

A new look at diagnostic radiology.

The relevance of the significant reduction of x-ray dose while increasing the resolution of diagnostic radiology, is it possible? A new look at diagnostic radiology.

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Abstract:

Currently, existing approaches to the construction of X-ray diagnostic systems do not allow the following characteristics to be combined in a single product:

- reducing the X-ray dose by an order of magnitude or more,
- reduction of the X-ray tube focal spot to 0.1×0.1 mm or less with a millisecond exposure time for X-ray images;
- reduction of the integral radiation power per image frame during the radiation period without increasing the instantaneous power of the X-ray tube;
- increasing the resolution of dynamic X-ray detectors while simultaneously increasing the frame rate per second;
- reduction of the signal-to-noise ratio and increase in the resolution of diagnostic images through mathematical image processing.

System limitations can only be overcome by creating a new class of X-ray diagnostic systems based on "Microsecond Radiography" technology, which incorporates the best features of all three types of radiography: Standard, Microfocus, and Nanosecond X-Ray Radiology.

Currently existing approaches to the construction of X-ray diagnostic systems do not allow for the combination of the following characteristics in a single product:

- reducing the X-ray dose by an order of magnitude,
- reduction of the focal spot of the X-ray tube to a value of 0.1×0.1 mm and less in the millisecond time shooting the X-ray image;
- decrease integral radiation power of the image frame coinciding with the period of radiation without increasing the instantaneous power of x-ray tube;
- increasing resolution, dynamic X-ray detectors with a simultaneous increase in the speed of frames per second;
- reduce the signal-to-noise ratio and increase the resolution of diagnostic images through mathematical image processing.

The output from the system of constraints is only possible through the creation of a new class of x-ray diagnostic systems, built on technology "Microsecond Radiology", which incorporates the best of all three rentgenologii – Standard, Microfocus and Nanosecond rentgenology.

Keywords:

Reduction of X-ray dose, increase in the resolution of X-ray images, Microsecond X-ray Radiology.

Index terms:

Reducing X-ray dose, increasing the resolution of X-ray images, Microsecond X-ray Radiology.

*Oh, how many wonderful discoveries
The spirit of enlightenment prepares
And experience, the son of difficult mistakes,
And genius, friend of paradoxes,
And chance, the god of invention...*

A. S. Pushkin

1. Introduction to the issue.

The basic principles discussed in this article were presented on November 24, 2017, at the St. Petersburg State Electrotechnical University "LETI" at the "IV All-Russian Scientific and Practical Conference of X-ray Equipment Manufacturers" in the form of a presentation of the Project and Technology "Microsecond Radiology."

The quality and diagnostic significance of images obtained in radiology, without taking into account tripod devices, depend on four main components: X-ray emitters (X-ray tubes), X-ray high-voltage generators, X-ray digital detectors, and systems for processing and visualizing the images obtained.

All four of these components affect the main characteristics of diagnostic images:

- the spatial and gradation resolution of images;
- the X-ray dose required to obtain diagnostically significant images;
- the ability to eliminate parasitic secondary radiation in the object under study;

unresolved issues, which will be discussed below and which can be characterized as "*systemic problems of radiology*."

2. On the resolution of diagnostic X-Ray radiology.

An integrated view of *standard* of X-Ray radiology, *microfocus* of X-Ray radiology, and *nanosecond* of X-Ray radiology (author's classification) has made it possible to identify systemic problems for each of the above types of radiography:

- a. **For standard radiology**, the inability to increase the actual resolution of the images obtained, especially dynamic ones, is due to:
 - the inability to increase the power of the X-ray tube by 4 times while increasing the resolution of diagnostic images by 2 times (the dose per pixel of the image must remain within the established limits);
 - the inability to increase the resolution of images by reducing the focal spot – when its size is reduced by a factor of 2, with the same X-ray dose per image frame, the power per unit area of the anode increases by a factor of 4, which is unacceptable;
 - the impossibility of increasing image resolution by mathematically processing X-ray images exceeding a value (0.7:-0.5) of the focal spot size, even with a significantly higher resolution of the X-ray detector (Fig. 1);
 - the impossibility, even at the minimum X-ray dose per frame, frame, create a dynamic microfocus X-ray system.
- b. **For microfocus radiography**, there are no problems in creating high-resolution of the images obtained (Fig. 4), but there are significant limitations when creating dynamic images:
 - the inability to reduce the exposure time of a single frame to eliminate image blurring when the object being photographed is in motion, due to the inability to increase the power of the X-ray tube – for a focus of 0.1*0.1 mm, the power cannot exceed 10 W (at a current of 0.10 mA) for a shot anode, and 1 kW (at a current of 10-20mA) for a rotating anode;
 - the impossibility, even with the minimum X-ray dose per image frame (see comment on Fig. 4) *, of creating a microfocus dynamic diagnostic X-ray system.

- c. *Nanosecond radiography* is characterized by a significant reduction in the X-ray dose per image frame by a factor of 27-30, there are no problems in creating a high-power pulse (current of **250-300A** with a duration of **10-20nS**) and up to 5kHz in a pulse train, but there is a very significant limitation in the resolution of the images obtained:
- it is impossible to reduce the size of the focal spot to less than 1.5 mm in diameter, reducing it, and the instantaneous pulse power, the anode may evaporate;
 - the use of Kumakhov X-ray optics allows the focal spot size to be reduced spot size to **0.5 mm** in diameter, but with a multiple reduction in the X-ray dose on the the detector (by more than an order of magnitude), the actual resolution does not reach **350-400 μ m**.

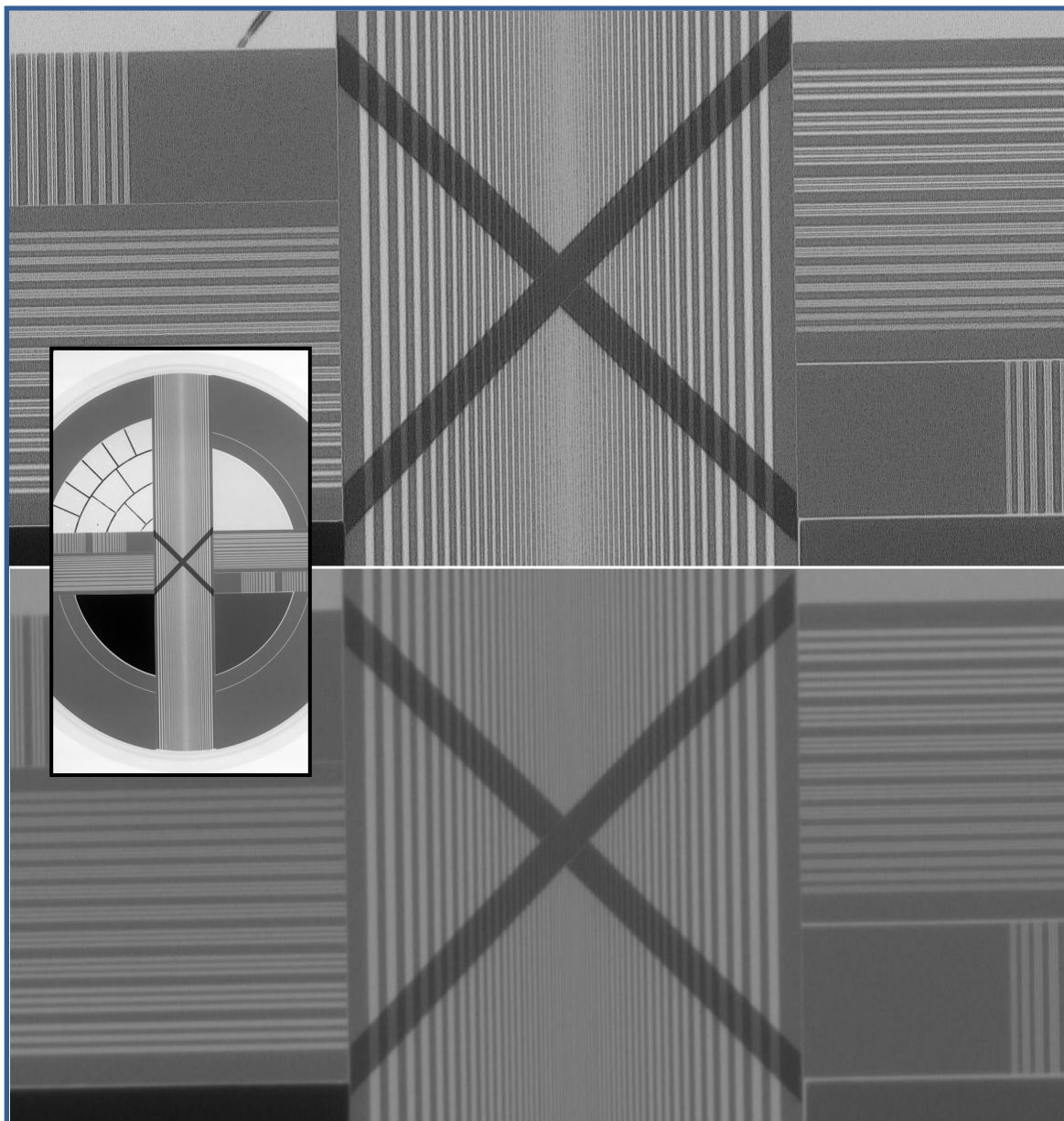


Fig. 1. Siemens X-ray test, corresponds to the lungs of an average patient, mode **60kV/20mAs**.
 A fragment of the test is highlighted $H*V = 73*29$ mm (pixel $\sim 85\mu$ m), focus **0.5*0/5mm**.
 The original image is at the bottom, and the image after multi-stage processing is at the top, with a visible resolution of up to 0.25mm; on the left is the full image of the Siemens test.

3. About X-ray dose in diagnostic radiology.

The X-ray dose required to create a correct diagnostic image, is directly dependent on the initial quantum efficiency **DQE(0)** of flat panel detectors (**FPDs**), as shown in Fig. 3.

Many FPD manufacturers do not provide very meaningful characteristics of the initial dependence of quantum efficiency $DQE(0)$ on the incoming X-ray dose, and here is why:

even for direct conversion FPDs made with a **CsI** scintillator and an **a-Se** amorphous selenium amplifier (Fig. 2) at a gain factor of 1.0, in the low dose range of **1.0-10 nGy (0.1-1.0 μ R)**, the change in the $DQE(0)$ value ranges from **0.10 to 0.30** (green line in the low dose range in Fig. 3), so it is necessary to set the amplification factor in the a-Se layer to ~ 50 and above, which leads to a proportional increase in quantum noise!

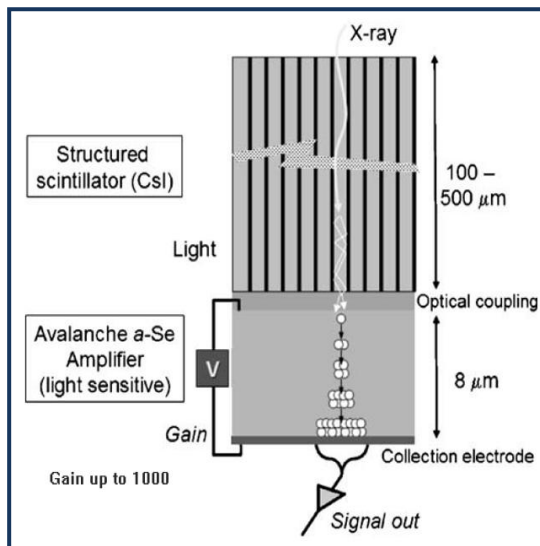


Fig. 2. FPD on a-Se

Thanks to the use of sensitive elements manufactured using **CMOS** technology, X-ray detectors will have an initial conversion coefficient $DQE(0)$ ranging from **0.50 to 0.70** and above (blue line in the low-dose range), which undoubtedly offers a significant advantage compared to the most common FPD detectors with direct conversion on a **CsI** scintillator with an amorphous selenium (**a-Se**) amplifier in the low dose range (1.0-10 nGy).

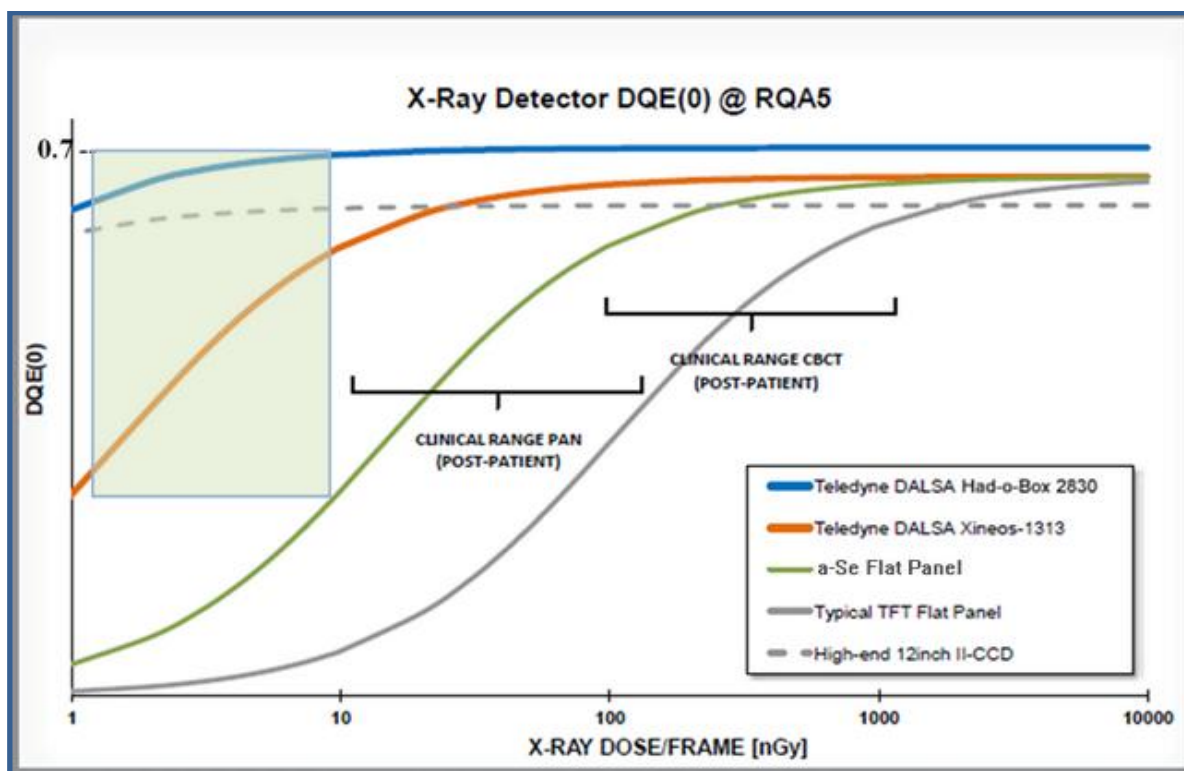


Fig. 3. Dependence of $DQE(0)$ of different types of FPDs on X-ray dose

Fig. 4 shows the result of a Siemens X-ray test using a microfocus X-ray generator with a focus of **0.1*0.1 mm** at **60 kV/0.1 mA/10 sec (1 mAs)** exposure settings.

* The Siemens X-ray test image (Fig. 4) shows a full resolution of up to $50\mu\text{m}$ at an X-ray dose **20 times lower** than in the same test (Fig. 1), despite the fact that the X-ray test image shown in Fig. 4 **has not been mathematically processed!****

** The image was taken on a special stand with a 16Mpix CMOS camera with the pixel correction and normalization system disabled to eliminate the influence of internal mathematical processing specified by the CMOS camera manufacturer. $\text{Gd}_2\text{O}_2\text{S:Tb}$ with a high amplification factor is used as an X-ray scintillator.

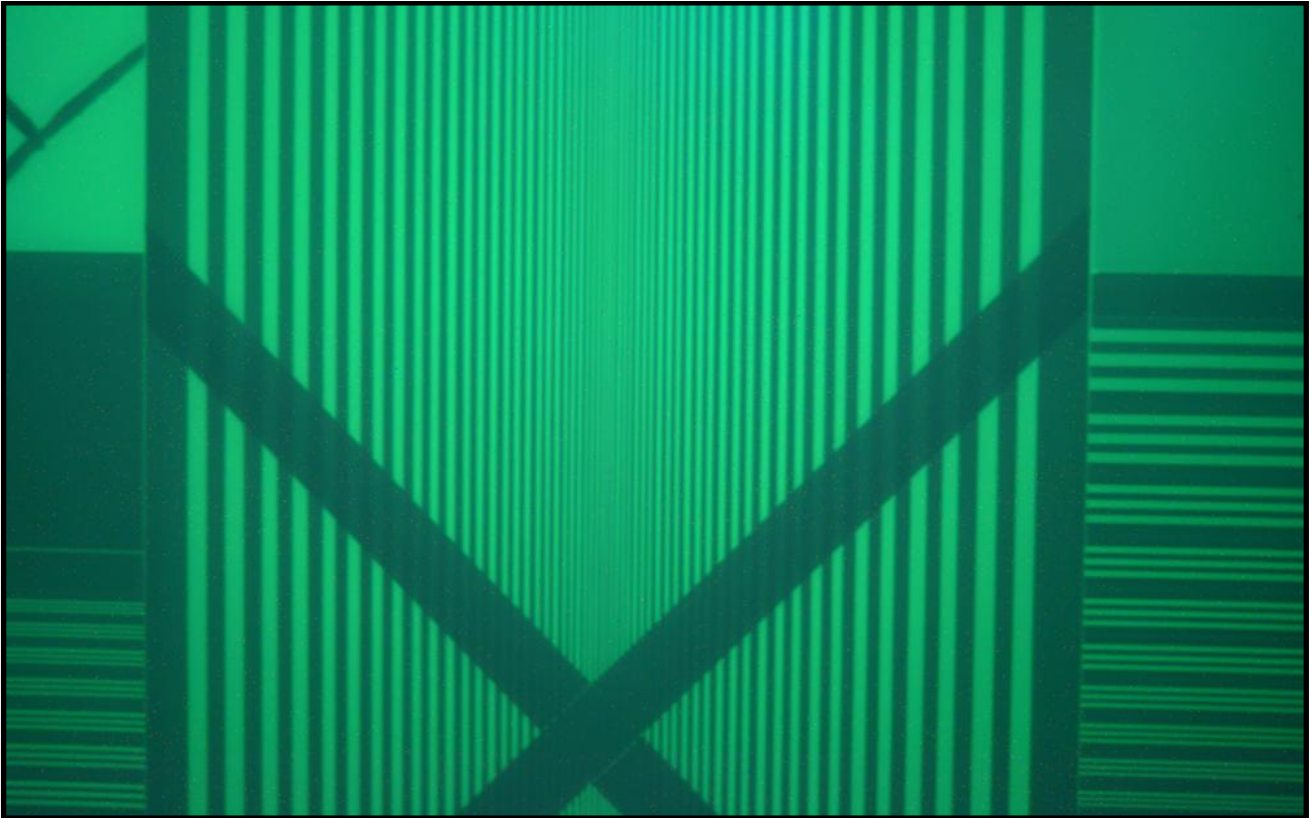


Fig. 4. Siemens X-ray test image taken with a CMOS camera on a microfocus X-ray machine. A fragment of the test $H*V = 56 * 35$ mm (pixel $\sim 56\mu\text{m}$) is highlighted.

4. On the elimination of secondary stray radiation

Currently available mathematical methods for partial levelling of secondary stray radiation arising in the object under study allow real-time processing of both the frame stream and the subtraction image stream, in 16-bit frame format up to $1024*1024$ (i.e. 1 megapixel = **1.0Mpix**) at 30 frames per second.

This is achieved by creating a flexible multi-stage 16-bit flexible functional pipeline for mathematical processing of the image stream with sequential application of sets of functional elements - matrix filters, nonlinear and spectral transformers, the parameters of which are available to the processing operator.

The quality of partial levelling of secondary parasitic radiation depends on the processing technology and the capabilities of the functional elements of the processing pipeline.

At the same time, the physical data flow can reach **120MB/s** at 60 frames per second (for the $1024*1024*16\text{b}$ format), while the data flow required for visualization without display delay and perceivable by the human eye is sufficient at **60MB/s** at 30 frames per second.

Fig. 5 shows the stages of pipeline processing from the primary source image to the subtractive image, which allows partial, but not complete, elimination of secondary parasitic radiation. The degree of elimination characterizes the quality of mathematical processing.

The demand for increased dynamic display of large-format images of **9-12 Mpix** at 30-60 frames per second requires an increase in the power of the computing pipeline by an order of magnitude or more, due to an increase in the input stream to **1440 MB/s** (12Mpix at 60 frames per second), which is a very non-trivial task of creating an image stream processing pipeline.

Fig. 6 shows the stages of pipeline processing of a series of frames to obtain a subtraction series in real time, with the creation of an integral picture of the contrast filling of the vascular system (first frame). To create this type of image, so-called "cellular automata" and significantly more powerful computer systems with greater computing capabilities are required, especially for images with a format of 9-12Mpix and above.

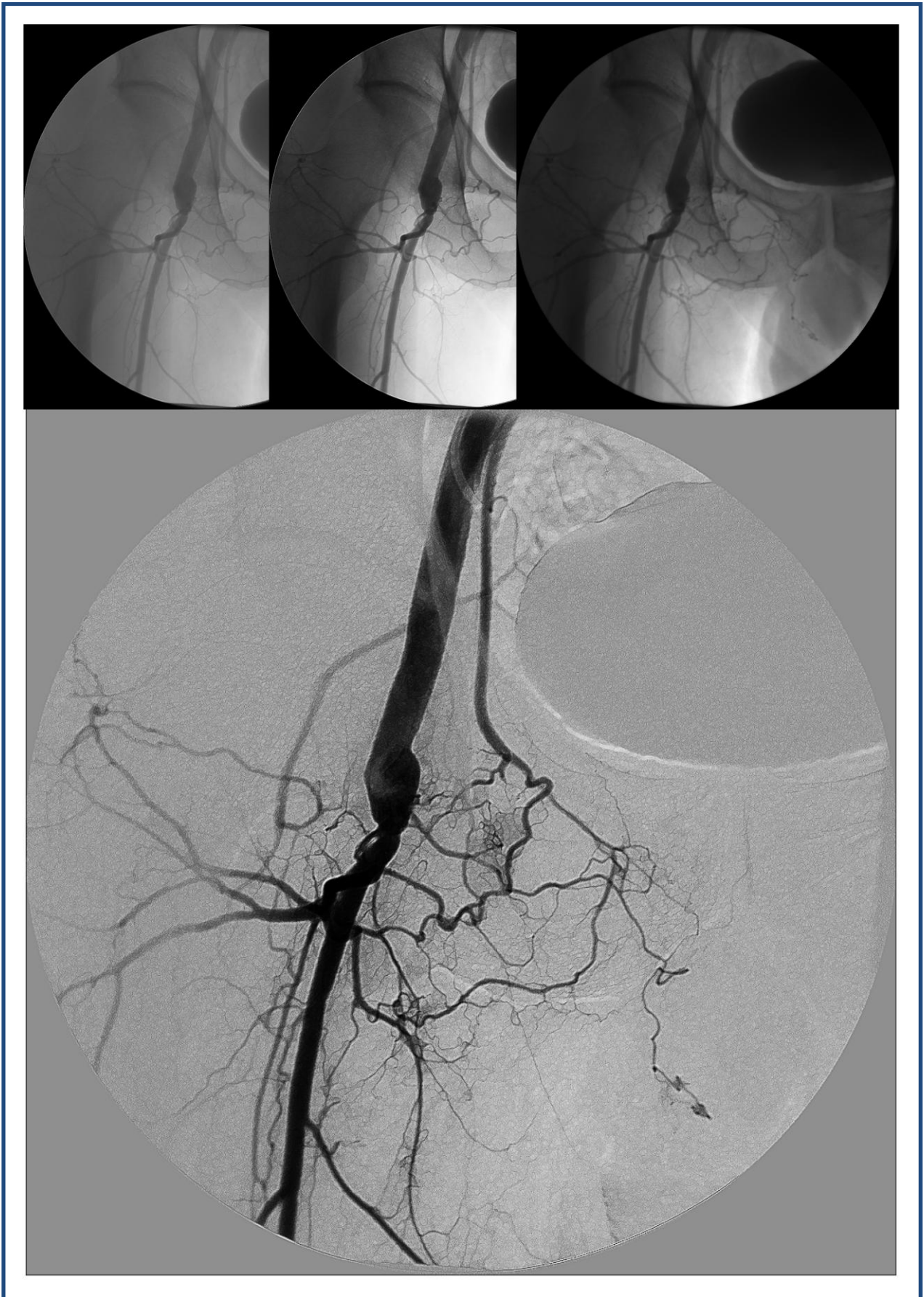


Fig. 5. The stages of image processing from the original to the subtractive image, in which even the smallest blood vessels are clearly visible.



Fig. 6. Subtraction series, in the first frame - an integral frame of contrast passage for the series.

5. Ways to overcome systemic technical problems in radiology

Systemic limitations can only be overcome by creating a new class of X-ray diagnostic systems that incorporate several fundamental differences from existing radiology systems:

- multi-pulse radiation mode for creating an X-ray image frame;
- transfer of current, high voltage, and X-ray pulse control systems from the X-ray generator to the processing and visualization system;
- changes in the design and technology of the X-ray emitter to convert it to multi-pulse mode;
- application of radiation parameters based on the results of measurements taken during the previous radiation cycle and on the parameters of the image obtained;
- changing the design of the X-ray detector using the most advanced imaging components;
- creation of a parallel multi-core pipeline for real-time processing and visualization of ultra-high-resolution image streams.

All of the above is combined in the "Microsecond Radiography" technology, which incorporates the best features of all three types of radiography—standard, microsecond, and nanosecond radiography:

- microfocus with high instantaneous input power of X-ray radiation and more than an order of magnitude lower integral power per image frame;
- X-ray microsecond emitters (tubes), including tubes for stereo mode, with the ability to dynamically change the size of the focal spot and built-in measurement of radiation parameters for each image frame;
- X-ray generators with more than an order of magnitude lower integral power and direct primary measurement of generation parameters;
- dynamic microsecond X-ray detectors with ultra-high resolution, direct computer control, and data acquisition without intermediate conversions;
- a multi-stage, multi-core, real-time pipeline for pixel-by-pixel normalization, processing, and visualization of ultra-high-resolution diagnostic image streams.

X-ray detectors manufactured using "Microsecond Radiology" technology will move down the dose scale by an order of magnitude or more, into the region where a-Se FPDs are not effective (into the translucent region in Fig. 3, top left).

Currently, research and a series of experiments have been conducted, some of the results of which are reflected in this article, on which the "Microsecond Radiology" project is based.

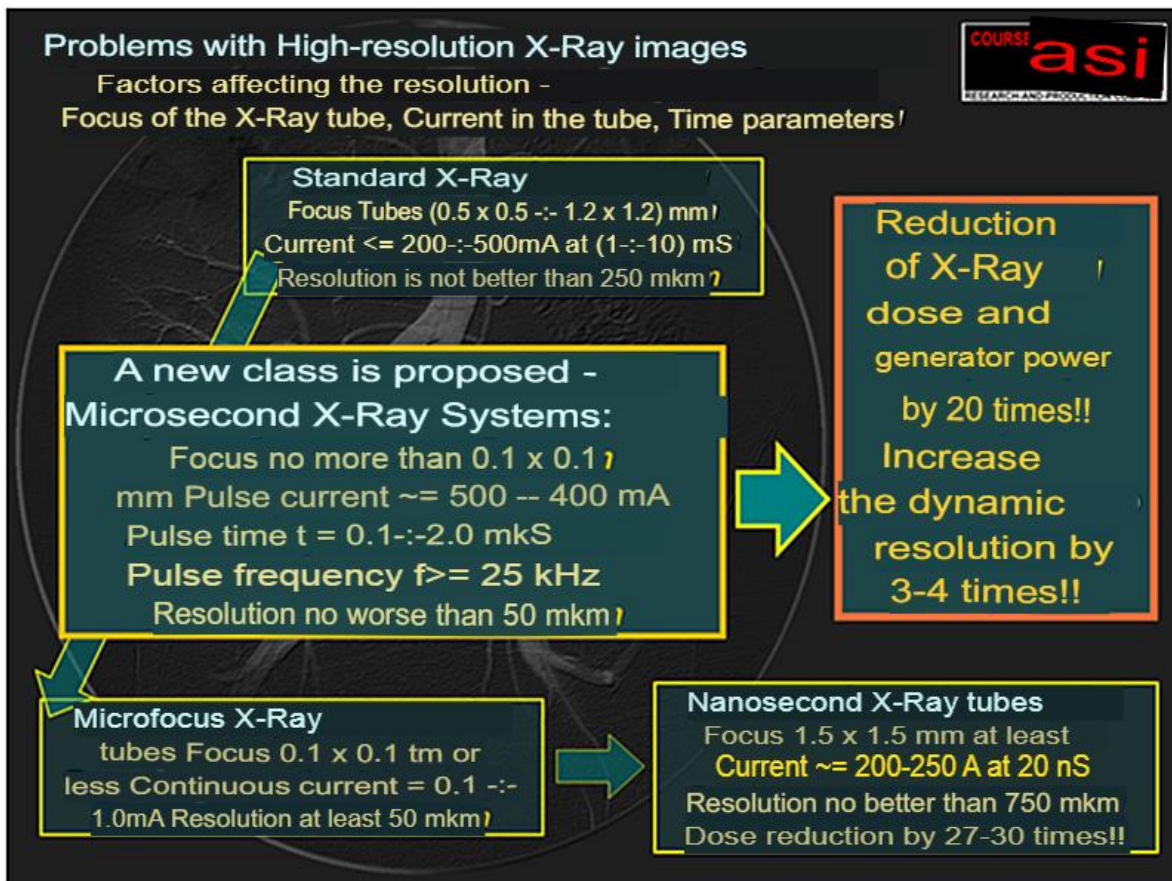


Fig. 6. Stages of creating radiography by type of technology used.

6. Prospects for the technology and the "Microsecond Radiography" project

The main result of implementing this technology under the "Microsecond Radiography" project, as opposed to existing X-ray equipment, will be:

- **A dramatic reduction in X-ray dose by more than 20 times or more!** for all types of X-ray examinations, such as medical examinations, especially mammography and angiography, X-ray examinations based on the principles of "tomosynthesis," as well as in X-ray non-destructive testing systems and X-ray inspection systems;
- At the same time, with a significant reduction in X-ray dose by a factor of 20, **the resolution of dynamic images will increase by a factor of 3-4**, i.e., to (100-:-50) μm versus (400-200) μm at 30/60 frames per second, compared to modern X-ray systems, which will require the creation of new standards for the diagnostic process in general radiology, angiographic studies, computed tomography, etc.;
- An additional effect is **a more than 20-fold reduction in the integral power of the X-ray generator** from (50-:-120) kW to (2-:-4) kW with **instantaneous X-ray tube power** from (30-:-100) kW to (15-:-30) kW, ensuring that X-ray tubes and generators remain virtually cool and significantly extending their service life;
- **Real-time stream processing (over 1500MB/s)** to reduce X-ray noise in dynamic images, based on **unique real-time parallel computing tools**, while increasing the resolution and clarity of the images obtained.
- **Increase in the resolution of the computer tomograph to 100-:-50 microns** with the X-ray tube focus ranging from **0.15x0.15mm** to **0.1x0.1mm**.

- **Multimodality** - combining a high-resolution X-ray diagnostic device and a computer tomograph in a single device.
- **Reduction in the cost of** microsecond X-ray tubes, microsecond X-ray generators, and microsecond X-ray detectors, associated with the design and technical features of the latter and the high technological complexity of their manufacture, which will lead to **a reduction in the "Total Cost of Ownership" (CTO) of the entire X-ray complex by up to 50%**.

Chief architect of the project

Evgeny Mikhailovich Avsharov.

Moscow, November 2017.

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