Computer Science Journal of Moldova, vol.15, no.2(44), 2007

SONARES - A decision support system in ultrasound investigations

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In order really to know things, we have to know them in detail; and since detail is almost infinite, our understanding is always superficial and imperfect.

(La Rochefoucauld, Maxims, nr. 106)

Abstract

The article represents synthesis of results obtained in the process of development of SonaRes – the decision support system for ultrasonographic diagnosis. The system structure, its main components are described, the series of problems with which the developers of Clinical Decision Support Systems confront are examined.

1 Introduction

Decision Support Systems (DSS) for medical assistance are considered to be truly the first DSS in the history of artificial intelligence [1]. Being initially conceived just as systems for medical diagnosis, in the sequel they extended the area of their functionality, covering the aspects of administration, management, treatment control, and as a matter of fact the assistance in diagnosis as well. Below we will concentrate on the last of the enumerated functions. In general aspect we will treat the decision support systems in compliance with following definitions:

- Decision support systems are a class of informatics systems with anthropocentric characteristics, adaptive and evolutional, which integrate a set of informatics technologies and communications of general use and specific communications and interact with other parts of global informatics system of an organization [2].
- DSS are the computerized assistants which help the manager with information transformation to actions which are effective for a system [3].

From the multitude of definitions for Clinical Decision Support Systems (CDSS) we will follow the one by Dr. Robert Hayward (taken from www.openclinical.org): ,,Clinical Decision Support systems link health observations with health knowledge to influence health choices by clinicians for improved health care."

Just as in any DSS the human-computer interaction in CDSS manifests itself in the following way:

- DSS cooperates with the decision maker in all considerable operations of the decision process besides the computational ones.
- The decision-making evolves in conditions of partial lack of information and at the enhanced level of uncertainty.
- In DSS the decision maker is the one who initiates and controls the process of decision-making in correlation with his personal objectives, the one who interprets the results and determines the solution choosing.
- Every decision maker is guided by his own specific rules of reasoning and makes the decisions having his own view on the problem.

The decision support in the process of ultrasonographic examinations constitutes our domain of interests. This process has the following characteristics:

Advantages:

- Paraclinic noninvasive investigations,

- Efficiency,
- Easy execution by *qualified* specialist,
- Reduced cost of equipment (comparatively with another imagistic equipment).

Disadvantages:

- Dependence on operator (in images obtaining and interpreting),
- Obtaining of false-negative or false-positive images,
- Reduced quality of images (comparatively with those radiographic),
- Lack of highly qualified personnel.

Especially we will emphasize that in reality the sequence of information exactness losses is inherent to the process of ultrasonographic investigation: analog signal emitted by probe is transformed in the digital one, which in its turn, serves as a source for image construction. This image is accepted (subjectively) by operator, obtaining as a result a written interpretation, which is more or less adequate to this image, depending on the operator's experience and professional skill. Our purpose when projecting the system SonaRes consists in decreasing of these information losses.

The system plays a consultative role and offers to users its variants of diagnosis. The primary use of the system might be as a 'second opinion' in difficult cases and in emergency; it does not replace physician who interprets echograms. Thus, SonaRes is destined to improve health care by providing a highly efficient diagnostics tool. In [4] one can find a comparison with existing systems according to the following functional capabilities: use of both the images and their descriptions, an interactive interface for knowledge acquisition, an intelligent interface, expertise reporting, explanation of the decision, possibility of adding to knowledge base on the basis of precedents, examination of the organs interaction, image processing, the standardized descriptions and decisions, possibility to use the system in automated learning, treating of patient's state in dynamics.

2 The system structure

Coming out of the experience of other systems exploitation we have taken and developed their advantageous aspects, having supplemented them with new qualities, namely [4]: to develop an approach which includes interaction between organs and uses current and precedent similar images in decision making process. Special attention is paid to ergonomic user interface, which is generated dynamically by system according to the DB content and is adaptable to preferences and objectives (of investigation type) of the physician-echographist.

We will offer to specialist, even without wide experience, an access to a resource where the process of ultrasound examination is detailed and formalized and includes an enormous amount of useful information on anatomy, ultrasonic semeiology, differential diagnostic as well as condensed presentation of the main nosologic entities that should appear in the physician's mind at the moment of examination of each organ.

The system SonaRes helps the specialist in ultrasonic analysis to draw the conclusion more correctly, especially, in emergency cases or in unspecific clinic/paraclinic cases, which do not seem to be included in any classical presentation; in cases where the obtained ultrasonic semeiology can provide a correct diagnosis without complicated and, often difficult of access, medical investigations.

SonaRes offers to a user a second opinion with necessary explanations and images that are similar to the examined case. Images can be processed and problem zone, if it is necessary for the user-physicist, can be marked out.

The main components of the system are the following:

- Knowledge acquisition
- Examination support
- Unified database (knowledge, images, annotations etc.)

- Image processing algorithms
- Reports generator

In order to develop these components we are elaborating and adapting:

- formalized descriptions of the abdominal organs, pathologies, anomalies;
- formalized descriptions of the ultrasound investigations methodology;
- unified, standardized disease descriptions;
- knowledge acquisition methods based on ultrasound investigations characteristics;
- a diagnostics validation tool;
- a database model for the medical images, their annotations and fuzzy information storage;
- images clusterization and quick database searching algorithms;
- an ergonomic, dynamically generated and user friendly interface;
- reports' prototypes and their generator.

At the first stage we deal with abdominal zone investigation. The investigation process of this zone is especially difficult (more organs with additional interactions, higher level of confusion, etc.). We have approved our technique on gall bladder and extend it on other organs.

3 Knowledge Structure Modeling in Ultrasound Investigation Domain

Ultrasound investigation domain, just as all medicine as a whole, is a weakly formalized subject domain. Therefore creation of the computer aided informational systems (for diagnostics, for learning, etc.) in this area needs a preliminary research of used knowledge structure, its acquisition and formalization.

Traditionally during knowledge acquisition process two persons are involved. The first one is the expert, the knowledge of which it is necessary to use. He should explain how he makes the decision basing on the initial information. The other person is "knowledge engineer". He does not possess knowledge of the expert, but understands how to present this knowledge in a format accessible for further use in computer systems. Also "knowledge engineer" defines the method of knowledge storage and representation, so he defines the structure of the future knowledge base, where the formalized knowledge received from the expert will be collected.

Inconveniences of "knowledge engineer" usage during the knowledge acquisition process are obvious. Time spent for interaction between the expert and the engineer influences terms of knowledge base creation. The information received from the expert can be apprehended incorrectly by the engineer that will cause mistakes in the knowledge base. So the time-consuming procedures of the additional control are necessary.

The alternative method is creation of an expert environment – accessible to the expert knowledge base generator with intuitively clear process of its filling. In this case the expert himself can supervise knowledge base filling process from the beginning up to the end. So the "knowledge engineer" only defines the method of knowledge storage and representation.

We had realized both methods [5,6]. This enabled us to estimate all advantages and lacks of both variants and to choose the best for ultrasound investigation domain. Considering, that absence of mistakes in the knowledge base is more important, than the time factor, the decision was to accept the first variant. Nevertheless, realization of the second variant enabled us to estimate correctly knowledge volume of our problem area and helped to distribute necessary resources in the future.

As models of knowledge representation in the medicine domain a model based on rules or a semantic network usually are chosen. In both cases the problem is reduced to:

- determination of objects, concepts and their attributes which are used in the given problem area;
- definition of links between concepts;
- determination of metaconcepts and detailed elaboration of concepts;
- construction of the knowledge pyramid, being scale of metaconcepts ranks, rising on which means the deepening in understanding and increasing the level of metaconcepts generalization [7].

Common work of the “knowledge engineer” and experts has shown that in the ultrasound investigation domain a reasoning with metaconcepts (facts) and knowledge representation as a pyramid completely corresponds to experts mentality and reasoning. However the division of metaconcepts up to the level of objects, concepts and their attributes, and construction of further reasonings on their base is not always clear to the experts, especially, if we demand this procedure at the initial stage of knowledge acquisition.

Basing on our experience we can conclude, that in ultrasound investigation area the approach of knowledge structure modeling is effective, when the knowledge received during direct dialogue of “knowledge engineer” with experts is represented as a pyramid of metaconcepts.

The described approach has been approved on an example of ultrasonic investigation of separately taken organ – gall-bladder [8]. As a result of 23 work sessions of the “knowledge engineer” with experts the pyramid of knowledge (consisting from 9 root nodes, 399 facts, 13 levels deep and 60 rules) has been received.

The further division of metaconcepts up to the level of objects, concepts and attributes, and construction of reasonings on their base can be done easily. The necessity of this depends on concrete program applications which will use the obtained knowledge.

4 Knowledge validation

As it was mentioned above, the knowledge of medical experts has been stored in the knowledge base (KB) and represented in the form of a tree with hierarchical structure. Every node of this tree represents an attribute which corresponds to an aspect of the organ description (e.g. organ's form, tonicity, dimension etc). In its turn, each attribute has a set of children. A child can be of two types - a value or a hierarchical characteristic of a more deep level.

Basing on the arborescent structure of the data and using knowledge about organ's pathologies and anomalies, the set of trees for decision rules is constructed. These trees contain all the factors which can help when formulating the conclusion.

The purpose of validation is to state the degree of knowledge base correctness and completeness. It is necessary for that to carry out testing of the obtained rules. Since the testing has been carried out by medical experts, it was necessary to develop the knowledge validation tool, which will be easy in use, will permit the simulation of investigation and evaluation procedure for the obtained conclusions.

Interface for knowledge validation is divided into two parts: in the left part we have a form, which represents the organ description and in the right part – the list of rules obtained as a result of values selection from form.

The form has an arborescent structure, where the children of a node can have one of the following types: "exclusive" and "description". The "exclusive" nodes are the possible values of the attribute, which is the parent-node for these nodes in the tree. The nodes of type "description" are the descriptions of the attribute. The nodes representation in the interface depends on their type. If they are the child-nodes of type "exclusive", they are represented in the interface in the form of „SELECT"; if they are the child-nodes of type "description", they are represented in the form of a list (Fig.1).

The validation process is being implemented in the following way: the attributes values are being selected and after that the conclusion is being deduced, which is formed on the basis of the rules from KB. For validation process perfection the precedent session is memorized, where the selected values for each attribute are kept.

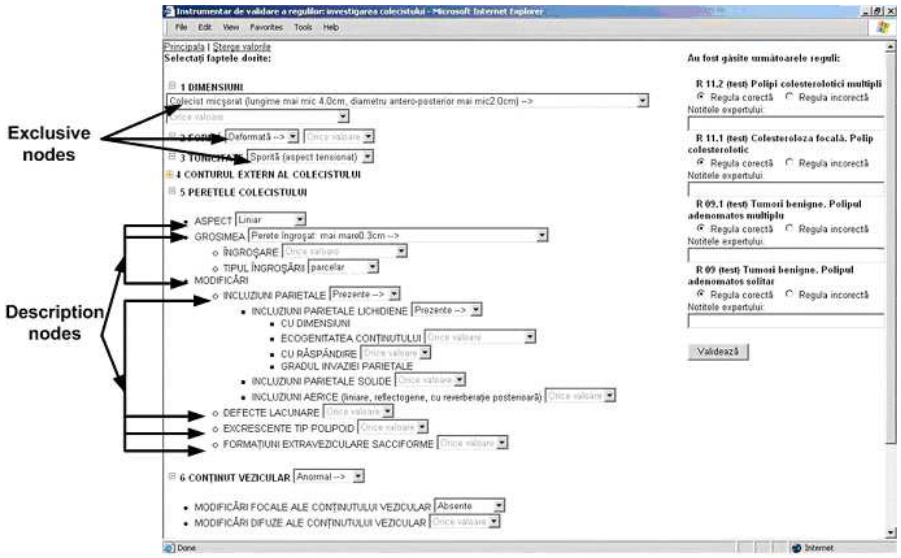

Figure 1. Knowledge validation tool

Hence for the simulation of new investigation, which differs from the precedent only by some values of some attributes, it suffices to modify only values of necessary attributes. For example, the rules "Acute lithiasic cholecystitis complicated gangrenous" and "Acute alithiasic cholecystitis complicated gangrenous" differ from each other only by different values of the attribute "Focal modifications of gall bladder content": in the first case this attribute gets the value "present", in the second – "absent". Also it is easy to verify in which decision rules every combination attribute-value is met.

It is necessary to mention that there are cases which are often met, when the values of some attributes may have not been selected, because they are considered not to be necessary, but which can take part in the rules description, on the basis of which the conclusion is deduced. For this reason in order to obtain a conclusion, all the rules are selected from the KB at the first iteration. Next there are excluded the rules which are described by the attributes, the values of which differ from the values of selected attributes.

During the validation process the expert can make some notes for the deduced rules and to indicate if the rule is described incorrectly. In order to view these notes, made during the validation process, every validation process can be saved as a session. The sessions have been saved in the data base and can be restored by request of the expert or knowledge engineer to be viewed (Fig.2). Each session contains the attributes selected by expert in the validation moment and the obtained rules. Each incorrect rule is followed by: a) some notes of the expert, in which an explanation of given decision is indicated; b) a field for knowledge engineer, in which his notes concerning this rule are indicated (e.g. the rule was modified in KB).

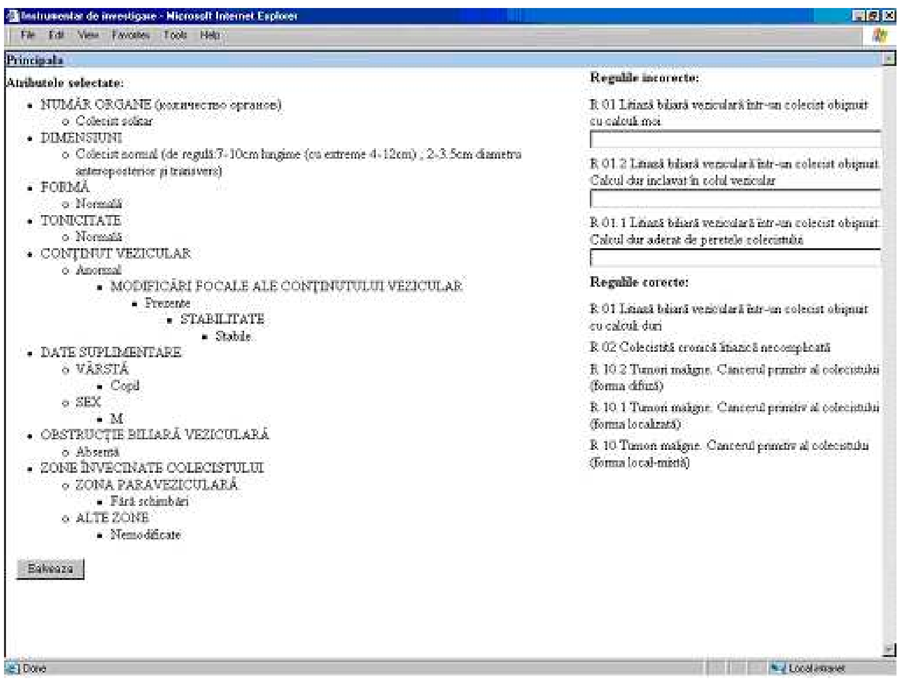

Figure 2. Tool for sessions viewing

At present there was validated the knowledge about one organ – gall-bladder, which serves for determination of the technology for KB formation. After validation the following modifications were made:

- new hierarchical characteristics of the tree were added;
- the values of a set of attributes in the trees for decision rules were modified;
- the set of trees for decision rules was modified;
- new decision rules were added.

The process of validation of knowledge about gall-bladder permitted to state the complete knowledge set for this organ diagnosis.

5 Image processing

Besides its advantages the ultrasound method has a serious drawback – ultrasound images are often affected by noise, possess poor contrast, and suffer from variations in illumination or from self shadow problems that result in masking the regions of interest [9]. So, for a novice in ultrasound diagnostics or even for an inexperienced physician it is complicated to identify what organ is referred to in the image on the basis of just one organ image. Moreover, the ability of getting the "correct" organ image itself strongly depends on the physician's experience.

Developing the system for both an experienced ecographist and inexperienced one, we put as the main scope quick and relevant image retrieval. Therefore, our system will achieve (and hence will propose to the physician) two kinds of images in database – the original image and the processed one. This processed image can be obtained as a result of the application of image processing operations (e.g. noise reduction or contrast adjustment algorithms). If it is necessary, image processing can be applied only to the region of interest, which needs to be marked out by the physician.

5.1 Image clusterisation

At first, all images from database are classified (clusterisation I) depending on the organ diagnosis – there may be some pathology or a description of the normal state of the organ. Organ diagnosis is based on qualitative and quantitative descriptors – organ characteristics, which are determined by a physician-ecographist. For example, in gallbladder investigation the location, shape, tonicity, contour, wall structure, ecogeneity and contents are qualitative descriptors. Dimensions and volume are quantitative descriptors. Such a classification helps one to extract images from image database, which have the same descriptors as the current (investigated) image. So, in the simplest case images from database can serve as "well done" illustrations for some fixed organ diagnosis.

One of the important tasks is the image query (where query is itself an image) with the purpose of retrieving those images which are 'close' to the query image. In this case another clusterisation (clusterisation II) will help us in classification of images depending on image statistics. It is necessary to specify the region of interest as well as to compute the distance between the query image and the images in the database. Consequently, some statistical descriptors (e.g. histogram, average and standard deviation of the image intensity, average of the standard deviation of the region intensities) are computed for every image. The advantage of these statistical descriptors in comparison with those mentioned above is that they are direct image related and independent of the specific physician's experience. An efficient iterative clustering method of ascendant hierarchical classification, which can be applied in the case of quantitative descriptors, is described in [10]. Once the hierarchical index structure for the images database is constructed, it can be used to extract the images most similar to a query image rapidly.

5.2 Image processing methods and results

The creation of our software tool for ultrasound image processing is aimed to accomplish the following principle tasks: noise reduction; contrast adjustment; borders and organ contours determination; structure and texture analysis.

First two tasks are directed to improve general image aspect or the region of the interest. Automatic image segmentation with borders detection helps to avoid manual time-consuming and tedious work, which requires expert knowledge; while structure and texture analysis is useful in detecting pathology (e.g. tumors and cysts).

There are a number of image processing methods, many of them being problem-specific or organ-specific oriented. Currently there is no one single segmentation method, sufficiently good for all ultrasound images. We suppose that an "ideal" segmentation algorithm must incorporate many families of the image models. So, we press towards implementation of different segmentation methods, and their combination will provide the acceptable results for every specific organ.

Image Statistics.

This submenu gives the useful statistical representation of the loaded ultrasound image, e.g. histogram of frequency – number of times that a pixel with a particular gray-level occurs within the image (Fig. 3).

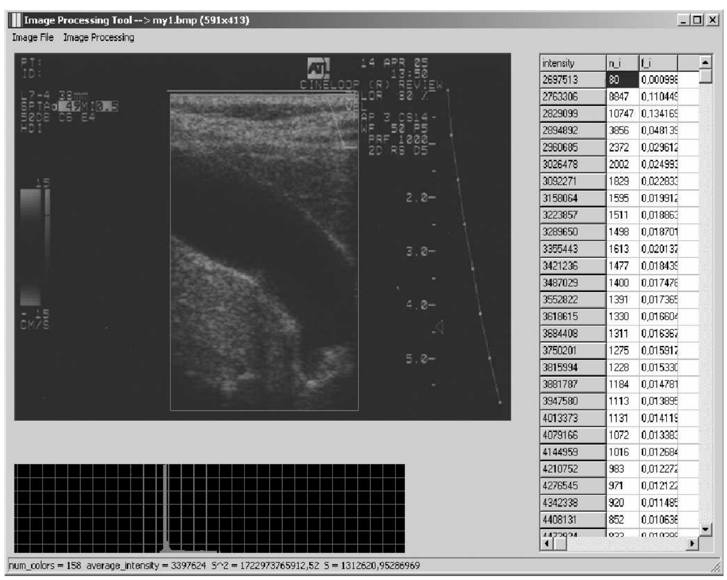

Figure 3. Image Statistics submenu (with specified region of interest

In the case of complex images which may consist of up to 256 gray levels, the resulting histograms will consist of many peaks. The distribution of these peaks together with the magnitude can reveal some significant information about the information content of the image. Average and standard deviation of the image intensity, average of the standard deviation of the region intensities can be computed. So, this submenu helps us in obtaining all necessary statistical descriptors.

Noise Reduction.

No edge detection algorithm can be expected to work well on raw unprocessed image data. Speckling presented in ultrasound images make accurate segmentation difficult, therefore noise reduction step is performed usually in the beginning. Gaussian and median filters were used with success in [9] for fetal ultrasound image smoothing. Currently we have realized this task by using Neighborhood Averaging Algorithm, which replaces each pixel with an average of its neighborhoods, and Median Filter, when each pixel of the filtered image is defined as the median brightness value of its neighborhoods in the original image (Fig. 4-5).

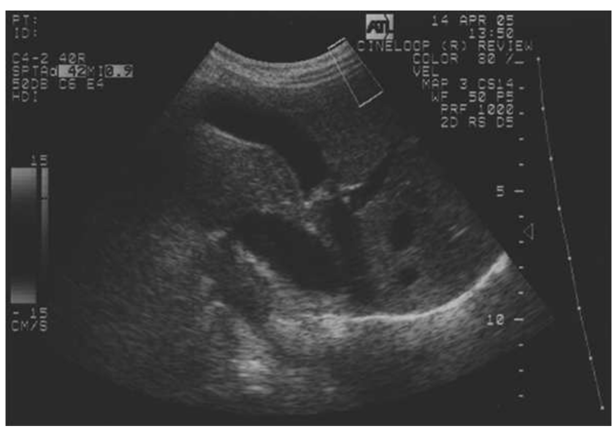

Figure 4. Original ultrasound image of the normal gall-bladder

For ultrasound images the averaging filter gives sometimes not better, and often quite worse image, than the original one.

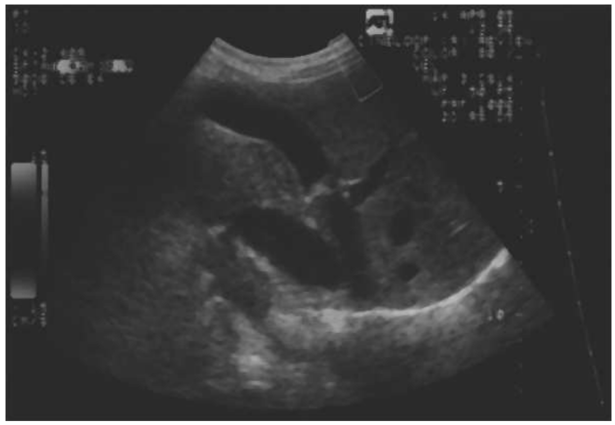

Figure 5. Image processed by applying median filter (filter window 3*3)

Contrast Adjustment. This approach renders the image more acceptable for the eye. We have implemented two methods to perform this task.

Thresholding of Intensity, which generally enhances the contrast in the image, is often used as an initial step in a sequence of the image processing operations. This is the technique of setting certain gray levels to zero relative to other one (threshold value separates the desired classes). The effectiveness of the method depends on the histogram of the gray level distribution on the original image exhibiting at least two identifiable peaks, so that at least one or other of the levels contributing to the peaks can be set to zero (Fig. 6-7). The major disadvantage of this method is that thresholding typically does not take into account the spatial characteristics of an image; this causes it to be sensitive to noise. This technique combined with the texture statistics was successfully used to segment ovarian cysts [11].

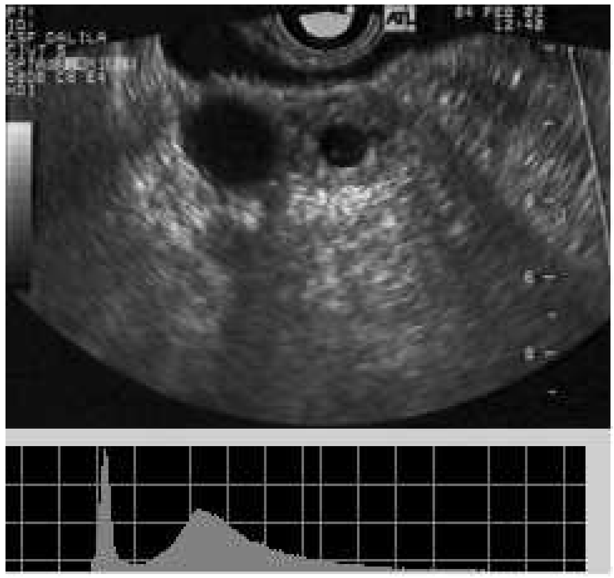

Figure 6. Original ultrasound image and its histogram

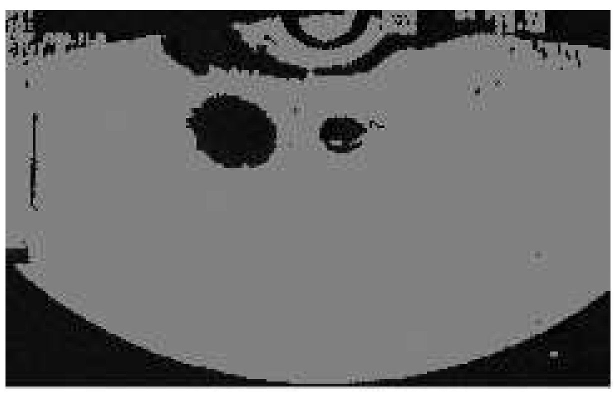

Figure 7. Images with thresholding of intensity, threshold value=1315860 (homogeneous light region intensity values were greater than threshold value)

Another method of contrast enhancement is the Histogram Equalization. This process increases the dynamic range (the ration between the minimum and the maximum of intensities) of intensities. Utilization of the transformation function equal to the cumulative distribution of the gray level intensities in the image enables us to generate another image with a gray level distribution having near uniform density (Fig. 8).

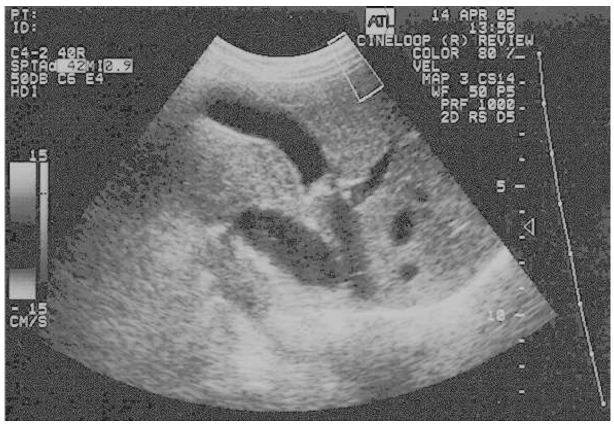

Figure 8. Image processed by applying histogram equalization (original 173 colors were transformed in 54 colors)

Borders and Organ Contours Determination.

This task is quite difficult one for ultrasound images. Usually, knowledge obtained from experts is directly coded in segmentation algorithms. Unfortunately, automatic image processing didn't give very good results. Therefore, automated segmentation is used with possibility of the initial learning [12] or in combination with genetic algorithms. Another interactive approach is more frequent, when physician-ecographist has possibility to determine the region of the interest. Thus, we have implemented some different algorithms.

Region Growing is the technique for extracting a connected region of the image. It may be used for delineation of small and simple structures as tumors and lesions. Usually it is not used alone, but within a set of image processing operations. The major disadvantages of this algorithm are that it requires the initial point to be manually selected and it is sensitive to noise. Split and Merge Algorithm is related to region growing, but does not require the initial point, so it can be used for "ideal" automated functioning. For the gall-bladder images these techniques give the promising results (after initial noise reducing), the future work is to test them on the ultrasound images of the other organs.

Deformable models can be applied for boundary detection using closed parametric curves [11]. It is an interactive technique too, because close curve (circle) must first be placed near the desired boundary (Fig. 9). The advantage of this algorithm is that it is robust to noise. Deformable models, which have good success in the segmentation of prostate boundaries [13], were used to determine boundary of the fetus and the fetus head respectively [14]. The results for gall-bladder ultrasound images are not stable – the fact, which needs to be studied more deeply.

Figure 9. Image processed by the deformable models technique (close curve must first be placed near the desired boundary)

6 Examination Support

The proposed method of acquisition (by means of expert shell) and storage of expert knowledge in Unified DB permits to effectuate a quick search of necessary information in two directions or modes [4]. The first direction is from the concrete case description to determination of pathology and/or anomaly; and the second one – from formulation of a hypothesis to its confirming or denying (Fig. 10).

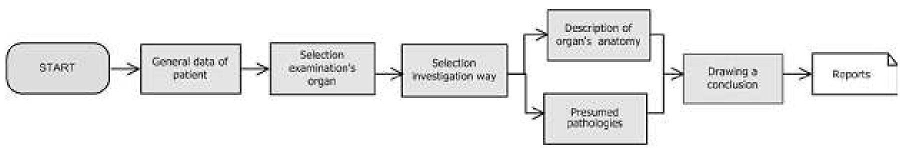

Figure 10. The structure of the interface for investigation

Following the first direction the user gives the necessary information describing a concrete case, and the system tries to determine if it is a pathology and/or an anomaly. To exclude at the early stage the input of inconsistent, erroneous or excessive information, this direction is followed step-by-step (Fig. 11). If at any step the system can determine, on the basis of the entered information, pathology and/or anomaly, it informs the user.

Following the second direction, the user forms a hypothesis about presence in the concrete case of pathology and/or an anomaly. Then the system by means of additional questions tries to confirm or to deny this hypothesis.

Realization of both modes within the framework of unified support system of ultrasonic investigation process corresponds to the daily work of physicians. The first operating direction satisfies the requirements of the detailed patient examination; and the second direction corresponds to a simplified one, when it is necessary to confirm or to deny any diagnosis.

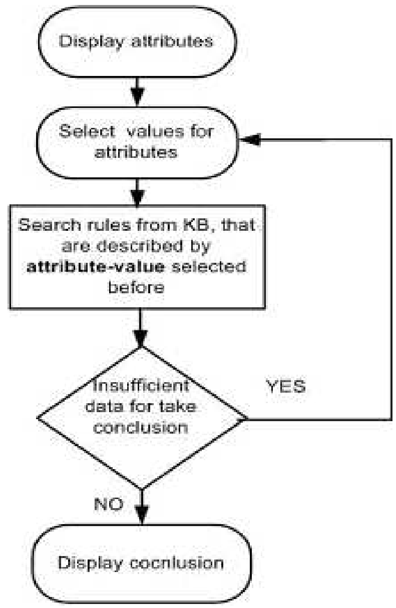

Figure 11. The scheme for the investigation process "step by step"

A convenient dialog with user-physician (due to dynamic intelligent interface which includes a standardized explanation of the decision proposed by system) involving images in decision making process (based on visualization and comparison of ultrasound examined image with similar images from Image DB) permits to create a comfortable environment for physician and helps him to prepare a standardized report, containing the examination results and, if necessary, the recommendations for additional investigation.

7 Reporting

The resulting report is the obviously unique result of ultrasound investigation that can be presented for view or saved for further reviewing. But traditionally the medical image report consists of both the well formalized part (patient and image data, digital measurement data) and the arbitrary formed description. Initially the description was a free-text that a physician prepare by his own way. The free-text form causes the ambiguity and is not suitable for quantitative analysis. Since the possibility of computer performance arose the researchers have being made attempts to structure the free-text description. The free-text description structuring is implemented by several methods. They can be grouped in two main approaches: extraction of meaning data from existing reports and generation of the reports by fixed rules. The first one is based on the analysis of existing radiology reports and uses the powerful AI techniques: natural language processing and data mining to extract regular data. The second way uses predefined elements for report construction. It takes some results of the first one to build the dictionaries of corresponding lexicon. Starting with proposing the standard phrases set by the second way has driven to definition of Structured Reporting.

Structured Reporting is both the image term and researching domain that covers the construction and processing of formalized and structured clinical reports. At the DICOM Structured Reporting Workshop (March 29 -30, 2000, Donald E. Van Syckle) Structured Report was defined as a "Databaseable Document" which: uses standardized or private lexicons; provides unambiguous "semantic" documentation of diagnosis; allows links to multimedia context. It means that the report context is the set of objects which have standard and recognizable attributes and can be easy packed in underlying clinical database.

But the choice of standards for structured reports remain difficult. There is the full set of different standards related to equipment, transition protocols and clinic documentation. The physicians keep trying to resolve unification problem, but even at 2006 at the conference IHE (Integrating the Healthcare Enterprise) Workshop there were mentioned several standards which are used in radiology reporting: DICOM SR, IHE "Report Integration Profile" that specifies a template for diagnostic reporting, HL7 (Health Level 7), CDA (Clinical Document Architecture), SNOMED (Systemized Nomenclature of Medicine, Unified

Medical Language System), HIPAA (Health Insurance Portability and Accountability Act), ACR (American College of Radiology) Standard for Communication. IHE is an industrial initiative to bring information resources in healthcare. IHE does not develop standards but annually issues the recommendations which have a high probability of a quick uptake in the medical market because of quantity of IHE participants. Between 1999 and 2005 more than 160 companies, including most of the market leaders in domains of RIS (Radiology Information System), and PACS (Picture Archiving and Communication System), have developed IHE-compliant systems. So the methods of structuring represent the essence of researching in this domain.

The most frequently used method of report structuring is the generation of reports by templates. This method provides the control of report design but also causes some problems because the user's choice between similar templates can be ambiguous.

The template controls both layout and content of the report. In terms of report layout the template marks some "widgets" and image multimedia which are the images and video clips. The report content templates usually belong to one of the two types. The form part of report is created by the template of the first type. In this part the patient and image data are set. The templates of the second type are essential for the results of investigation. As it was mentioned above these results contain both digital data and text descriptions. The templates for text description depend on structuring method. The template can propose the set of "brick"-phrases with predefined image meaning. Another method consists in the representation of the report by tree structure. This type of structure corresponds to the process of radiology investigation and can be easily stored and processed using XML paradigm.

Taking in consideration that our system is targeted at diagnostics we intend to use in reporting the data already collected during diagnostic session. This session is implemented by "down-tree-walking" methods and so the data are well structured. Only to add the data which can not be received from diagnostic session another interface will be proposed. The changeable template of report will be represented by external XML-file.

In [15] the complete solution for development of application implementing structured reporting is proposed. Some conceptual solutions announced here can be used to achieve the implementation of discussed features of structured report. The most important features for our future implementation are: generating of the report by assembling from components which are intelligent and verified; collecting of such components in knowledge base; tools for components generation and editing. The process of proposed application activity includes both the generation of reports and obtaining new components through analysis of newcoming reports.

8 Conclusion

The proposed system does not intend to replace completely the physician; it just offers him a second opinion. In all cases user can receive all rules and judgments on the basis of which the decision was made. If the user doesn't agree with the decision, proposed by the system, his opinion will be sent to expert group for examination.

ACKNOWLEDGMENTS

The research described here has been supported partially by Moldova State Program grant 06-411-03-01 P and the Science & Technology Center in Ukraine (STCU) grant 4035.

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Received July 10, 2007

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