data made it possible to obtain estimated dependences of radiation dose on the form and amplitude of voltage used to power X-ray tube, and to assess the impact of the form of supply voltage on the formation of this dose.

The curves shown in Fig. 8 reflect the value of equivalent dose of radiation that a patient of medium fullness will receive when achieving a desired (the same) level of blackening of X-ray film, depending on the amplitude of voltage applied to the various power supply sources. Since the dependences of equivalent dose for sinusoidal and distorted sinusoidal voltage are very close in values, the graph displays them as one curve.

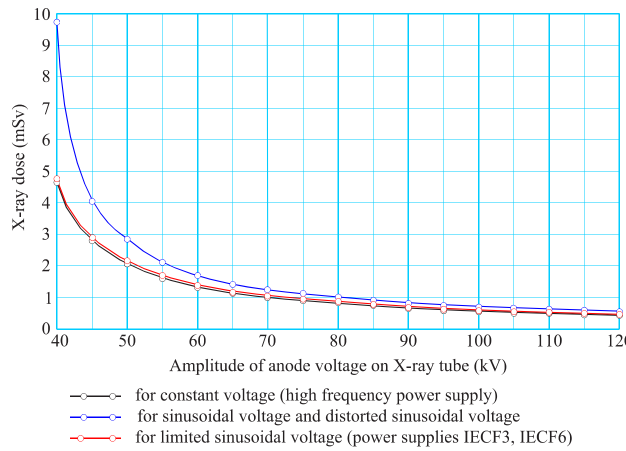

Fig. 8. Dependences of equivalent dose on the amplitude of applied voltage for various power sources, provided the same mean integral level of the blackening of film

Preliminary analysis of the results reveals that throughout the entire working range when using limited sinusoidal voltage, the level of phantom's exposure to irradiation comes close to the level of radiation that is registered when powering X-ray tube with constant voltage (in contrast to the sinusoidal and distorted sinusoidal voltage).

6. Discussion of results of the research and the possibilities of their application for the purpose of reducing population collective dose of radiation

In essence, when performing calculations, we simulated the operating modes of various X-ray power supply sources in the range of voltages from 40 to 120 kV, at which there will be achieved the degree of image processing similar to that under action of constant voltage. This is achieved by selecting duration of the exposure and magnitude of the anode current of the emitter. For the modes defined in this way, we calculate the integral radiation equivalent dose for a patient and compare its values to the value of the dose, which the patient would receive when powering the tube with constant voltage. The graphs of relative increase in the equivalent dose of radiation for different power supply sources, compared with a high-frequency source, are shown in Fig. 9.

An application of numerical simulation methods allowed us to estimate the magnitude of a patients' dose at different levels of voltage of X-ray tube power supply for different types of power sources used in the medical diagnostic X-ray devices.

Given the complexity of implementation of purely numerical mathematical model, predetermined by the diversity of physical mechanisms of interaction between X-ray radiation with patients and design elements of the devices, the use of experimental data, specially prepared for the calculation, allowed us to significantly simplify mathematical model and bring the results closer to real conditions.

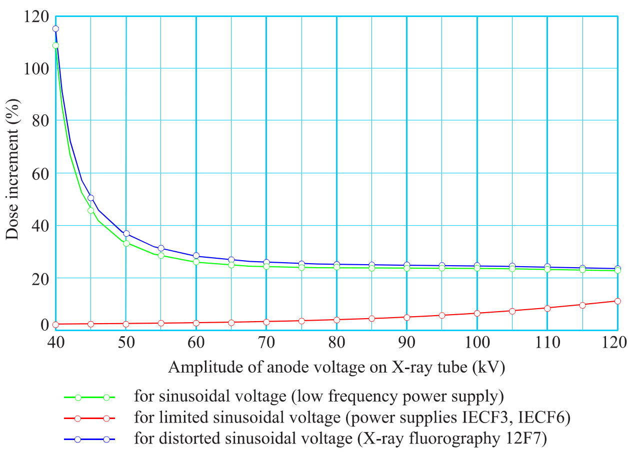

Fig. 9. Dependences of the equivalent dose increment on the amplitude of applied voltage relative to the dose, obtained when powered by direct current, for different power supply sources under condition of achieving the same level of X-ray image processing

Results of the conducted analysis demonstrate that, along with the optimization of regimes of performing X-ray examination, which is the subject of a number of papers, for example [24, 25], the total radiation dose of patients is significantly affected by the design and principle of operation of electronic equipment that is used for medical diagnostics. Thus, when taking fluorographic images in the same modes, the use of modern power supply units may reduce the dose of radiation by more than 20 % compared with the fluorographic X-ray device 12F7. But these devices comprise more than 70 % of the Ukrainian fleet of fluorographic X-ray equipment. One of the possible options for reducing collective radiation dose of the population when conducting screening examinations is the modernization of outdated X-ray equipment based on the principle of control of high voltage and transition to width-pulse regulation with limiting of sinusoidal voltage. This method, while significantly reducing the cost of equipment, allows coming closer to the minimum levels of dose, since with its application the growth of dose does not exceed a few percent relative to the modern high-frequency power supply units.

7. Conclusions

1. In the area of low voltages, we specified emission characteristics of the X-ray tube 20-50BD22-150, which is widely used in diagnostic devices, and, based on them, we constructed volt-ampere characteristics that are necessary for the calculation of operating modes of the tube when constructing a numerical model for performing subsequent research.

2. We experimentally obtained, normalized by the magnitude of anode current, dependence of power of exposure dose on the level of high voltage on X-ray tube that takes into account the influence of scattered radiation and is based on direct measurements of exposure dose in the zone of patient's location. By the nature of its growth, it is close to power function and can be approximated by it accurately enough.

3. The dependence of brightness of the flash of converting screen during X-ray examination on the operating parameters of the emitter was experimentally removed. This enabled us, in the course of performing numerical simulation of the process, to calculate the required exposure power.

4. Several mathematical models were constructed for the process of conducting exposure for different types of power supply sources of X-ray emitter, taking into account peculiarities of the formation of voltage and the ways to control parameters of examinations. They differ from each other by the method of calculating the instantaneous value of the anode voltage, because each power supply unit has its own design solution and physical principles of operation. The models we built will make it possible to calculate the instantaneous and integral values of all electrical parameters of X-ray tube, to find the integral dose of radiation in the plane of a patient's location and to model a generalized reaction of the converting screen on the X-ray flow that passes through the object of examination.

5. Based on numerical simulation, we calculated exposure characteristics of emitter and calculated in relative units the patient's equivalent dose in the case of using different types of power supply sources. On the example of conducting a fluorographic examination, we run comparative analysis of the radiation dose that a patient receives depending on the form of voltage under condition of receiving images with the same degree of blackening of X-ray film or brightness of the digital X-ray image. Results of the analysis indicate the feasibility of modernization of the outdated X-ray equipment, since, if applied, a radiation dose the patients receive may be reduced by 20 %.

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