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Formalizing the stages of mammographic examinations in designing a medical decision support system

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ABSTRACT

The paper considers the formalization of the stages and modeling of the mammographic examination procedure in the design of medical computer decision support systems. The mammographic examination process is presented in a generalized model, which consists of functional, structural, and mathematical models. The functional model (context diagram) is made using the functional modeling methodology. When analyzing the context diagram, four main functional blocks were identified: register a patient; perform registration and analysis of mammograms; carry out diagnostics; form a survey protocol. If there are standards for maintaining medical records and drawing up examination protocols, the first and last blocks are easily automated. The article focuses on the second and third blocks. At the mammogram analysis stage, the sub-stages "Perform preliminary processing" and "Perform morphological analysis" are essential. Preprocessing of mammograms (adaptive filtering, changing brightness or increasing contrast, etc.) is carried out using digital image processing methods to improve visualization quality. The result of morphological analysis is selecting structural elements and forming a set of diagnostic signs in the form of parameters of the found structural elements. Because some elements of mammograms (microcalcifications) have an irregular structure, specialized morphological analysis methods are used, based on taking into account the features of the images under consideration and their transformation methods in the form of the useful signal, in particular, fractal dimension models. The developed formalized models made it possible to reasonably design the decision support system's structure during mammographic examinations, information, mathematical, software, and hardware to increase medical services' efficiency and minimize the risks of medical errors.

Keywords: mammographic examination; modeling; functional model; structural model; mathematical model; decision support system.

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INTRODUCTION

Modern medicine is characterized by a sharp increase in the amount of processed information during solving traditional medicinal problems: from registering biomedical information to making a diagnosis, determining the prognosis, choosing and correcting treatment tactics based on the diagnosis results.

There is a wide range of computer decision support systems (DSS) in various subject areas of medicine [1-5]. They use such mathematical methods as deterministic logic [6], probabilistic approach [7-8], fuzzy logic [9], neural networks [10], etc. As well they use modern information technologies, for example, telemedicine [11-14].

Because a significant portion of diagnostic information is occupied by biomedical signals and images (BMS / I), much attention is paid to themethods of their processing in order to improve the quality of visualization, morphological analysis (highlighting of diagnostically significant structural elements amid noises), and determination of diagnostic signs [15-18].

Biomedical images (BMI), such as X-rays, mammograms, ultrasound, etc., are essential sources of obtaining visual information about the human body's internal structures and functions, which are not directly perceived by sight.

The use of modern methods of processing and analyzing medical images involves improving the quality of images and morphological analysis of data, classification of images, work with complex-structured samples, with non-obvious patterns and features that are often noticeable only to specialists in this field. It makes it possible to facilitate working with images, increase diagnosis reliability, and choose the right treatment tactics.

In particular mammograms, BMI are grayscale images with locally lumped signs (LLS); that is, they have a structure in which diagnostic signs are focused on small fragments of their definition area. The task of morphological analysis is to highlight informative fragments (structural elements) amid noises, resulting from which diagnostic signs are formed in the form of parameters of the found structural elements.

Existing digital image processing methods do not consider BMI features with LLS. They have a limited scope for processing BMS because these images are low-contrast, contain a significant noise component, and diagnostic elements have significant variability. In addition, some elements have an irregular (fractal) structure (for example, microcalcifications in mammography). Therefore, the relevance of the topic lies in formalizing the stages of mammographic examinations, in the development of specialized methods for improving visualization and morphological analysis, which are based on formal BMI models, for example, on a fractal dimension model in order to improve the quality of mammographic examinations of patients while designing a DSS.

Thus, the analysis showed that while designing a DSS for mammographic examinations, the examination process can be represented in a generalized model, including functional, structural, and mathematical models.

The work aims to design medical computer decision support systems by formalizing the main stages, modeling the mammographic examination procedure based on BMI analysis.

The following tasks are solved to achieve the aim:

– perform formalization of the mammographic examination process by developing a generalized model that includes functional, structural, and mathematical models;

– develop a functional model and perform its decomposition;

– develop a mathematical model that formalizes the knowledge formed due to stages of morphological analysis and diagnostics.

– develop a block diagram of a decision support system for mammographic examinations.

– perform software implementation and test verification of the mammogram morphological analysis module.

DEVELOPMENT OF GENERALIZED MODEL OF MAMMOGRAPHIC EXAMINATION

Mammographic examination results by specialist doctors are diagnostic conclusions formed based on the analysis of mammograms. To improve the examination's efficiency, it is necessary to perform a systematic analysis of the decision-making process to highlight the critical elements of the DSS that can lead to incorrect decisions or refusal to make decisions.

We represent the process of mammographic examination in the form of a generalized model $\boldsymbol{M_G}$ of the form:

$$\boldsymbol{M_G} = \{\boldsymbol{M_F}, \boldsymbol{M_S}, \boldsymbol{M_M}\},$$

where $\boldsymbol{M_F}$, $\boldsymbol{M_S}$, $\boldsymbol{M_M}$ are functional, structural, and mathematical models of the mammographic examination process, respectively.

Let us consider in more detail the functional and mathematical models. As a structural model of $\boldsymbol{M_S}$, as a rule, a directed graph is proposed, reflecting the primary states of this process and their interactions. As a result of graph analysis, probabilistic-temporal characteristics of transitions from one state of the graph to another are determined to identify bottlenecks and optimize the process. The development of the $\boldsymbol{M_S}$ structural model is a separate task and is beyond this article's scope.

We represent the functional model $\boldsymbol{M_F}$ using the functional modeling methodology IDEF0 [19]. It is necessary to define the inputs, outputs, controls, and mechanisms to build a contextual diagram that presents the mammography examination as a whole and shows the connection with the outside world.

Patient data (name, sex, age, medical history, indications for mammographic examination, etc.) are considered as an input. As a result of the examination, the patient should receive an examination protocol and recommendations on tactics for further examination and/or treatment, which we will consider as outputs of the functional model $\boldsymbol{M_F}$.

Various legislative acts and regulatory documents (including standards for the formation of examination protocols) act as management. They regulate the process of mammographic examination of a patient. In addition, the examination of the patient is carried out by the medical staff (mammologist, nurse, laboratory assistant, technician, etc.), using a specialized mammography complex, which allows registering mammograms, and a personal computer (PC), which inputs, stores and processes the information. The context diagram's main mechanisms are the patient, the specialist doctor, the diagnostic complex, and the PC.

Thus, based on the selected inputs, outputs, controls, and mechanisms, a context diagram of the functional model $\boldsymbol{M_F}$ of mammographic examination of a patient, shown in Fig. 1, was built.

Let us perform the functional decomposition of the model context diagram. Taking into account the peculiarities of the mammographic examination process, four main functional blocks (work) were identified: register the patient (work 1); perform registration and analysis of mammograms (work 2) carry out diagnostics (work 3); form an examination protocol (work 4).

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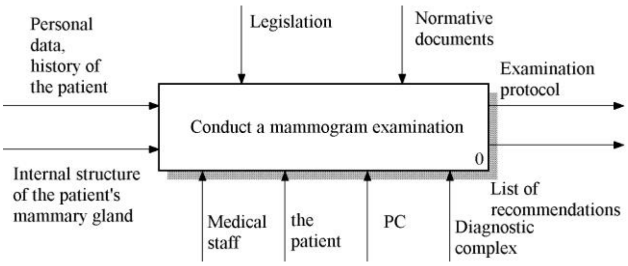

Fig. 1. **Context diagram of mammographic examination functional model M_F**
***Source:* compiled by the author**

The decomposition of the context diagram is shown in Fig. 2.

For *work 1* "Register the patient," the initial data is the patient data specified above, and the output data is the medical record.

The medical record is filled out using a PC by the medical staff based on the patient's data from the referral for examination and the patient's interview. Thus, the patient, the medical staff, and the PC are the mechanisms of this work, while the legislation and regulatory documentation are the controls for the work 1.

The *input of work 2* "Perform registration and analysis of mammograms" is the patient's mammary gland's internal structure, control-regulatory documentation, and data from the medical record.

These data allow configuring (if necessary) the essential parameters of the diagnostic complex (for example, the duration and parameters of X-ray radiation).

With the help of a diagnostic complex associated with a PC, the medical staff performs registration and subsequent analysis of mammograms in order to determine diagnostic signs (parameters of structural elements), as well as pathological changes (morphological changes in structural elements, the absence of structural elements that are present under normal conditions, and/or the presence artifacts in the form of additional structural elements that should not be normal). Thus, the initial data of work 2 are diagnostic signs and identified pathological changes, and the mechanism is the patient, medical staff, diagnostic complex, and PC.

The *outputs of work 2* and data from the medical record are the *inputs of work 3* "Carry out diagnostics", at the output of which a diagnostic solution is formed. The diagnostic decision is made by a mammologist using a PC, on which various specialized programs, including DSS, can be installed.

As a *result of performing work 4* "Form an examination protocol" based on data from the medical record and the generated diagnostic solution (inputs of work 4), the medical staff using a PC (mechanisms of work 4) fills out the examination protocol and compiles a list of recommendations (outputs of work 4). At the same time, legislative acts and normative documentation is the control of work 4.

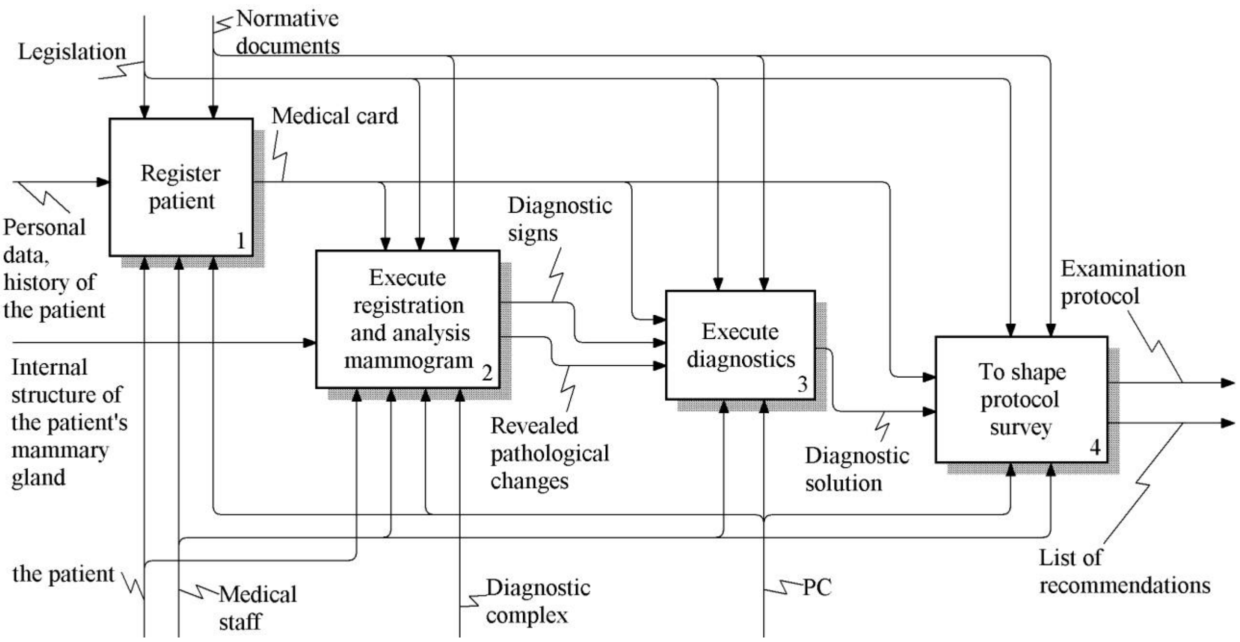

Fig. 2. **Decomposition of functional model M_F context diagram**
***Source:* compiled by the author**

It should be noted that the first and last work is fairly easily automated, especially if there are standards for maintaining medical records and drawing up examination protocols. Simultaneously, the second and third works are the most responsible, affecting the examination's quality and efficiency. In addition, possible errors during the mammogram analysis stage are critical for the entire mammographic examination process. Therefore, further decomposition of functional blocks 2 and 3 (Fig. 3) and (Fig. 4) was performed.

For the *decomposition of work 2* "Perform registration and analysis of mammograms," the works register a mammogram (work 21), perform preliminary processing (work 22), perform morphological analysis (work 23), analyze the parameters of structural elements (SE) (work 24) were allocated.

The *input of work 21* "Register mammogram" is the patient's mammary gland's internal structure. As a result of the work performed with the help of digital mammography, the medical staff takes X-rays of the patient's mammary gland in the given projections, so the output is recorded digital mammograms, the data from the medical record, as well as legislation and regulatory documents, act as a control, and the mechanisms are the patient, medical staff and diagnostic complex.

The registered mammograms are sent to the *input of work 22* "Perform preliminary processing", in which the medical staff with the help of PC and using digital image processing methods [20-21] performs various kinds of preliminary processing of mammograms (for example, filtering, changing the brightness or increasing the contrast, etc.), which provides an increasing quality of visualization.

From the *output of work 22*, processed BMIs with LLS are fed to the *input of work 23* "Perform morphological analysis", due to which diagnostic signs are formed in the form of parameters of the found structural elements. Because some elements of mammograms (microcalcifications) have an irregular structure, specialized methods of morphological analysis are used, based on taking into account the features of the considered images and methods of their transformation in the form of useful signal models [22], in particular, fractal dimension models [23-24].

Morphological analysis can be carried out both in automatic and semi-automatic or manual modes. In automatic mode, the mammologist only confirms the correctness of the morphological analysis results, confirming that all structural elements were found correctly, and their parameters were measured correctly.

In the case of the semi-automatic mode, after the selection of structural elements by specialized computer programs, the mammologist corrects the results of the morphological analysis using a specialized computer program, that is, marks the missing structural elements and/or removes marks from areas of the image that were recognized as structural elements, but not are.

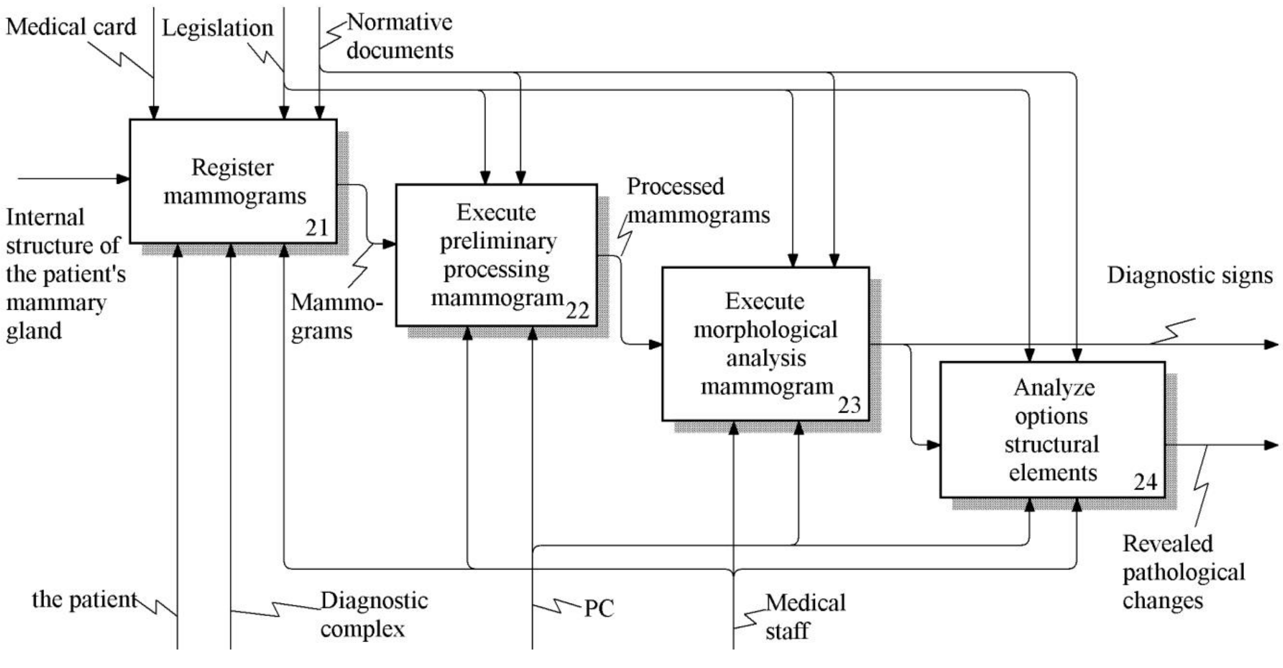

Fig. 3. **Decomposition of functional block 2 "Perform registration and analysis of mammograms" of the functional model M_F mammographic examination**

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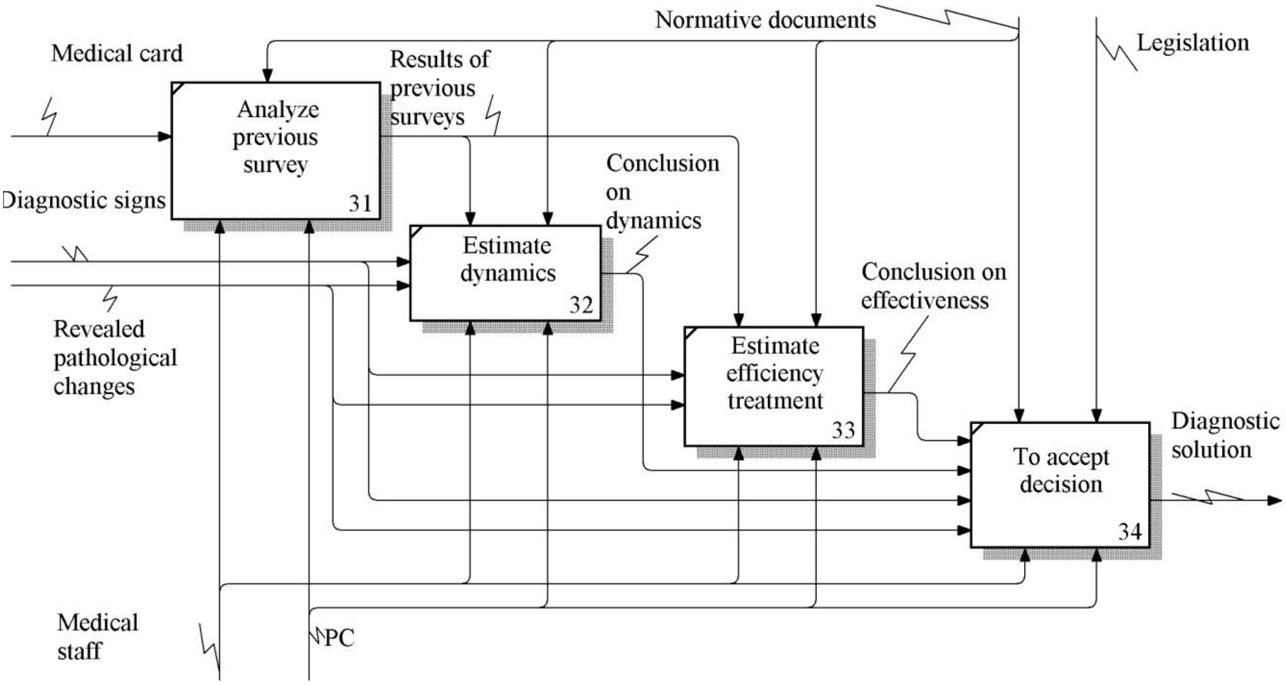

Fig. 4. **Decomposition of functional block 3 "Carry out diagnostics" of the functional model M_F of mammographic examination**
Source: **compiled by the author**

If the manual mode is used, then the morphological analysis is wholly performed by a mammologist. Simultaneously, specialized programs are used to improve the quality of visualization of images or their individual selected areas.

The diagnostic signs obtained as a result of performing *work 23* are outputs of work 2. In addition, they enter the input of *work 24* "to analyze the parameters of structural elements," the output of which is the detected pathological changes, if they were found, or the conclusion that there are no such pathological changes. Similarly to work 23, the mammologist performs work 24 using specialized programs installed on the PC.

This work can also be performed in automatic (the doctor only confirms the decision made by the DSS), semi-automatic (the doctor can correct the decisions generated by the DSS), or manual (specialized programs are used as a visualization tool) modes. In works 22, 23 and 24, various legislative acts and regulatory documents are controls.

As a result of decomposition of work 3 "Carry out diagnostics", the following works were identified (see Fig. 4): analyze the previous examination (work 31), evaluate the dynamics (work 32) and evaluate the effectiveness of treatment (work 33); make a decision (work 34).

There is often a situation when a patient undergoes a mammographic examination repeatedly (for example, in the case of screening or evaluating the dynamics of the development of a particular disease). Therefore, to develop a complete diagnostic solution, the mammologist must obtain data about previous examinations if they were. Therefore, the input of work 31 "Analyze previous examinations" receives information from the patient's medical record. With computer information retrieval systems (mechanisms), the medical staff searches for data on previous examinations (output).

If the previous examinations were found, then one of the works can be performed further: work 32 "Evaluate the dynamics" or work 33 "Evaluate the effectiveness of treatment". It should be noted that for the execution of works 32 and 33, data about previous examination results act as a control. When previous examinations were carried out due to screening, then work 32 "Evaluate the dynamics" is performed. In this case, diagnostic signs and pathological changes have identified the inputs of work 32. The output is a conclusion about the dynamics of the development of the pathological process or its absence. Suppose preliminary examinations were carried out after the treatment. In that case, work 33 "Evaluate the effectiveness of treatment" is performed, for which the inputs are also diagnostic signs and identified pathological changes. The output is the conclusion about the effectiveness of treatment.

In addition to the controls mentioned above for works 31, 32 and 33, the controls are various regulatory documents that regulate what information and in what form must be provided to perform these works.

If previous examinations were not carried out, work 34 is performed only based on diagnostic signs and detected pathological changes. Otherwise, additional inputs of work 34 are the conclusion about the dynamics or the effectiveness of treatment. After processing all the data, the final diagnostic solution is formed at the output. Control of work 34 is normative documents and legislative acts. Like work 31, work 32, 33 and 34 are performed by medical staff using a PC (mechanisms).

Decomposition of works 2 and 3 showed that one of the most important is work 23 “Perform morphological analysis of mammograms”, since possible errors in determining diagnostic signs, which are obtained based on the found structural elements, can lead to incorrect diagnostic decisions. One of the reasons for the appearance of such errors can be the low quality of the registered mammograms. Therefore the work 22 “Perform preliminary processing of mammograms” is also very important.

It should be noted that the context diagram discussed above is a generalized functional model of image processing and can be used in other subject areas of medicine. The peculiarities of mammogram processing, taking into account their fractal dimension, are taken into account in blocks 22 “Perform preliminary processing of mammograms” and 23 “Perform morphological analysis of mammograms”. A feature of these blocks is considering the mathematical model of the mammographic examination process developed below.

DEVELOPMENT OF A MATHEMATICAL MODEL

Based on the previously considered functional model, the following mathematical model $\boldsymbol{M_M}$ of the process of mammographic examination is proposed:

$$M_M = \left\langle SP, SP^p, SP_v^p, X, X^p, D, D^p, S_D, S_X, T, Q_t \right\rangle,$$

where $SP = \{sp_i[\cdot] | i \in \{1,\ldots,n_{SP}\}\}$ is a set of digital mammograms;

$SP^p = \{sp_i^p[\cdot] | i \in \{1,\ldots,n_{SP}\}\}$ is a set of digital mammograms that are measured in the patient;

$SP_v^p = \{sp_{v_i}^p[\cdot] | i \in \{1,\ldots,n_{SP}\}\}$ is a set of digital mammograms of the patient that are preprocessed to obtain the required imaging quality;

$X = \{x_i \in X^{(A)} \cup X^{(SP)} | i \in \{1,\ldots,n_X\}\}$ is a set of diagnostic signs;

$X^{(A)}$ and $X^{(SP)}$ are the subset of primary (measured directly at the patient) and secondary (obtained by processing mammograms) diagnostic signs;

$X^p = \{x_i^p | i \in \{1,\ldots,n_X\}\}$ is a set of diagnostic signs which are measured in the patient;

$D = \{d_k | k \in \{1,\ldots,n_D\}\}$ is a set of possible diagnostic statuses, i.e., the alphabet of diagnoses;

$D^p = \{D_i^p | i \in \{1,\ldots,n_D\}\}$ is a set of diagnostic conclusions that are made to patients;

S_X, S_D are the hierarchical structures of diagnostic signs and diagnosed statuses, respectively;

$T = \left\{ t_{SP^p SP_v^p}, t_{SP X}, t_{SP_v^p X^p}, t_{X^p D^p} \right\}$ is a set of mappings between corresponding sets;

Q_t is a set of mapping criteria *t*;

$n_X, n_{SP}, n_D \in N$ are cardinalities of the corresponding sets;

N is a set of natural numbers.

The mapping $t_{SP^p SP_v^p}$ implements preprocessing mammograms. Since mammograms are low-contrast images containing a significant noise and gradient background component, the adaptive filtration method developed with the authors’ participation, described in [24], improves the visualization quality.

The mapping $t_{SP X}$ determines the algorithm, and $t_{SP^p X^p}$ realizes the procedure for the morphological analysis of mammograms [22, 25], and determines a vector of secondary diagnostic signs. The calculation of the fractal dimension of mammograms during their morphological analysis is presented below.

The mapping $t_{X^p D^p}$ implements the diagnostic decision rule governed by hierarchical structures S_X and S_D [26].

Thus, a mathematical model of mammographic examination of a patient has been developed, with the help of which the formalization of knowledge has been carried out that are formed as a result of the following stages of information processing: preliminary processing; morphological analysis; diagnostics.

CALCULATION OF THE FRACTAL DIMENSION OF MAMMOGRAMS

A mammogram is a digital halftone image that is defined by many points

$$F = \{Z_{ij}, i = \overline{0,k}, j = \overline{0,l}\}, \quad (1)$$

where $Z_{ij} \in \{0, 255\}$ is the intensity value for a pixel with coordinates (*i*, *j*).

If we assume that the set *F* is a fractal set, then to calculate its fractal dimension, a method is used,

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the main idea of which is to construct the surface of the graph of the grayscale function, calculate the volume of a special "cover" for this surface, and then calculate the fractal dimension of the surface [23].

Since grayscale is only defined for a pixel, F can be considered as a function of integer arguments. Let us extend F for points with real coordinates (x, y), $i \le x < i+1$, $j \le y < j+1$, then we can talk about the surface area of the graph of the constructed function F (we can add it with the values of Z_{ij} or using any approximation).

Let us consider all points located at a distance δ from the surface of the graph of the grayscale function. They form a "cover" with a thickness of 2δ, which is a δ-parallel body and is defined by the upper surface $u_\delta(i, j)$ and the lower surface $b_\delta(i, j)$. For δ=1,2,... the surfaces are determined iteratively:

$$u_\delta(i, j) = \max\{u_\delta(i, j)+1, \max_{|(m,n)-(i,j)\le 1|} u_\delta(m,n)\} \quad (2)$$

$$b_\delta(i, j) = \min\{u_\delta(i, j)-1, \min_{|(m,n)-(i,j)\le 1|} u_\delta(m,n)\} \quad (3)$$

It can be seen from (2) and (3) that we use four nearest neighbors in the extreme points' calculations.

A point $F(x, y)$ is included in a δ-parallel body if

$$b_\delta(i, j) \le F(x,y) < u_\delta(i, j).$$

The volume of a δ-parallel body is calculated as

$$V_\delta = \sum_{i,j} (u_\delta(i,j) - b_\delta(i,j)). \quad (4)$$

The following formula calculates the surface area of the fractal

$$S_\delta = \frac{V_\delta}{2\delta}. \quad (5)$$

Then the fractal dimension D is determined from the relation [23]:

$$D = 2 - \frac{\log_2 S_\delta}{\log_2 \delta}. \quad (6)$$

Calculation of the surface area of the graph of the function F can be performed for the whole image or a selected fragment.

Considering that the fractal dimension D calculated according to (6) will differ for different δ, the average value of the ratio

$$\frac{\log_2 S_\delta}{\log_2 \delta}, \quad (7)$$

is found by the method of least squares as the slope a_1 of the straight line $y = a_0 + a_1 x$ in coordinates

$$x = \log_2 \delta;\ y = \log_2 S_\delta.$$

Based on the above, the following algorithm for calculating the fractal dimension of halftone images is proposed.

1. For the whole image or a selected fragment, construct a grayscale function Z_{ij}.

2. Determine the initial values of the two-dimensional array of points of the upper and lower surfaces of the δ-parallel body for δ = 0:

$$u_0(i, j) = b_0(i, j) = Z(i, j),\ i = \overline{0, k},\ j = \overline{0, l}.$$

3. Organize a cycle of changing the scale δ ($\delta = \overline{1, 256}$), at each stage of which the following actions are performed:

3.1. Two-dimensional arrays of points of the upper $u_\delta(i, j)$ and lower $b_\delta(i, j)$ surfaces of a δ-parallel body are calculated by formulas (2) and (3).

3.2. The volume of a δ-parallel body V_δ is calculated by the formula (4).

3.3. The surface area S_δ of the fractal is calculated by the formula (5).

3.4. The values $\log_2 \delta$ and $\log_2 S_\delta$ are calculated and stored in the corresponding arrays.

4. By the method of least squares, calculate the linear regression coefficient a_1 of the form $y = a_0 + a_1 x$ in coordinates $x = \log_2 \delta;\ y = \log_2 S_\delta$. The calculated value is taken as the average value of the ratio (7), which is then used in the formula (6).

5. Using the formula (6), find the fractal dimension of an image or a selected fragment.

THE DISCUSSION OF THE RESULTS

Proposed solutions for this article are the basis for the development of a DSS structure for mammographic examinations.

Requirements for the DSS are formulated, such as:

– ease of input, processing, analysis, and storage of heterogeneous biomedical information (text, numerical, BMI, and so on), as well as the ability to store and use reference information;

– clarity of presentation of input and output information in the form of tables, graphic display of signals and images, etc.;

– creation and use of knowledge base (description of models and rules for transforming information while conducting a morphological analysis of BMI, diagnosis, and treatment);

– modular principle of software construction, which provides the ability to adapt, modify and expand software while implementing a DSS in a specific subject area of medicine;

– compatibility of data transfer between individual DSS modules based on the use of typed data structures.

The structural diagram of the DSS is shown in Fig. 5.

Consider the correspondence between the DSS blocks (Fig. 5) and the functional model blocks (Fig. 2; Fig. 3 and Fig. 4). Block 12 DSS corresponds to block 21 of the functional model; block 12 – block 22; block 14 – blocks 23; 24; block 11 – to block 34 taking into account the results of blocks 31-33; the rest of the DSS blocks ensure the operation of the previously marked blocks. In addition, in the DSS scheme, the roles are detailed – the roles of the decision-maker are separately highlighted – a mammologist and an expert doctor with different powers (see below). The administrator's role has also been introduced – a mandatory role in computer systems and DSS operation. The input and output data are also detailed, represented by the mathematical model variables.

Let us consider the functional purpose of the modules.

The database stores information about patients and the results of their examinations, diagnostics, and treatment, received BMI, various reference information (regulatory documents, protocol forms, ICD-10 disease classifiers, and so on), and other information necessary for the functioning of a biomedical DSS.

The knowledge base stores the methods and rules for transforming information. Transforming methods include morphological analysis of BMI, formalization of input information, development of diagnostic solutions, and recommendations for the appointment of MA.

The knowledge building module is responsible for forming knowledge frames represented by the methods of morphological analysis of BMI, hierarchical structures S_X and S_D, decisive rule parameters.

The module for preliminary processing of medical data is intended to provide the operation of the hardware component of the DSS, input, and storage of medical data, including BMI, performs standard processing methods, such as formalization of heterogeneous medical data (numerical, rank, dichotomous), filtering, contrast correction of BMI, and so on, carries out the maintenance of the patient's medical record, the formation, and printing of diagnostic conclusions and recommendations for treatment methods.

A graphical user interface represents the user interaction module. It allows collecting examination data, entering BMI, visualizing work results, administering data, and entering expert data that are used in the formation of system knowledge.

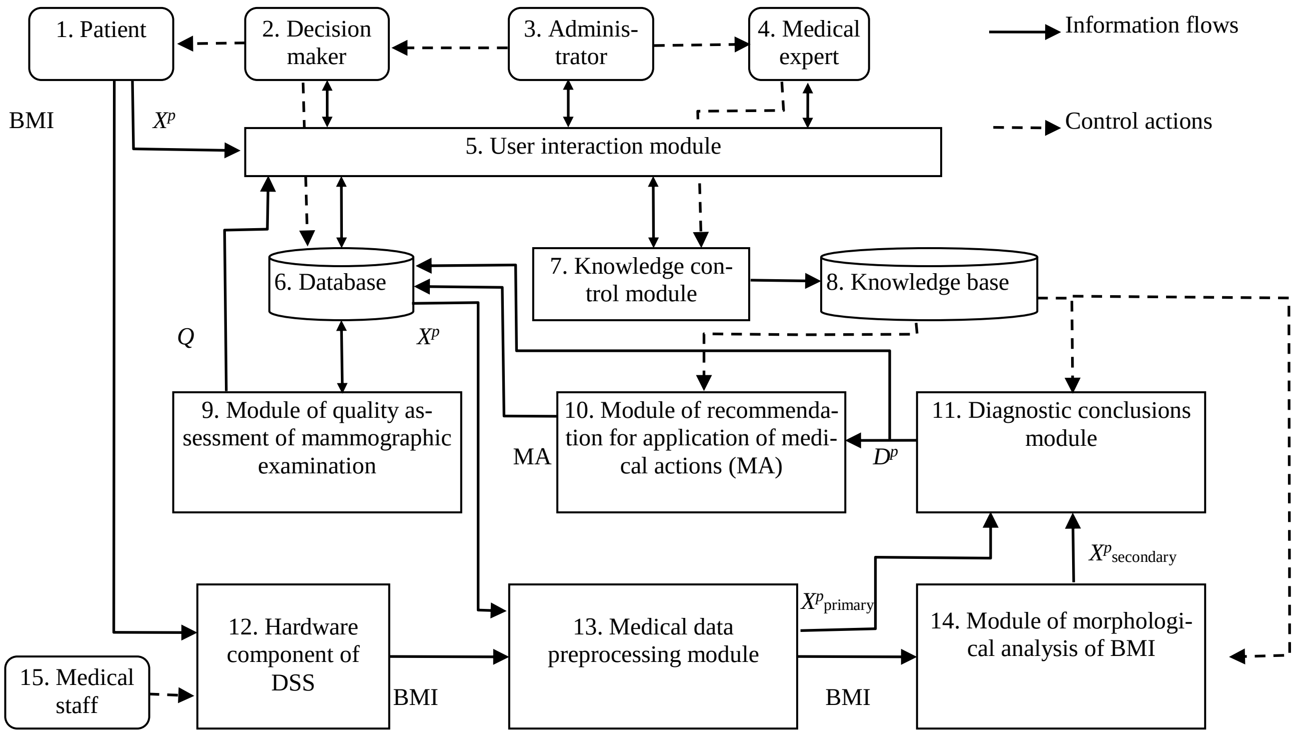

Fig. 5. **Structural diagram of the DSS**
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Simultaneously, the following users are defined: administrator, medical expert, and decision-maker – user-doctor. The administrator determines what powers to grant to other users. However, he cannot independently make changes to the database and knowledge base and verify the system solution since he is not a doctor.

The medical expert has the most significant powers. He can revise and correct the database (delete, change data), make changes to the knowledge base, and correct the system solution. However, the main task of an expert is to form a knowledge base. The user-doctor can only revise the database and, by entering the patient's personal data, receive the system's decision regarding the diagnosis and the list of recommended treatment methods. He is also allowed to make changes to the resulting solution by verifying it – the system interface changes depending on the type of user.

During visualization, text information is displayed on the monitor screen, BMI is visualized with the possibility of interactive work and changes in visualization parameters (for example, selecting a particular area of the BMI with subsequent zooming, fixing marks, correcting the brightness and/or contrast of the BMI, and so on).

The morphological analysis module implements specialized BMI analysis methods, as a result of which a vector of secondary diagnostic signs is formed.

The modules of diagnostic conclusions and recommendations for using treatment methods are designed to formulate decision-makers' recommendations and argumentation. The decision-maker confirms or corrects the decisions of the system.

In the quality assessment module, various criteria for evaluating individual DSS modules' work can be implemented depending on the task.

Software implementation and testing. The software implementation of the morphological analysis module has been completed, which is developed in the MATLAB environment and can be connected to the main program in the form of a DLL module. The module has been tested on real mammogram images. Mammogram files in *.mam format were kindly presented by the domestic mammographs developer – the Radmir company, Kharkiv. 60 mammograms were analyzed; among them, 40 were without obvious pathologies, and 20 were with pathological structures of various types (tumors, intraductal formations, and microcalcifications).

The fractal dimension of the entire image and selected fragments was calculated. Based on the test results, it was concluded that the entire image's fractal dimension does not give statistically significant results in the sense of Fisher's criterion for the presence or absence of pathologies. In all mammograms, the fractal dimension ranges from 2.4 to 2.5. However, if you calculate the fractal dimension on the selected fragments, the results are statistically significant – the fractal dimension is greater than 2.6. One can trace the pattern that the more apparent pathologies on a fragment, the greater the fractal dimension.

CONCLUSIONS

The modeling of the mammographic examination process based on the BMI analysis allowed us to reasonably design a specialized medical computer decision support system to increase the efficiency of medical services.

Using the IDEF0 functional modeling methodology, a functional model has been developed that represents the mammographic examination as a whole and shows the connection with the outside world; its inputs, outputs, controls, and mechanisms are determined. A two-level decomposition of the model was carried out, as a result of which the stages of mammographic examination were formalized with due detail.

A mathematical model has been developed, with the help of which the formalization of knowledge is carried out, which is formed due to stages of morphological analysis and diagnosis. For the morphological analysis of mammograms, a method and algorithm for calculating the fractal dimension of medical images or selected fragments have been developed.

Based on the developed models, a generalized structure of the decision support system for mammographic examinations is synthesized.

The software implementation of the module for morphological analysis of mammograms and its test check was performed. They confirmed the statistical significance of the fractal dimension parameter on the selected fragments in identifying pathological structures.

The results obtained in this work are of methodological importance and can be used to analyze medical images in other applied fields of medicine.

Further research aims to develop a method for the classification of mammograms taking into account their fractal dimensions, software implementation of the mathematical model, and experimental verification of the system's efficiency.

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Формалізація етапів мамографічних обстежень при проектуванні медичних систем підтримки прийняття рішень

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АНОТАЦІЯ

В роботі розглянута формалізація етапів і моделювання процедури мамографічних обстежень при проектуванні медичних комп'ютерних систем підтримки прийняття рішень. Процес мамографічного обстеження представлено у вигляді узагальненої моделі, яка включає в себе функціональну, структурну та математичну модель. Функціональна модель (контекстна діаграма) виконана за допомогою методології функціонального моделювання. При аналізі контекстної діаграми були виділені чотири основних функціональних блока: зареєструвати пацієнта; виконати реєстрацію та аналіз мамограм; виконати діагностику; сформувати протокол обстеження. Відзначено, що при наявності стандартів ведення медичних карт і оформлення протоколів обстеження, перший і останній блок досить легко автоматизуються. У статті приділено основну увагу другому і третьому блокам. На етапі аналізу мамограм важливими є підетапи «Виконати попередню обробку» і «Виконати морфологічний аналіз». Попередня обробка мамограм (адаптивна фільтрація, зміна яскравості або підвищення контрасту і т. д.) реалізується методами цифрової обробки зображень з метою підвищення якості візуалізації. Результатом морфологічного аналіз є виділення структурних елементів і формування множини діагностичних ознак у вигляді параметрів знайдених структурних елементів. Так як деякі елементи мамограм (мікрокальцинати) мають нерегулярну структуру, то застосовуються спеціалізовані методи морфологічного аналізу, засновані на врахуванні особливостей розглянутих зображень і методів їх перетворення у вигляді моделей корисних сигналів, зокрема моделей фрактальної розмірності. Розроблені формалізовані моделі дозволили обгрунтовано спроектувати структуру системи підтримки прийняття рішень при проведенні мамографічних обстежень, створювати інформаційне, математичне та програмно-апаратне забезпечення з метою підвищення ефективності надання медичних послуг та мінімізації ризиків лікарських помилок.

Ключові слова: мамографічне обстеження; моделювання; функціональна модель; структурна модель; математична модель; комп'ютерна система; прийняття рішення

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Формализация этапов маммографических обследований при проектировании медицинских системы поддержки принятия решений

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АННОТАЦИЯ

В работе рассмотрена формализация этапов и моделирование процедуры маммографических обследований при проектировании медицинских компьютерных систем поддержки принятия решений. Процесс маммографического обследования представлено в виде обобщенной модели, которая включает в себя функциональную, структурную и математическую модель. Функциональная модель (контекстная диаграмма) выполнена с помощью методологии функционального моделирования. При анализе контекстной диаграммы были выделены четыре основных функциональных блока: зарегистрировать пациента; выполнить регистрацию и анализ маммограмм; выполнить диагностику; сформировать протокол обследования. Отмечено, что при наличии стандартов ведения медицинских карт и оформления протоколов обследования, первый и последний блок достаточно легко автоматизируются. В статье уделено основное внимание второму и третьему блокам. На этапе анализа маммограмм важными являются подэтапы «Выполнить предварительную обработку» и «Выполнить морфологический анализ». Предварительная обработка маммограмм (адаптивная фильтрация, изменение яркости или повышение контраста и т. д.) реализуется методами цифровой обработки изображений с целью повышения качества визуализации. Результатом морфологического анализ является выделение структурных элементов, и формирование множества диагностических признаков в виде параметров найденных структурных элементов. Так как некоторые элементы маммограмм (микрокальцинаты) имеют нерегулярную структуру, то применяются специализированные методы морфологического анализа, основанные на учете особенностей рассматриваемых изображений и методов их преобразования в виде моделей полезных сигналов, в частности моделей фрактальной размерности. Разработанные формализованные модели позволяли обоснованно спроектировать структуру системы поддержки принятия решений при проведении маммографических обследований, создавать информационное, математическое и программно-аппаратное обеспечение с целью повышения эффективности оказания медицинских услуг и минимизации рисков врачебных ошибок.

Ключевые слова: маммографическое обследование; моделирование; функциональная модель; структурная модель; математическая модель; компьютерная система; принятие решения

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