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Abstract: The study aims to enhance the outcomes of differential diagnosis of obstructive pathology of the common bile duct by leveraging the results of endoscopic ultrasonography (EUS) using hybrid fuzzy decision-making technologies. The main diagnostic methods are endosonography and the hybrid fuzzy decision rule synthesis methodology, developed at Southwest State University in Kursk, Russia. Based on expert assessments of endosonograms depicting common bile duct pathology, and the hybrid fuzzy decision rule synthesis methodology, a hybrid fuzzy model for differential diagnosis of the studied pathology was developed. Mathematical modelling and statistical calculations demonstrated the effectiveness of this differential diagnostic model, providing a confidence level of 0.93 in the desired diagnosis which is an acceptable result when working with poorly formalised initial data.

Keywords: fuzzy mathematical models; common bile duct obstruction; reference images.

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1 Introduction

Among diseases of the pancreatobiliary zone, pathology complicated by obstructive jaundice syndrome, which is a common surgical pathology, is of particular relevance (Styazhkina et al., 2016). Up to 80% of the etiological factors of cholestasis are benign diseases that develop against the background of cholelithiasis, which affects up to 30% of the population in the age group over 70 years. In 20% of cases, bile duct obstruction is caused by tumour growth (Podoluzhny, 2018). Malignant neoplasms of the pancreatobiliary zone account for up to 15% of all gastrointestinal tumours, and there has been a rise in the number of patients with common bile duct (CBD) obstruction; the bile ducts, which connect the organs of the pancreatobiliary region, require detailed visualisation for differentiating pathologies in this area, but this can be a complex undertaking (Fomicheva, 2018; Chen et al., 2015).

A highly informative method for diagnosing the pathology of the CBDs is endoscopic ultrasonography (EUS). Experience in the practical use of EUS has shown that in the process of its implementation, complexly structured images are formed, the segmentation and classification of which requires highly qualified physicians, since due to the peculiarities of subjective visual perception, information content is lost, the parameters are assessed subjectively, which makes it difficult to formulate a standardised conclusion. Because of this, only a few authors objectify the results of EUS using methods of mathematical statistics (Solodinina, 2016). One promising approach to improving the accuracy of analysing medical images, including endosonograms, is the application of artificial intelligence methods for their analysis and interpretation (Hawes and Focken, 2006). Our research has shown that using fuzzy decision logic, particularly the methodology for synthesising hybrid fuzzy decision rules (MSHFDR), can produce high-accuracy models when analysing endoscopic ultrasound (EUS) images (Belozerov and Korenevskiy, 2020, 2021). This technique allows for the synthesis of hybrid fuzzy decision rules, which can significantly enhance the precision and reliability of interpreting EUS images through the power of artificial intelligence.

Southwest State University developed the MSHFDR specifically for solving poorly formalised problems, including problems with uncertain boundaries of the studied classes of states, with an uncertain and fuzzy data structure, etc. (Korenevskiy et al., 2019, 2023a, 2024a; Korenevskiy, 2005, 2012, 2013, 2015). A distinctive feature of the MSHFDR is its ability to actively combine the natural intelligence of medical experts (clinical thinking) with the intelligence of a cognitive engineer, leveraging artificial hybrid intelligence. This interaction between ultrasound diagnostic experts and the cognitive engineer helps to compensate for the lack of statistical data and build formal models for poorly formalised problems. The exploratory analysis conducted as part of this approach allows the knowledge engineer to select mathematical models that best correspond to the data structure of the problems being solved. The MSHFDR algorithms then determine the optimal interaction of all intellectual components, generating qualitatively new medical information systems. These systems enable effective interpretation of medical images, improving disease diagnosis to a higher level and ensuring efficient handling of poorly formalised initial data structures. The effectiveness of medical information systems based on MSHFDR has been repeatedly demonstrated in solving diagnostic problems in medicine, as well as a wide range of issues in ecology, ergonomics, and occupational safety (Korenevskiy et al., 2009a, 2009b, 2012, 2013a, 2013b, 2017, 2021a, 2021b, 2021c, 2022a, 2022b, 2023b; Al-Kasasbeh et al., 2011a,

2011b, 2012, 2013, 2014, 2016, 2018a, 2018b, 2018c, 2019a, 2019b, 2019c, 2019d, 2019e, 2020a, 2020b, 2021, 2025; Filist et al., 2022a, 2022b; Shatalova et al., 2021).

In relation to the differential diagnosis of CBD pathology, the clinical thinking of doctors is used to analyse poorly structured images of sonograms, while ensuring the selection of informative areas in the area of interest that are characteristic of the diagnosed pathology (Korenevskiy et al., 2023a, 2024a). At the same time, the process of formation and recognition of pathology is influenced by factors that are often inaccessible to artificial intelligence.

2 Research objectives

In order to improve the results of differential diagnosis of pathology of the CBD and objectify the results of endosonography, systematise EUS criteria for the differential diagnosis of CBD obstruction of various etiologies. To quantitatively assess endosonograms, create reference diagrams from reference endosonograms of a typical recognisable echo structure, which experts could analyse and evaluate and assign them the appropriate confidence coefficients for differentiating pathology into the corresponding classes using the developed production decision rules. The objectives of the study also include assessing the quality of operation of decision rules in a group of patients with confirmed diagnoses.

3 Research method

In the Kursk Regional Multidisciplinary Clinical Hospital on the basis of the endoscopy department, endosonography was performed on 173 patients for obstructive CBD pathology. The study included patients with clinical and laboratory signs of bile duct obstruction, who underwent EUS and in whom no pathological formations of the pancreas were detected during the initial examination. Patients whose disease outcome was unknown were excluded from the study. Tumours of the CBD were detected in 24 (13.9%) patients, among them there were 13 (54.2%) women, 11 (45.8%) men, the average age was 66±5.7 years. Benign bile duct obstruction was diagnosed in 149 (86.1%) cases. In most cases, choledocholithiasis was detected – 97 (65.1%) patients. CBD strictures of various origins were diagnosed in 43 patients, which amounted to 28.1%. Extracholedochal compression, localised distal to the cystic duct, mainly by enlarged lymph nodes, was found in 9 (6.1%) cases. Among all patients with benign pathology, women predominated – 102 (68.5%) people. The average age of these patients was 59±6.4 years. Video recordings of all studies were archived on electronic storage.

'In addition to the above-mentioned benign diseases, we diagnosed Mirizzi syndrome (five cases), biliodigestive fistula (four cases), and CBD cyst (four cases). However, due to the small number of these pathologies, these patients were excluded from the study'.

This revision adds a slight emphasis on 'these patients' for clarity.

When performing EUS, the focus was on differentiating between benign strictures and strictures of tumour etiology. The criteria identifying a malignant lesion of the bile ducts include: heterogeneous hypoechoic formation in the lumen of the duct and beyond with uneven, unclear contours, irregular shape of the formation, connection of the

formation with the wall of the duct, hypoechoic infiltration of surrounding tissues, lack of structure of the duct wall at this level, unevenness external contour of the duct, 'breakage of the duct' or its sharp narrowing with thickening of the walls in this area, asymmetric thickening of the walls of the duct, narrowing of the duct lumen without change or with an increase in its overall diameter, the length of the narrowing is more than 1 cm, a symptom of two ducts, lymphadenopathy with signs of malignancy, signs of invasion of vascular structures.

4 Results

As part of the study, we came to the conclusion that the systematisation of echographic criteria for CBD pathology is best presented in the form of reference diagrams of reference sonograms of the echographic structure, which most fully reflect the characteristics of the object, including all its echo signs, which will allow the user to most accurately guide the user in correct decision-making and identify the desired object in a mass of anatomical structures. Using a set of reference diagrams of reference endosonograms, we have formed a scale where the images are arranged in the order of changes in the nature of obstructive pathology from benign to malignant. A joint analysis of the observed pictures by doctors and image processing specialists made it possible to come to the conclusion that it is advisable to synthesise differential diagnostic models using two variants of reference schemes: with a longitudinal image of the structure of the pathological formation and with a transverse image. This representation of pathology is due to the fact that the structure of the analysed images, unlike texture pictures, almost always has an irregular shape and differs during longitudinal and transverse scanning.

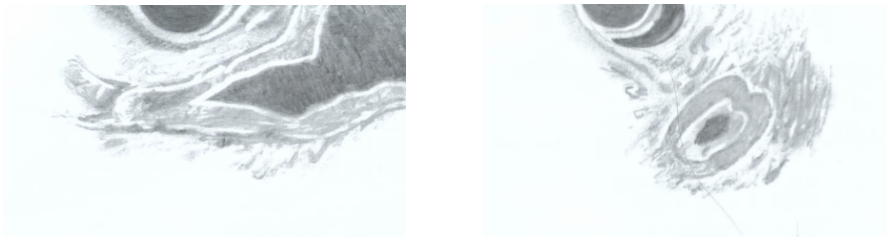
Figures 1–3 show examples of three of the six reference diagrams of the reference endosonogram describing the norm and underlying pathology of CBD.

- Benchmark 1. Diagram of the structure of CBD in choledocholithiasis (Figure 1).
- Benchmark 2. Scheme of the structure of CBD in a benign scar-inflammatory stricture (Figure 2).
- Benchmark 3. Diagram of the structure of CBD in cholangiocarcinoma with expanding into neighbouring structures (Figure 3).

Figure 1 Reference image: reference scheme of the reference endosonogram of the structure of choledocholithiasis, (a) longitudinal image, (b) transverse image (see online version for colours)

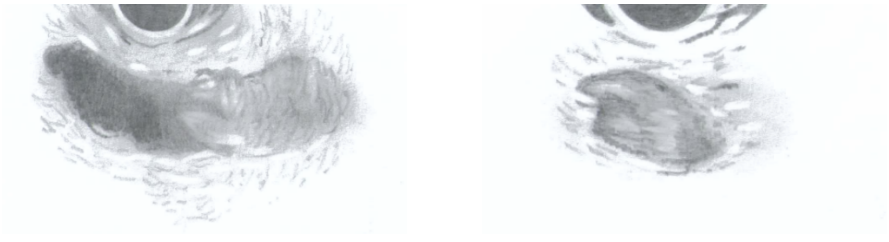
(a) (b)

Figure 2 Reference image: reference diagram of the reference endosonogram of the structure of benign scar tissue inflammation-induced stricture of the CBD, (a) longitudinal image, (b) transverse image (see online version for colours)



(a) (b)

Figure 3 Reference image: reference diagram of the reference endosonogram of cholangiocarcinoma with spreading into neighbouring surrounding structures, (a) longitudinal image, (b) transverse image (see online version for colours)



(a) (b)

Using the recommendations of the methodology for the synthesis of hybrid fuzzy decision rules (MSHFDR) for creating decision rules for the differential diagnosis of periampullary obstruction, a cognitive engineer, together with ultrasound specialists, forms a group of experts competent in the field of pathology of the pancreaticobiliary zone. Experts are introduced to the basic principles of MSHFDR. The quantitative and qualitative composition of the expert group is determined by qualimetry and adjusted taking into account the concordance coefficient (Korenevskiy et al., 2019, 2024b, 2024c; Korenevskiy, 2005). The quantitative composition, taking into account the specifics of the problem being solved, is determined to consist of 8 specialists. Experts determined the confidence coefficients in classifying patients into one of the classes of conditions using six developed reference schemes (C1…..C6). The Delphi technology allowed experts to construct fuzzy decision tables (Table 1), the elements of which are the confidence coefficients Kci in classifying patients into one of the studied classes of conditions. The results of the experts' work are shown in Table 1. Experience in performing at least 1,500 diagnostic studies of the pancreatobiliary zone.

In accordance with the confidence coefficients, the ultrasound diagnostic physician, observing a real endosonogram, selects the closest reference diagram of the CBD structure, and from the tables selects a pair of corresponding average confidence coefficients, making a decision on the class with the highest confidence coefficient.

A joint analysis of typical endosonograms and average confidence coefficients led to the conclusion that specialists are quite confident in comparing and assessing the similarities of the real sonograms and reference patterns they observe. The accuracy of

decisions can be increased by using a more powerful interval scale that reflects the similarity between the reference and diagnostic images. The scale is designated by the symbol S and allows you to judge the degree of similarity of the diagnostic object with the corresponding reference point based on the membership functions constructed on it to the classes ωP and ωD with the base variable S. In this case, the values of the membership functions are interpreted as the values of confidence in the diagnosed CBD pathology.

According to MSHFDR, the S scale was constructed. At the same time, reference diagrams of reference endosonograms were placed along the x-axis in order of increasing confidence in malignant pathology (each reference point corresponded to an integer 1–6). The unit of measurement is taken to be a scale segment of 0.1. According to the Delphi method, experts constructed graphs of membership functions for classes ωP and ωD on an interval scale S (Figure 4).

Analytically, the graphs are described by the expressions:

$$\mu_{\omega_D}(S) = \begin{cases} 0, & \text{if } S \le 1 \\ 0.98S - 0.98, & \text{if } 1 < S \le 2 \\ -0.245S + 1.47, & \text{if } 2 < S \le 6 \end{cases}$$

$$\mu_{\omega_P}(S) = \begin{cases} 0, & \text{if } S \le 2 \\ 0.242S - 0.484, & \text{if } 2 < S \le 5.8 \\ 0.92, & \text{if } 5.8 < S \le 6 \end{cases}$$

Moreover, the conclusion of the ultrasound examination includes objective information presented numerically as a confidence coefficient

Private confidence U_{ω_ℓ} in the studied classes of states l = *D*, *P* is determined by the corresponding membership functions:

$$U_{\omega_D} = \mu_{\omega_D}(S); \tag{1}$$

$$U_{\omega_P} = \mu_{\omega_P}(S). \tag{2}$$

As a result, in the practical use of decision rules, the doctor, using the selected sonogram, determines the value of *S* with an accuracy of 0.1 and calculates the values of the membership functions that determine the corresponding confidence.

The decision about the nature of the differentiated pathology is made based on the maximum value of U_{ω_ℓ}.

In addition, this work considers the criteria for differentiating between malignant and benign strictures, which cannot be fully represented within the framework of a reference sonogram. These include the nature of lymphadenopathy, the relationship between the CBD tumour and vascular structures, and the thickness of the CBD wall, each of which is assigned a corresponding confidence coefficient. These criteria are detailed in the study [differential diagnostics of distal cholangiocarcinoma and benign stricture of the CBD based on the results of endoscopic ultrasonography using hybrid fuzzy technologies]

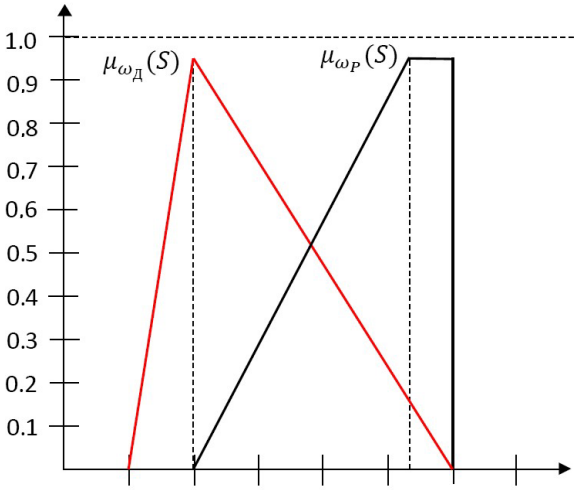
When analysing the obtained decision rules using expert assessments, it was shown that the confidence in decisions made using fuzzy models (1) and (2) exceeds 0.9, which is a good practical result for the class of problems under consideration.

Table 1 Recommended values by experts in class ωP « malignant obstruction CBD» and ωD 'benign obstructive pulmonary embolism'

Recommended values by experts in class ωP «malignant obstruction CBD»							*Confidence coefficients for the class ωD 'benign obstructive pulmonary embolism'*						
Standard	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*Standard*	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*
S1	0	0	0.15	0.45	0.70	0.95	S1	0	0.98	0.80	0.58	0.20	0
S2	0	0	0.18	0.50	0.70	0.95	S2	0	0.98	0.78	0.60	0.20	0
S3	0	0	0.20	0.45	0.65	0.90	S3	0	0.99	0.70	0.48	0.15	0
S4	0	0	0.15	0.48	0.62	0.92	S4	0	0.96	0.75	.0.55	0.10	0
S5	0	0	0.10	0.45	0.60	0.90	S5	0	0.98	0.70	0.50	0.10	0
S6	0	0	0.15	0.50	0.72	0.92	S6	0	0.98	0.75	0.55	0.12	0
S7	0	0	0.18	0.38	0.60	0.85	S7	0	0.96	0.75	0.62	0.15	0
S8	0	0	0.10	0.48	0.65	0.95	S8	0	0.98	0.70	0.60	0.18	0
Average value	0	0	0.15	0.46	0.65	0.92	Average value	0	0.98	0.75	0.56	0.15	0

Note: C1–C6 are corresponding reference images; S1–S8 expert confidence coefficients.

Figure 4 Interval scale with membership function to the classes ωP 'malignant obstruction of CBD' and ωД 'benign obstruction of CBD' (see online version for colours)



The diagnostic efficiency, reflecting the accuracy of the decision rules, was determined for the class ωP. This class represents the most homogeneous group of diseases, and the timely diagnosis of the pathologies included in this class is the most relevant, as it dramatically affects the results of treatment. To assess the classification accuracy, a control group of 22 people was formed for the class ωP. Additionally, an alternative class was created; consisting of 62 patients without pathology in the periampullary region. The control of the decision rule (2) operation was determined by the number of errors made by this rule in relation to the alternative class. The results of these control tests are presented in Table 2.

Table 2 Results of triggering decision rules

Patients		*Observation results*	
		Positive	*Negative*
ωP	Np = 22	19	3
	Nap = 62	3	59

According to the data presented in the table, the sensitivity, which characterises the diagnostic quality of the decision rule (2) for the class ωP, is equal to 0.86. This indicates that the rule correctly identifies 86% of the patients belonging to the class ωP. The specificity, which characterises the quality of the decision rule (2) for the class ωP, is equal to 0.95. This means that the rule correctly identifies 95% of the patients who do not belong to the class ωP. The overall efficiency of the decision rule, calculated as the ratio of correctly classified cases to the total number of cases, is 0.93. This high efficiency score confirms the effectiveness of using fuzzy decision rules for diagnostic purposes. The combination of high sensitivity and specificity, along with the overall efficiency, demonstrates the reliability and accuracy of the fuzzy decision rule (2) in differentiating between patients with pathologies in the class ωP and those without such conditions.

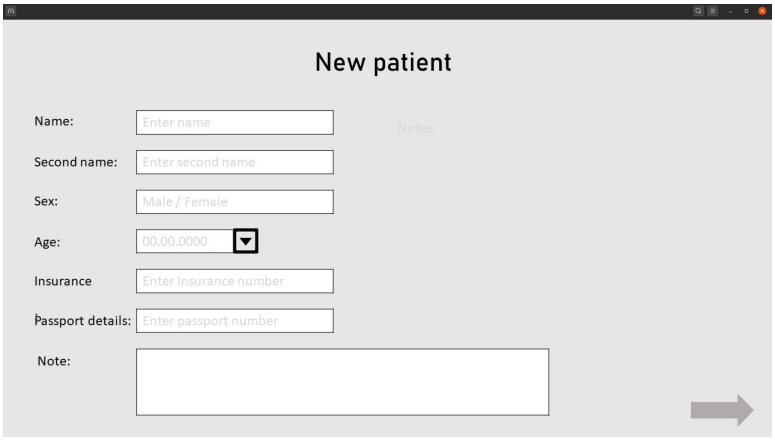
5 Decision support system (DSS)

For the decisive rules obtained in the work and for the implementation of the mechanisms of their interaction with each other and with all the necessary software modules of the selected system, it was necessary to develop an original knowledge base, which was subsequently implemented in a universal shell.

The learning process for the DSS utilises interactive software modules focused on exploratory analysis, fuzzy logic, informative feature formation, synthesis of hybrid fuzzy decision rules, and image formation. The interaction between these software modules and the operator-doctor is facilitated by an algorithm that manages the decision-making process. When operating the DSS, technical means of monitoring the human condition, such as diagnostic equipment for endoscopy, is employed. The interaction between the doctor and the DSS is enabled through a user interface that operates in an interactive mode, providing support for graphics and the functioning of an information and reference system in the medical subject area. The application program package for the gastroenterologist's DSS is designed to solve the problem of learning with the synthesis of decision rules and the differential diagnosis of benign and malignant pathologies of the CBD using fuzzy mathematical models. The learning task is conducted by a subroutine for building hybrid fuzzy decision solutions. The diagnostic task is implemented using the software and hardware employed in the learning process, as well as with the help of tablet computers and mobile phone applications. To demonstrate the operation of the program, the interface windows of the expert system, implemented in C++ for the Windows operating system, are shown.

The expert system application for analysing extrahepatic bile duct pathologies offers a range of functionalities to streamline diagnostic workflows, including maintaining a patient database, solving differential diagnosis problems, synthesising decision rules, and integrating with video endoscopes for image acquisition and processing; the 'menu' window serves as the central hub for navigating between tasks such as patient management, differential diagnosis, decision rule synthesis, and video endoscope integration, allowing healthcare professionals to enhance their diagnostic capabilities, improve patient outcomes, and optimise their overall workflow.

Figure 5 Program operation menu (see online version for colours)



The ‘patient card’ button provides access to the database of patient records, containing their personal information as well as data on their health status. This allows for comprehensive patient management within the expert system. The ‘differential diagnostics’ button, on the other hand, opens a subsystem dedicated to the synthesis of decision rules for diagnosing the functional state of the pancreas. This feature enables healthcare professionals to leverage the system’s advanced diagnostic capabilities for improved patient care.

Figure 6 Fragment of synthesis of decision rules (see online version for colours)

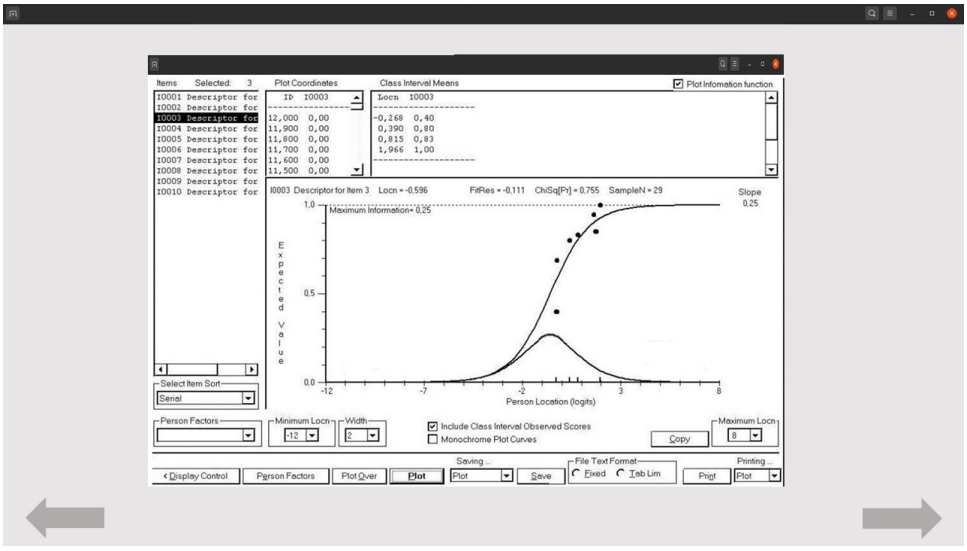
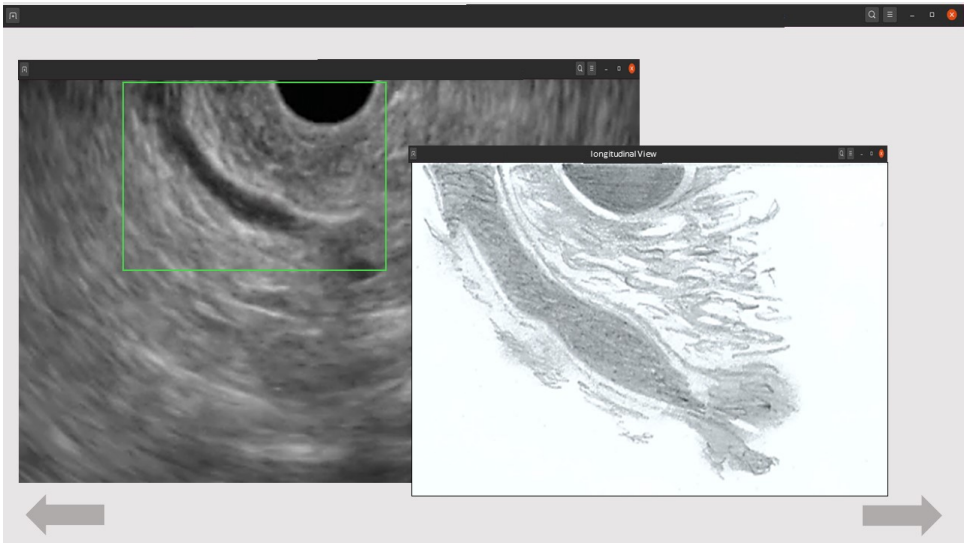


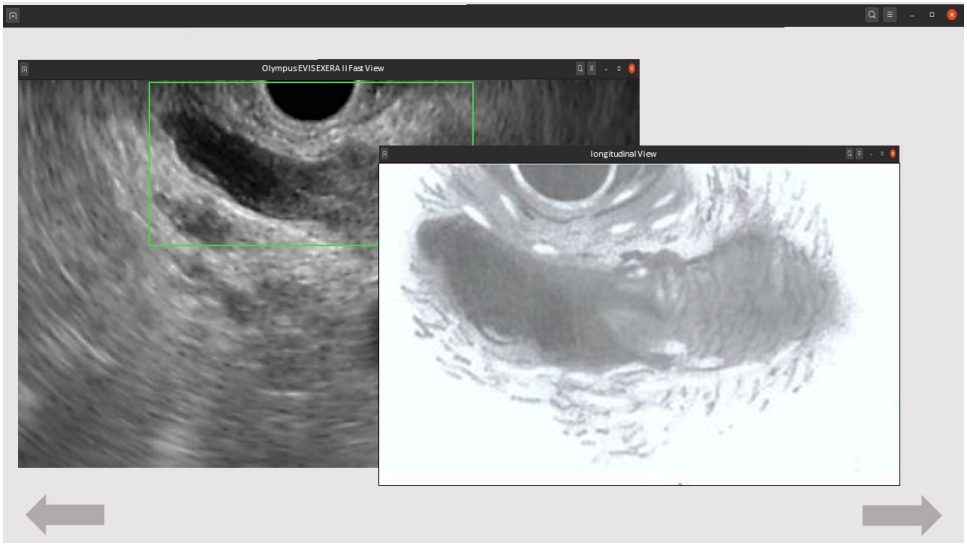
Figure 7 Endosonogram of a normal bile duct (see online version for colours)



The diagnostic subsystem allows users to input relevant medical information and proceed to work with the endoscopic examination device. This seamless integration ensures a streamlined workflow for healthcare professionals. Figure 7 showcases the subroutine that generates endosonograms from the area of interest based on the images obtained during the endoscopic examination. The figure displays an endosonogram of a normal bile duct, providing a visual reference for healthcare professionals to compare against potential pathologies. By incorporating endoscopic examination data and generating corresponding endosonograms, the expert system enhances the diagnostic process, enabling more accurate and informed decision-making.

Figure 8 illustrates the bile duct affected by cholangiocarcinoma with extension into adjacent tissues.

Figure 8 Endosonography of the bile duct in cholangiocarcinoma with extension into adjacent tissues (see online version for colours)



6 Conclusions

Systematisation of EUS criteria for biliary obstruction of the CBD based on the analysis of the echographic structure using synthesised hybrid fuzzy decision rules specifies and objectifies endosonography data, increasing the quality of differential diagnosis. The horizon for increasing the information content of diagnostics is the synthesis of decisive rules, taking into account the relationship of pathological changes with the main vessels and the state of the lymphatic collectors.

Declarations

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