COLLIMATION OF X-RAY DIAGNOSTIC BUNDLE BY MEANS OF STEERING FERROFLUID

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Abstract: The study addressed the problem of the incoherence of an X-ray tube generated bundle. In spite of the large progress made in the area of the durability and efficiency of these devices, the problem of the inherent divergence of the bundle hasnt yet been resolved in a satisfying way. In the face of difficulties with concentrating X-rays, the only practical way of eliminating non-axial rays is by applying lead collimators of a suitable length and diameter as well as mechanical systems of movable distracting grids. An entirely new approach has been the use of electro-magnetorheological fluids as filters, which are capable of modifying their physical and quantum properties contingently based on the parameters of the applied external electric current, centrifugal force and magnetic field. The experiments carried out showed, that the described changes also concern the absorbtion, distraction or change in the direction of the X-ray beam. In the constructed prototype device, interesting and recurrent results in the modification or eleimination of non-axial rays were obtained, which resulted in the improvement of the quality of bone images. The following research questions were posed: (1) are changes in the photodensitometric parameters of joint (PIP) X-ray images containing soft and osseous tissues proof of alterations of the physical parameters of a diagnostic X-ray beam? (2) is there a relationship between the volume of ferrofluid in a lens and its capability to alter the parameters of a permeating X-ray beam? (3) is there a relationship between the r.p.m. of the collimator and its capability to alter the parameters of a permeating X-ray beam, and does it have a linear character? Based on the conducted research a non-linear dependancy was observed between the volume of ferrofluid in the lens as well as its rotational speed and the capability of the system to alter the parameters of the permeating X-ray beam.

1 INTRODUCTION

William Roentgens pioneer works began a completely new chapter in the history of medical diagnostics, enabling small invasive investigations of internal organs, especially the osseous tissue. Progress in the field of electronics resulted in X-ray tubes becoming increasingly more efficient, reliable and the repeatability of emission in relation to a given electric parameter was largely improved (Bankier et al., Carlson, Dyszkiewics, 2001, Dyszkiewics, Folster, Grampp et al., 1997b, Ławniczak and Milecki, 1999). From the dawn of the development of radio-photographic technology, beginning with tubes with a motionless, and later rotating and multi-focal anode, constructors struggled with the problem of the originally divergent diagnostic bundle, the geometry of which results from the way an X-ray beam is formed as a consequence of breaking the stream of accelerated electrons on the anode. A divergent bundle produces geometrical distortions and leads to a considerable worsening of the acutance of the photo. A large quantity of non-axial rays is the reason for this phenomenon. Constructors of X-ray tubes have been trying to achieve a larger coherence of the bundle for many years. As a result, the use of collimators began, that is, thick-walled tunnels, made of materials of a large thickness, able to absorb non-axial rays. Applying tubes with a multi-focal anode was another solution, which enabled a better adaptation of the bundle geometry to the distance of a photographed object. Still another solution was the use of stable filters or oscillating metal grates placed above the film, distracting non-axial rays (Czerny et al., 1997, Grampp et al., 1997a, Kainberger, et al., 1997, Kollmann, et al., 1997, Kramer et al., 1997). In spite of the results achieved in improving the quality of X-ray images, it can be clearly observed that these activities lead exclusively to the removal of part of the

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rays from the bundle by using materials of large density, which only increase the difference between the real and effective power of the tube and have a measurable influence on the weight and durability of the device (Dyszkiewicz, 1999, Dyszkiewicz, 2001, Majumdar et al., 1997, Phule, Rand et al., 1997, Sasaki). One new innovative solution used by scientists in Geneva has been the application of ferrofluids with variable physical and chemical parameters, which, after being introduced into capillary tubes placed in an X-ray beam axis allow the parameters of the beam to be changed contingently.

1.1 Ferrofluids

Ferrofluids display the characteristics of both fluids and magnetic substances at a very wide temperature range. With the absence of an external magnetic field they behave like normal newtonian fluids, where the shear stress is in direct proportion to the shear velocity without displaying any signs of magnetisation. The viscosity of controlled ferrofluids can be adapted within a range of 5 - 25 000 cP. Analogically to electrorheological fluids they are built of two basic components: carrier fluid (<85%) and ferromagnetic particles covered with a surface layer (from 2% to 15% , for ferrofluids, up to 80% for MRF). The carrier fluid is a non-magnetic substance; however the components of the particles of the suspension are solid soft magnetic materials which form micromagnets [27]. Removing the action of Van der Waals forces and magnetic attraction forces (grouping) makes it possible to cover the particles with a surface active agent (e.g. oleic acid). Depending on the size of the particles two types of ferrofluids can be distinguished: (1) nanomagnetorheological also called ferromagnetic; (2) magnetorheological fluids MRF. In ferromagnetic fluids the diameter of the particles (most commonly Fe_3O_4) ranges from 3 15nm. At smaller sizes they do not display any magnetic properties. Normally, synthetic oil is used as a carrier, or (not so often) light mineral oil, esters, glycerine, poliphenyl or water. The maximum magnetisation of 0,6T domains limits the magnetic absorption of the fluids (0,005 0,13 T) and the maximum shear stress is less than 5 kPa. They can operate at temperatures from -65 to 200 C, as it is within this range that magnetisation is independent from temperature. Their durability depends on the evaporative power of the carrier fluid, which should be as low as possible whilst the conductivity of the entire system should be the highest. As the particles are of small dimensions they do not accumulate at the bottom of the container even if the fluid remains still for long periods of time (they are raised as a result of thermic motions). In magnetorheological fluids the size of the particles ranges from 0,5 to 8 mm. Mineral or silicon oil with a low evaporative power is used most often as the carrier fluid. In industrial applications the magnetic induction can total 1,2T (max.2,15T). These properties do not change within the temperature range of -50 $\div$ 150C. The maximum shear stress at a magnetic field strength of 150 $\div$ 250 kA/m is 50 to 250 kPa. A characteristic feature of magnetorheological fluids is their capability of rapidly (<10ms) changing their viscosity after a relatively weak magnetic force is applied. Leaving the magnetorheological fluid still leads to the accumulation of particles at the bottom of the container, which is their drawback. However, their production is much easier, making them significantly cheaper compared to ferromagnetic liquids. In the situation when an external magnetic field is not present, the magnetic moments linked to the particles are distributed at random, which leads to a complete dissipation of their forces. After applying an external force, the magnetic moments of the particular particles line up along the flux created by the force field and thus are no longer subject to thermal currents. This mechanism is similar to the mechanism of chain creation in electrorheological fluids. Magnetorhelogical fluids display considerably stronger magnetisation than ferrorheological fluids. By controlling the strength of the magnetic field we can influence the viscosity of the fluid, e.g. with a field of ca. 200 kA/m it can reach a value of 700 P for magnetorheological fluids and 50 P for ferromagnetic fluids, which allows for the application of shear stress of 100 kPa and 5 kPa respectively.

1.2 New Methodology

The prototype device has been shown in fig. 1a. It consists of a ring with grooves adapted to the dimensions of the electromagnets or solid magnets active elements, which are synchronised geometrically and parametrically to work at a desired angle within the ring, where a suitable container with ferrofluid has been placed.

1.3 Collimator Function

A collimator (fig. 1a) is composed of a cylinder filled with ferrofluid which serves as a diffraction crystal. The ferrofluid, being situated inside a ring containing several or more powerful magnets with alternate or compatible polarities becomes spatially organised, forming the shape of a convex lens with a relatively large curvature and containing additional smaller lo-

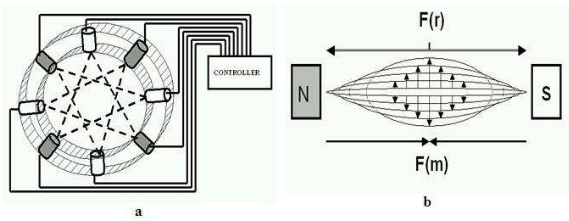

Figure 1: Collimator for modifying the geometry and energy of the diagnostic X-ray radiation: (a) example arrangement of fixed magnets or electromagnets in induction ring; (b) concept showing the relation between the induction of the magnetic field (increasing the thickness of the lens) and centrifugal force in a rotating motion, the action of which flattens the curvature of the ferrofluid lense.

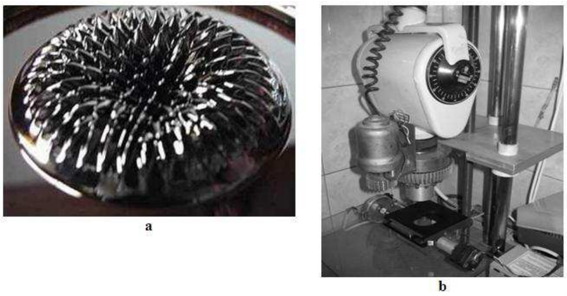

Figure 2: Collimation system: (a) view of ferrofluid inside the inducting ring of the collimator at one magnet configuration; (b) laboratory unit on a adjustable stand equipped with a dental X-ray tube.

cal convexes. After putting the entire arrangement into motion by an electric motor, the action of centrifugal forces which act in an opposite direction to the magnetic inductance vector decrease the size of the lens curvature proportionally to the speed with which the magnetic ring turns and in inverted proportion with the value of the magnetic inductance (fig. 1b).

The X-rays emitted from the tube, when passing through a collimator are curved to the axis, concentrated in the focal point or are diverged away from the axis (dispersed) depending on the type of ferrofluid used, the shape of the field (depending on the number and induction of the used magnets or additional electrodes) as well as on the rotational speed of the collimator.This allows the rays which are outside the axis to be aligned towards it or focused. Using a collimator also enables energetic filtration to take place which eliminates image distortions resulting from an uneven distribution of radiation on the images plane (initially divergent beam) (fig. 2a).

The operation of the new generation collimator Patent P366266 is based on Lawrence Braggs law, which explains the mechanism of how the path of hard radiation is distributed in a crystal. Ray 1 falls

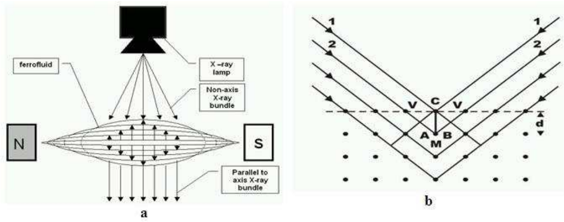

Figure 3: The central element of the collimator is its rotating ferrofluid lens, the curvature of which is determined by the relation between the centrifugal force and the magnetic induction of the rings magnets. (a) the initially divergent X-ray bundle is modified especially within the range of non-axial beams (b) Braggs law describes this process.

onto the surface of the crystal at angle V and affects the electron layer of atom C, whilst the second beam which is parallel to beam 1 affects the layer of atom M. The electron layers of the atoms scatter the X rays. The symmetry straight AC which is perpendicular to the incident rays constitutes the face of the incident wave. Such is also line BC a wave scattered at angle V. As a result the difference between the paths of rays 1 and 2 is AM + MB. Triangle AMC produces the following formula:

$$AM = dsinV(1)$$

where d is the distance between neighbouring planes in the crystal. AM = MB, thus the difference between the paths of beams 1 and 2 is:

$$2dsinV(2)$$

Amplification takes place when the difference between the paths of two rays equals an integral multiple of the the length of wave 1. Thus the condition for amplification can be expressed by:

$$2dsinV = nl(n = 1,2,...)(3)$$

If this condition known as Braggs formula - is fulfilled, then the scattered beams 1 and 2 become amplified and a reflection will occur. It can be noticed that the reflection is a result of scattering and interference (Bankier, et al.). Experiments have shown that the computer controlled prototype collimator allows a sharp focus of the divergent beam to be obtained in a precisely determined point of a structure (fig. 4a, b), and the focus to be precisely moved within the tested structure (scanning). Such a system creates the foundations for gradient tomography without a need to use the expensive gantry system and multislice scanners.

2 AIM OF WORK

The subject of the clinical tests was the RTG UDR1 prototype collimator. The tests were conducted

Figure 4: One of the first images taken- the authors hand showing two extreme parametrical compositions: (a) image taken by axial beams at 770 r.p.m., displaying a sharp bone trabeculae structure with an almost complete elimination of soft tissue; (b) image taken with a non-axial beam component at 650 r.p.m. displaying soft tissue with an almost completely faded bone trabeculae structure.

among a group of healthy volunteers employed as researchers at the Laboratory of Biotechnology. The aim of the research was to answer the following questions:

(1) Does a ferrofluid which is spatially organised in a magnetic field and put into a spinning motion change the properties of a permeating diagnostic X-ray bundle produced by a dental X-ray unit?

(2) Are changes in the photodensitometric parameters of joint (PIP) X-ray images containing soft and osseous tissues proof of alterations of the physical parameters of a diagnostic X-ray beam?

(3) Is there a relationship between the volume of ferrofluid in a lens and its capability to alter the parameters of a permeating X-ray beam?

(4) Is there a relationship between the r.p.m. of the collimator and its capability to alter the parameters of a permeating X-ray beam, and does it have a linear character?

2.1 Subjects Tested and Method

Male white-collar volunteers aged 356,7 , in good health were qualified for the research.

Excluding Criteria. History of hand injury (bruises, dislocation, fracture) treated by immobilisation, inflammation of the joints, osteoporosis, diabetes, heavy physical work or extreme sports, contact with vibration, ionising radiation.

Testing Apparatus. The tests were carried out in a standard room of the Laboratory of Biotechnology in Cieszyn under the supervision of a Radiology Protection Inspector (of the Central Laboratory for Radiological Protection), on a prototype UDR1 collimator linked to a small-size Siemens X-ray unit for standard dental diagnostics. All photos were made with a 0.5 second exposure time using 50kV to power the tube. The registration of the bone structure radiograms and their conversion to digital form was carried out on a DIGORA dental 30 x 50mm matrix.

Test Method. The aim of the experiments was to test the possibilities of controlling an X-ray beam by using different rotational speeds of a ferromagnetic lens composed of different volumes of ferrofluid and also to determine the applicability of the obtained photos, which were modified in terms of quality, in diagnostic medicine. The experiment schedule included:

1. Performing a series of shots of the PIP 3 (R) joint with a lens containing 0.5 ml of ferrofluid at 11 ascending and repeatable rotational speeds of the collimator.
2. Performing a series of shots of the PIP 3 (R) joint with a lens containing 1.5 ml of ferrofluid at 11 ascending and repeatable rotational speeds of the collimator.
3. Performing a selective densitometric analysis of bone trabeculae groups in standard measurement area locations (fig. 5) by means of the Structure 1.0 software.
4. Performing an analysis in measurement areas located diagonally to the length axis of the long bone with visible soft tissue on one side of the bone P(1) and on the other P(2) by means of the authors trademark "Density 1.0" software (fig. 6,7).

Following a 5 minute acclimatisation in the laboratory, the tested persons were seated in a comfortable position at station UDR1, placing their hands loosely on the positioning pad. The trunk and legs of the patient were screened by a standard protective lead rubber apron. The geometric axis of the lamp was directed at the center of the picture converting matrix size 20 x 30 mm, and the hand position pad forced the third finger of the right hand to be situated so that the axis also passed through the center of the PIP III (R) gap. The distance between the bottom opening of the X-ray tube collimator and the surface of the matrix was 100mm. In the first series the shot was taken through a still lens containing 0.5 ml of ferrofluid. Then the collimator was put into a spinning motion for the 10 subsequent rotational speeds and shots were taken at approx. 30-40 second intervals following the stabilisation of the successively set speed. In the second series the lens was replaced with one containing 1.5 ml of ferrofluid and all of the above procedures were repeated for the 10 rotational speeds. A standard system of DIGORA converting matrices was used to register the images and enabled the X-ray shadow to be saved directly and repeatably in the computers operational memory in BMP format which, as a result,

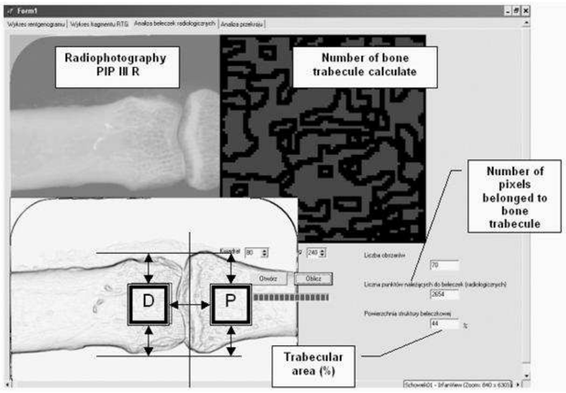

Figure 5: ”Structure 1.0” graphical interface allowing for the determination of the surface area of pixels belonging to the visible bone trabeculae groups in measurement fields P and D.

allowed for the complete elimination of errors which could occur if the images were processed photochemically.

X-ray Image Analysis

(1) Analysis of the visible bone trabeculae groups surface area compared to the surface of the entire image performed via the authors trademark Structure 1.0 software implemented in the C++ environment. The standard area around the proximal phalangeal II (P) epiphysis and the distal phalangeal I (D) epiphysis, proximal interphalangeal joint of the right hands third digit.

(2) Analysis of the X-ray shadows photdensitometric cross-section - was performed by the authors trademark ”ensity 1.0” software implemented in the ”Delphi 7.0 Professional” environment. The program enables a photodensitometric evaluation to be made of the image in the measurement field situated crosswise to the long bone axis with consideration given to the soft tissue background on one side of the bone (P1), the bone area (P3) and the soft tissues (P2) on the other side of the bone area (fig. 5,6).

2.2 Results

Next pictures shows the results of photodensitometric tests of bone trabeculae groups visible macroscopically in X-ray shadows of the PIP III joints, made in a stand which positioned the axis of the bone against the X-ray beam, and processed by the ”Structure 1.0” software. The averaging results for the relative density in measurement field P (proximal epiphysis) and D (distal epiphysis) were based on the 11 tested collimator rotational speeds. The picture fig. 8 presents

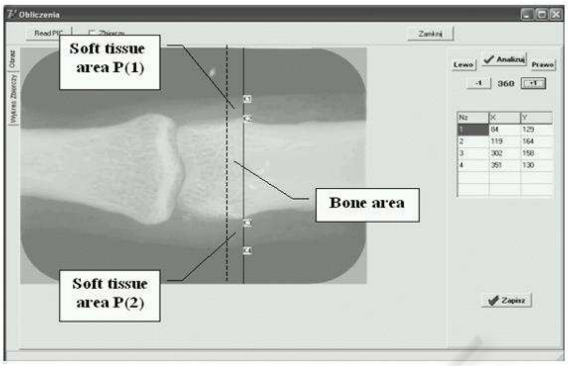

Figure 6: ”Density 1.0” graphical interface enabling the preparation of a histogram displaying the optical density in the measurement field situated typically around the distal phalangeal epiphysis of the right hand’s third digit. The program performs a measurement in the soft tissue areas P(1), P(2) and in the bone area.

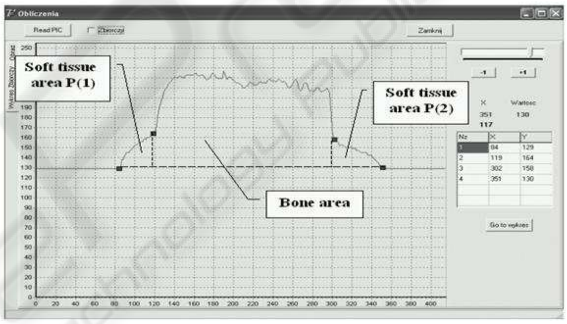

Figure 7: Example histogram displaying the optical density in area P(1), P(2), B(bone area).

differences between the average values in measurement areas P and D.

Measurement data displayed in diagrams 8-10 show the non-linear dependency between the degree of the modification of the X-ray beam and the rotational speed.

3 CONCLUSIONS

(1) The ferrofluid which has been spatially arranged in a magnetic field and put into a rotational motion changes the properties of the permeating diagnostic X-ray (with constant and repeatable parameters), inducing changes in the clarity and optical density of the soft tissue and bones.

(2) Changes in the optical clarity and translucency of the analysed fragments of X-ray images of soft tissues and bones obtained from a repeatable lamp exposition at different collimator parameter settings prove that changes in the physical properties

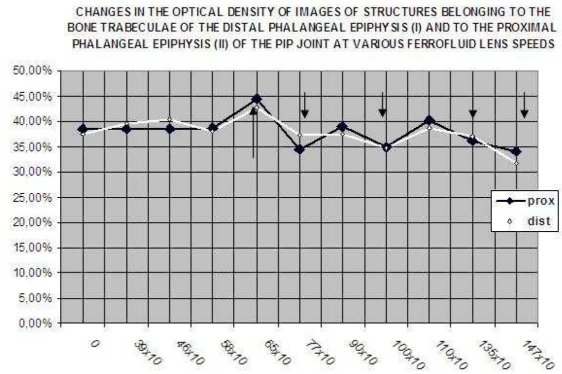

Figure 8: Averaging photodensitometric values of bone trabeculae groups in measurement areas P and D in X-ray shadows made by the collimator at 11 rotational speeds of the lens with ferrofluid (significant changes occurred at 650, 770, 1000, 1350, 1450 r.p.m).

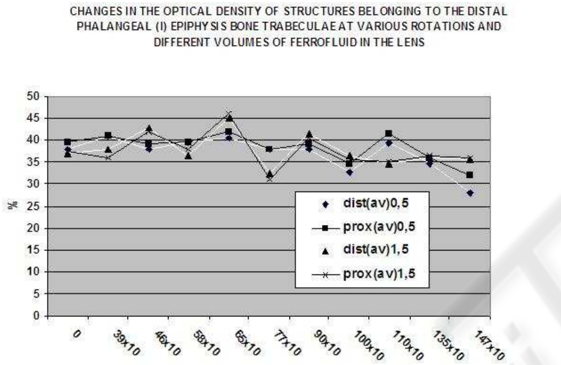

Figure 9: "Structure 1.0" diagram presenting the averaging optical density values of structures belonging to macroscopically visible bone trabeculae in areas (P1) and (P2), (D1) and (D2) for images made by lenses containing 0.5 and 1.5 ml of ferrofluid respectively.

of X-ray beams have occured

(3) A dependency has been noted between the volume of ferrofluid in the lens and its capability of changing the permeating X-ray beam

(4) A non-linear dependency has been noted between the rotational speed of the collimator and its capability of changing the permeating X-ray beam

4 DISCUSSION

The original divergence of a diagnostic X-ray bundle resulting from the design of the X-ray tube is an issue which has been accompanying radiological diagnostics ever since the emergence of the method. The heterogeneity of the beam leads to significant geometrical changes of the image and causes an uneven distribution of radiation on the surface of the registering matrix. Attempts at a compensating this issue focus on two main areas:

(1) computer image processing

(2) technical elimination of non-axial beams

The collimation of non-axial diagnostic X-ray beams has for long been performed by means of moving filters (grids) or by lead collimators with thick walls and a narrow pass which allowed only axial beams to pass through. One drawback of using this type of collimator is facing a significant loss of the tube's effective power as the axial beams constitute a small share of the entire emission. Correcting an X-ray image by homogenising the optical density and restoring the geometric relations to a 1:1 status entail a complete remodelling of the image matrix which results in breaching the principle of filing patients' test results in lossless formats (Dyszkiewicz, Wrbel; ICXOM Vienna 2001). An interesting approach to solving this issue were attempts at modifying the direction of non-axial beams (Atkinson K, Folkard M et all; ICXOM Chammonix 2003) based on magnetorheological fluids which made it possible to make immediate changes to the parameters of the beam by using filters of varying densities (Remesh, N; Malagodi D at all; ICXOM Chammonix 2003). A completely different approach, on the other hand, was the idea of constructing a collimator which would be able to modify the propagation angle of non-axial beams towards the axis and even to focus them (Dyszkiewicz, Wrbel ICXOM Chammonix 2003), which would result in an insignificant loss of energy from the initially divergent beam while maintaining relatively good control over the parameters of the produced image (e.g. exposition of soft tissue (fig. 4b) or hard tissue (fig. 4a)). The conducted laboratory experiments have proved that the ferrofluid which has been spatially arranged and put into motion by a magnetic field changes the properties of the permeating diagnostic X-ray beam generated in a parametrically repeatable manner by the tube (permanently coupled with the collimator), located at a fixed distance away from the tested digits on the hand (positioned against the tubes axis by means of a special stand), inducing changes in the optical clarity and density of the contours of soft tissue and bones. Changes in the contrast and thickness of the edge contour of the bone tissue's structure are accompanied by a change in the proportions between the axial and non-axial rays in the diagnostic beam, enabling or disabling the development of a sharp and narrow border line in the presence of an excess numer of rays. Changes in the optical clarity and translucency of the analysed fragments of X-ray images of soft tissues and bones obtained from a repeatable exposition at a fixed distance from the object and different collimator parameter settings prove that changes in the physical properties of X-ray beams occur. Proof of the existence of a dependency between the volume of ferrofluid in the lens and the lens' capability for modifying the parameters of the permeating X-ray beam was of significant importance in confirming the influence of ferrofluid on the physical properties of an X-ray bundle. This may in the future lead to the creation of lenses for various practical applications. A non-linear dependency has also been found between the collimator's rotational speed and its ability to modify the parameters of the permeating X-ray beam. This feature seems to be best evidence that interference occurs at closely quantized electron orbits of atoms belonging to the rotating quasi-crystal of the ferrofluid as it should be remembered that if the crystal was understood to operate as a simple stop, the characteristics would most probably have a linear character. Therefore the clear dependency between the modifying properties of the collimator and the rotational speed, exluding changes in the volume of ferrofluid, seems to be of significant value for the future perspective of creating easily-controllable units, serially produced devices broadening the diagnostic capabilities of standard X-ray tubes or enhancing the further development of work on gradeint tomography. Although the research results have been quite interesting, it is important to bear in mind that the presented scientific evidence concerning the modification of an X-ray bundle has an intermediate character, this due to the fact that it deals with a secondary evaluation of effects induced in the tested object following a conversion of the ray's energy into the visible light range. The main reason why such an approach for conducting this research was chosen is that the medical community has become used to utilising X-ray diagnostics in such a manner, as well as for its considerably lower costs. Currently work is underway in the Laboratory of Biotechnology on the next stage of research which involves making direct measurements of difraction and interference in the output X-ray bundle after being modified by the collimator.

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