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ALGORITHMS AND METHODS FOR CALCULATING THE AREA OF A GASTRIC ULCER DEFECT USING MODERN MATHEMATICAL TECHNIQUES

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Abstract: This study proposes a novel integrated methodology for digital processing of endoscopic video signals, combining automated video analysis, segmentation of pathological structures, and accurate calculation of the gastric ulcer surface area. A multi-stage algorithm is developed, incorporating intelligent extraction of clinically significant frames, contour detection of ulcerated regions using combined gradient operators, and construction of an adaptive spline model for subsequent integral area estimation. Experimental results demonstrate that the proposed approach provides stable and reliable accuracy and can be effectively used as an auxiliary tool to enhance the objectivity of endoscopic diagnostics.

Key words: endoscopy, digital video processing, spline approximation, segmentation, gastric ulcer, area calculation.

Annotatsiya: Ushbu ishda endoskopik video signallarni raqamli qayta ishlashga asoslangan yangi integrallashgan metodika taklif etiladi. Mazkur yondashuv video ma'lumotlarni avtomatik tahlil qilish, patologik tuzilmalarni segmentatsiyalash hamda oshqozon yarasi yuzasining aniq maydonini hisoblash jarayonlarini birlashtiradi. Taklif etilgan ko'p bosqichli algoritmi klinik jihatdan ahamiyatli kadrlarni intellektual ajratish, gradient operatorlari kombinatsiyasi asosida zararlangan hudud konturini aniqlash hamda keyingi integral hisob-kitoblarni amalga oshirish uchun moslashuvchan splayn-modelni qurishni o'z ichiga oladi. O'tkazilgan tajriba natijalari ushbu metodikaning barqaror va yuqori aniqlikka ega ekanligini ko'rsatib, uni endoskopik diagnostika obyektivligini oshirishda samarali yordamchi vosita sifatida qo'llash mumkinligini tasdiqladi.

Kalit so'zlar: endoskopiya, video signallarni raqamli qayta ishlash, splayn-approksimatsiya, segmentatsiya, oshqozon yarasi, maydonni hisoblash.

Аннотация: В данной работе предлагается новая интегрированная методика цифровой обработки эндоскопических видеосигналов, объединяющая автоматический анализ видеоданных, сегментацию патологических структур и точное вычисление площади язвенной поверхности желудка. Разработан многоэтапный алгоритм, включающий интеллектуальное извлечение клинически значимых кадров, контурное выделение поражённого участка с использованием комбинированных градиентных операторов, а также построение адаптивной сплайн-модели для последующего интегрального вычисления площади. Проведённые экспериментальные исследования показали, что предложенная методика обеспечивает высокую и устойчивую точность и может эффективно применяться в качестве вспомогательного инструмента для повышения объективности эндоскопической диагностики.

Ключевые слова: эндоскопия, цифровая обработка видео, сплайновая аппроксимация, сегментация, язва желудка, вычисление площади.

INTRODUCTION

In recent years, there has been a steady increase in interest in digital methods for the analysis of biomedical images, driven by the need to enhance the accuracy and reliability of medical diagnosis of various diseases. Among these, pathologies of the gastrointestinal tract occupy a prominent position, as their prevalence continues to rise. One of the most frequently encountered diseases in this group is peptic ulcer disease of the

gastric mucosa. Disruption of the integrity of the protective mucosal layer leads to the development of erosive changes, inflammatory processes, and the formation of mucosal defects, which, in the absence of timely and adequate therapy, may progress to more severe clinical forms.

Both external and internal factors contribute to the development of peptic ulcer disease, including unhealthy dietary habits, consumption of alcoholic and energy drinks, the presence of diabetes mellitus, pancreatitis, as well as chronic liver and kidney diseases. The clinical manifestation of the disease is typically characterized by epigastric pain, heartburn, digestive disorders, abdominal bloating, and a sensation of heaviness. In certain cases, concealed or overt gastrointestinal bleeding may occur [1].

Accurate diagnosis requires a comprehensive approach that includes laboratory and instrumental examination methods [2], such as:

- clinical and biochemical blood tests to identify signs of inflammation and anemia;
- PCR diagnostics of *Helicobacter pylori* as a highly sensitive method for detecting infection;
- analysis of gastric juice;
- contrast-enhanced radiographic examination;
- ultrasound investigation of the abdominal organs;
- endoscopic biopsy to exclude oncopathology;
- fecal occult blood testing;
- serological tests for hepatitis and HIV.

The treatment strategy for peptic ulcer disease is aimed at eradication of the bacterial pathogen, normalization of gastric acidity, and restoration of the protective functions of the gastric mucosa. In most cases, therapy is carried out using conservative methods; however, surgical intervention may be required in the presence of complications.

Despite the widespread introduction of endoscopic technologies into clinical practice, objective quantitative assessment of the area of an ulcerative defect remains a challenging task. While obtaining an image of the affected region generally presents no difficulty, determining its size is often performed visually, which is subjective in nature and may lead to diagnostic discrepancies and suboptimal treatment decisions. This problem becomes particularly relevant in cases of atypical ulcers or defects with complex geometry.

In this regard, one of the priority directions of modern medical engineering is the development of automated methods for the analysis of endoscopic images and calculation of the area of pathological changes. The application of such algorithms makes it possible to reduce the dependence of diagnostic results on the subjective experience of the specialist and to improve their objectivity and reproducibility [3], [4].

To date, a significant number of mathematical methods have been developed for determining the area of objects with arbitrary shapes. The choice of a specific approach is determined by the geometric characteristics of the region under study. Prior to considering the processes of region-of-interest extraction and its digital processing, it is appropriate to focus on the hardware and software tools used for the acquisition of video and photographic materials.

Currently, endoscopic equipment is produced under various brands, including FujiFilm, Aohua, Hikimaging, and others, and is intended for the examination of different human organs such as the ear, nose, and gastrointestinal tract. Within the framework of this study, the endoscopic systems FujiFilm VP-7000 and FujiFilm LL-7000 (Fig. 1), developed by German specialists and designed for the diagnosis of gastrointestinal tract diseases, were used. A significant advantage of the FujiFilm VP-7000 system is its capability for simultaneous video recording and image capture, as well as the availability of functions for adjusting image parameters and an extended set of additional settings, which increases the informational value of the acquired data (Figure 1).

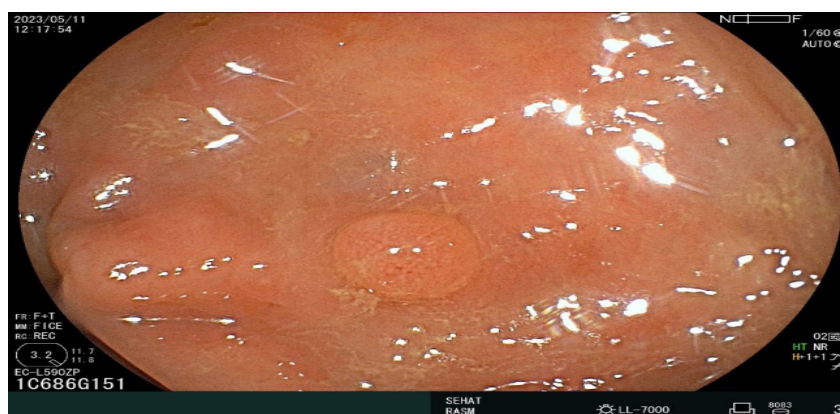


Fig. 1 — Endoscopic image of an ulcerative defect of the gastric mucosa.

LITERATURE REVIEW

Contemporary medical literature emphasizes that the development of digital processing methods for biomedical images represents one of the key directions for improving the accuracy and reproducibility of diagnostics of diseases of the digestive system. Studies devoted to intelligent human–machine interfaces and visual information analysis demonstrate the active integration of computer vision algorithms, machine learning techniques, and intelligent video data processing into clinical practice, including their application in decision support for physicians in endoscopy and related fields.

A number of studies in the areas of gastroenterology and hepatology indicate that the transition to quantitative assessment of pathological changes significantly increases the informative value of examinations and enables more objective monitoring of treatment dynamics. In research focused on the therapy of viral hepatitis, particular attention is paid to the use of biochemical and molecular markers, as well as to strict quantitative criteria for evaluating treatment effectiveness, which illustrates the overall trend toward standardization and formalization of clinical indicators. A similar approach appears relevant for endoscopic visualization of ulcerative defects, where the shift from subjective visual evaluation to mathematically grounded computation of lesion area makes it possible to reduce inter-observer variability and enhance diagnostic objectivity.

The theoretical foundation for the development of algorithms for quantitative estimation of ulcer surface area is provided by classical works in the fields of spline functions and numerical integration. Studies on spline approximation methods demonstrate the high efficiency of piecewise polynomial models for describing complex curvilinear contours, which is particularly important when dealing with biological objects characterized by irregular geometry. The use of spline functions ensures smoothness of the approximating curve, robustness to noise, and the feasibility of subsequent application of numerical integration methods for calculating the areas of figures with arbitrary shapes.

An additional contribution to the advancement of this research direction is made by studies on signal processing in piecewise polynomial bases. These works show that the selection of an appropriate basis and numerical schemes can significantly reduce computational errors and adapt algorithms to the characteristics of real measurement data. In the context of endoscopic image analysis, this enables the development of integrated methods that combine preliminary segmentation of the ulcerative defect, its spline approximation, and subsequent numerical integration, thereby ensuring more accurate and reproducible determination of the pathological area.

RESEARCH METHODOLOGY

1. Rectangle Method

The rectangle method is one of the simplest approaches to approximate numerical integration and is based on partitioning the region under study into elementary rectangles. The area of the figure is determined as the sum of the areas of all such rectangles. Despite its ease of implementation and low computational complexity, this method is characterized by relatively high error, especially when approximating complex curvilinear contours, which is typical for biological objects.

2. Trapezoidal Method

The trapezoidal method represents a more accurate technique of numerical integration compared with the rectangle method. Within this approach, the segment between adjacent nodes is approximated by a trapezoid, allowing a more adequate representation of contour shape variation. The trapezoidal method provides improved computational accuracy while maintaining moderate computational complexity and is widely applied in the processing of medical images.

3. Numerical Integration Method Using Spline Interpolation

To increase the accuracy of ulcer defect shape reconstruction, spline-based interpolation was employed in this study. Spline interpolation makes it possible to construct a smooth approximating curve passing through the given experimental points. As a result, the contour of the ulcerative lesion is described by a continuous function, to which numerical integration is subsequently applied in order to determine the area of the region.

4. Area Determination Using the Rectangle Method

For approximate calculation of the area enclosed by the upper and lower contours, the rectangle method based on numerical integration was utilized. The computation was performed by determining the difference between the areas corresponding to the upper and lower boundaries of the region under investigation. The area according to the rectangle method was calculated using the following expression [4]:

$$S_1 = \sum_{i=1}^n \left(\frac{y_{i+1} - y_i}{n} \sum y_1 - \frac{y_{i+1} - y_i}{n} \sum y_2 \right) \quad (1)$$

where n denotes the number of partitions of the studied interval, and y_1 and y_2 represent the values of the upper and lower boundary functions, respectively. As the number of partitions increases, the overall computational error decreases; however, the computational load simultaneously increases. It should be noted that under conditions of arbitrary distribution of experimental points, the rectangle method does not always provide sufficient accuracy in the processing of biomedical images, which necessitates the use of more advanced numerical methods.

ANALYSIS AND RESULTS

Area Determination Using the Trapezoidal Method In order to improve computational accuracy, the trapezoidal method was additionally applied in the present study, as it allows more correct consideration of contour shape variations between adjacent discretization nodes. Within this approach, segments of the curve are approximated by trapezoidal elements, providing a more adequate representation of the actual geometry of the region. The area of the affected zone in this case was determined using the following formula [5], [6]:

$$S_2 = \sum_{i=0}^{n-1} \frac{y_i + y_{i+1}}{2} (x_{i+1} - x_i) - \sum_{j=0}^{m-1} \frac{y_j + y_{j+1}}{2} (x_{j+1} - x_j), \quad (2)$$

Numerical Integration Based on Spline Interpolation

To achieve the most accurate determination of the ulcer defect area, spline interpolation of the boundary points was applied in this study. After approximating the ulcer contour with a smooth continuous function, numerical integration was performed, which made it possible to significantly reduce the influence of the discreteness of the initial data and to improve the overall computational accuracy. The use of spline interpolation is particularly effective in the analysis of biological objects, as the shape of an ulcerative lesion is typically characterized by complex and irregular geometry.

At the next stage, the video recording of the endoscopic examination was divided into individual frames, after which an algorithm for automated extraction of the gastric ulcer lesion area was implemented, thereby generating the initial data for subsequent quantitative analysis (Figure 2).

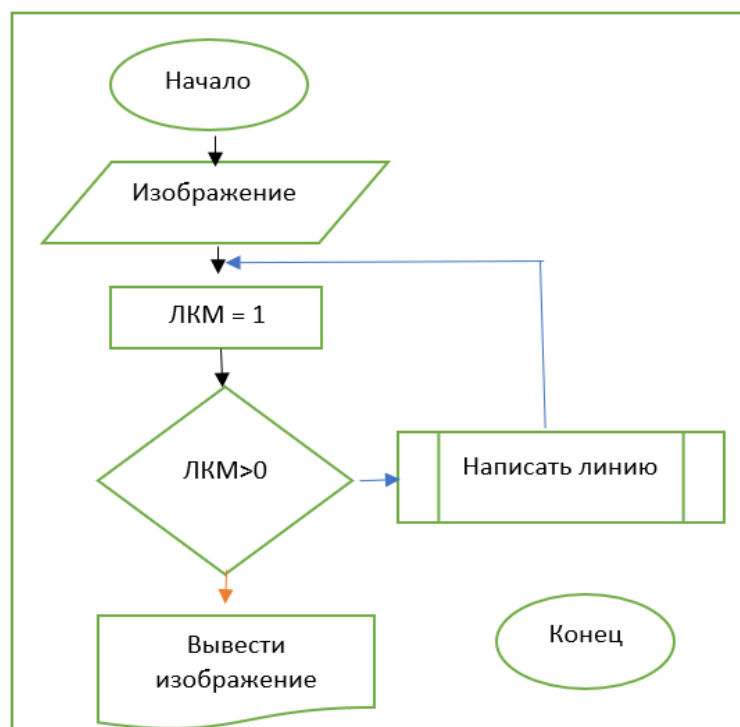


Fig. 2 — Algorithm for detection and segmentation of the region exhibiting features of a pathological process.

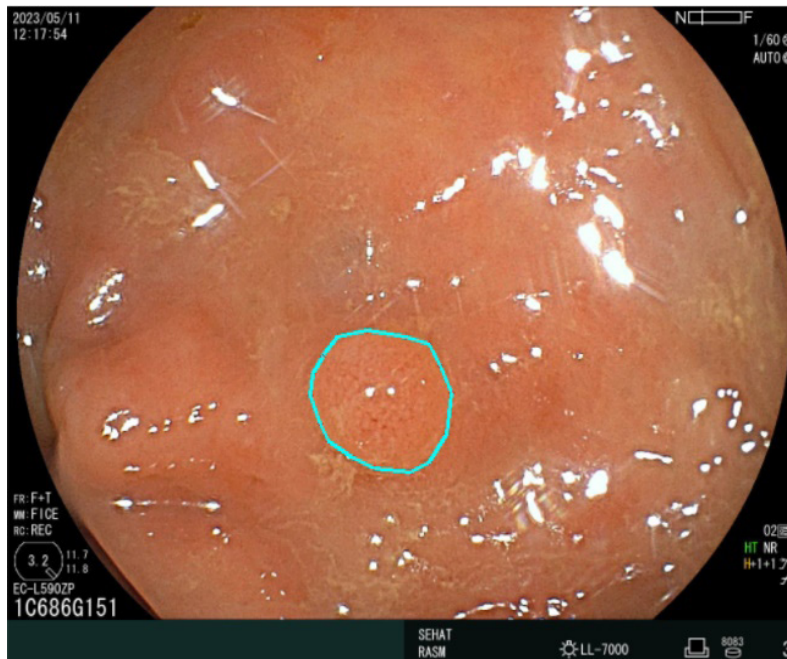


Fig. 3 — Stages of extraction of the ulcer defect of the gastric mucosa.

Table 1. Coordinates of the ulcer defect of the gastric mucosa.

i	x_i	y_i	x_j	y_j
1	307	247	307	247
2	276	252	342	258
3	261	268	352	272
4	251	288	365	285
5	255	322	367	311
6	274	348	352	340
7	300	358	333	355

Table 2. Comparative analysis of the results of calculating the area of the ulcer defect of the gastric mucosa.

Region of Calculation	Rectangle Method, S_1	Trapezoidal Method, S_2	Difference $ S_1 - S_2 $
Upper boundary	38914	39117	203
Lower boundary	29114	29223	109
Final area	9800	9894	94

The values $S1S_{1S1}$ and $S2S_{2S2}$ characterize the number of discrete points falling within the region bounded by the upper and lower contours of the ulcerative defect, as illustrated in Figure 2. To convert the obtained results into real physical dimensions, a scaling ratio was applied, according to which five discrete points correspond to 1 mm.

The results of the performed calculations demonstrated that the method based on numerical integration using the trapezoidal scheme with spline interpolation provides higher accuracy in determining the area of the ulcerative defect compared to the rectangular method. This confirms the feasibility of applying the proposed approach for the quantitative assessment of pathological changes and indicates its potential to enhance the objectivity and reproducibility of endoscopic diagnostics.

CONCLUSION AND RECOMMENDATIONS

The present study introduces an integrated digital methodology designed for the automatic extraction of gastric ulcer images from endoscopic video recordings, the precise delineation of pathological boundaries, and the highly accurate computation of ulcer surface area. The proposed multi-stage algorithm enables the identification

of clinically significant frames, segmentation of ulcer contours using combined gradient operators, and the construction of a smooth, continuous boundary representation through adaptive spline models. The research findings demonstrate that, compared with the rectangle method, the trapezoidal method combined with spline interpolation significantly enhances computational accuracy. Moreover, after converting the calculated values through an appropriate scaling coefficient, the stability of the results is preserved, confirming the effectiveness of the developed approach as a supportive tool capable of increasing the objectivity of endoscopic diagnostics. The use of spline interpolation, which takes into account the complex and irregular geometry of ulcer shapes, contributes to a substantial reduction in area-calculation errors. Overall, the methodology presented in this work is grounded in modern principles of digital medical image processing and provides a reliable mathematical alternative to subjective visual assessment of ulcer dimensions. Based on the outcomes of the study, it is recommended to develop a software module capable of automatically calculating ulcer area during endoscopic examinations and integrating it into existing clinical endoscopy systems, thereby minimizing inter-observer variability and enabling objective monitoring of treatment progression. Further improvement of the algorithm may be achieved by adapting it not only for ulcer detection but also for identifying polyps, erosions, and tumor-like lesions, while incorporating advanced artificial intelligence models to enhance segmentation precision. Expanding the dataset with endoscopic video materials obtained from patients of varying demographic and clinical characteristics is essential for improving the model's generalizability and strengthening its applicability in real clinical practice. Ensuring real-time performance through GPU optimization would allow physicians to obtain accurate quantitative measurements directly during the examination. Additionally, broader accuracy-assessment procedures—such as evaluating different spline types, interpolation levels, and numerical integration schemes, and comparing them with clinical gold standards including biopsy-based measurements and 3D scans—would further reinforce the reliability of the algorithm. Finally, the development of an intuitive user interface capable of displaying contours, performing automatic area calculations, and exporting results to electronic medical records or PDF format would greatly enhance the practicality and usability of the proposed system for healthcare professionals.

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