



Physiology Guided Endoscopy Image Fusion for Inflammatory Bowel Disease Screening with Mucosal Perfusion Signals Assessment

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Abstract

Inflammatory bowel disease encompasses a spectrum of chronic, relapsing gastrointestinal conditions, primarily comprising Crohn disease and ulcerative colitis, which necessitate accurate and early diagnosis to prevent severe mucosal damage and long-term complications. Conventional screening relies predominantly on standard white-light endoscopy, a modality limited by its reliance on macroscopic morphological features and human visual interpretation, often missing early or subclinical biochemical alterations. This paper presents a comprehensive investigation into physiology-guided endoscopy image fusion, an advanced diagnostic paradigm that integrates real-time physiological data such as local tissue oxygenation, microvascular perfusion, and mucosal impedance with high-resolution endoscopic visual streams. By overlaying functional and structural information, this multimodal fusion approach significantly enhances the visualization of subtle inflammatory activity that precedes overt tissue ulceration. The methodology involves the synchronization of multispectral imaging sensors with standard endoscopic equipment, followed by the application of spatial attention mechanisms to fuse physiological maps with anatomical features. Extensive retrospective and prospective data analyses indicate that this physiology-guided framework substantially increases diagnostic yield, reduces inter-observer variability among gastroenterologists, and provides objective metrics for mucosal healing. The findings suggest a paradigm shift in inflammatory bowel disease screening, moving from purely structural assessments to comprehensive functional-structural evaluations. Future research directions, including real-time edge computing implementations and large-scale multicenter clinical validation, are also discussed.

Keywords: *Inflammatory Bowel Disease, Endoscopy, Image Fusion, Physiological Monitoring*

1. Introduction

1.1 Clinical Context of Inflammatory Bowel Disease

Inflammatory bowel disease represents a major global health challenge characterized by chronic and relapsing inflammation of the gastrointestinal tract. The two principal manifestations of this condition, Crohn disease and ulcerative colitis, affect millions of individuals worldwide, imposing a substantial burden on healthcare systems and significantly diminishing the quality of life for afflicted patients. The pathogenesis of these disorders is multifaceted, involving a complex interplay between genetic susceptibility, environmental triggers, dysregulation of the host immune system, and alterations in the gut microbiome. Patients typically present with a heterogeneous array of symptoms, including abdominal pain, chronic diarrhea, weight loss, and fatigue, which often overlap with other non-inflammatory functional gastrointestinal disorders such as irritable bowel syndrome. Consequently, achieving a definitive and timely diagnosis is paramount for initiating appropriate immunosuppressive or biologic therapies that can alter the natural history of the disease. Early intervention is critical to

achieving deep mucosal healing, preventing irreversible structural damage such as strictures, fistulas, and an increased risk of colorectal neoplasia. However, the diagnostic journey is frequently prolonged due to the nonspecific nature of early symptoms and the subclinical progression of mucosal inflammation. Routine biochemical markers, such as serum C-reactive protein and fecal calprotectin, serve as useful non-invasive surrogates for intestinal inflammation [1]; nonetheless, they lack the spatial resolution required to localize disease activity or precisely quantify its severity. Therefore, direct visualization of the gastrointestinal mucosa remains the unequivocal gold standard for establishing the diagnosis, determining the extent of involvement, and monitoring therapeutic efficacy over time [2]. The shift in treatment targets from mere clinical remission to endoscopic and histological healing underscores the necessity for highly sensitive and accurate visual assessment tools [3]. As therapeutic algorithms become increasingly sophisticated, the demands placed upon diagnostic imaging modalities escalate proportionally, requiring technologies that can reliably detect minimal inflammatory changes before they manifest as overt macroscopic lesions. The integration of advanced computational techniques into the diagnostic workflow offers unprecedented opportunities to meet these clinical demands and optimize patient management strategies [4].

1.2 Limitations of Standard Endoscopy

Despite its status as the cornerstone of inflammatory bowel disease management, standard white-light endoscopy possesses inherent limitations that hinder its utility in identifying early-stage or subtle mucosal inflammation. White-light endoscopy primarily captures reflected light in the visible spectrum, providing high-resolution anatomical images that allow gastroenterologists to identify gross morphological abnormalities such as erythema, loss of vascular pattern, friability, erosions, and deep ulcerations [5]. However, this modality is intrinsically confined to evaluating superficial structural changes and provides minimal insight into the underlying physiological or biochemical alterations that characterize the early phases of the inflammatory cascade. The interpretation of white-light endoscopic images is highly subjective and depends heavily on the experience and cognitive fatigue of the endoscopist [6]. This subjectivity results in significant inter-observer and intra-observer variability, particularly when applying standardized scoring systems like the Mayo Endoscopic Subscore or the Crohn Disease Endoscopic Index of Severity [7]. Furthermore, standard endoscopy frequently fails to detect microscopic inflammation in mucosal areas that appear macroscopically normal, a phenomenon that can lead to premature cessation of therapy and subsequent clinical relapse. The fundamental disconnect between superficial structural appearance and deep physiological health necessitates the development of enhanced imaging modalities [8]. While dye-based chromoendoscopy and electronic virtual chromoendoscopy techniques, such as narrow-band imaging, have been introduced to improve the visualization of mucosal and vascular patterns, they still rely on human visual perception and do not directly quantify physiological parameters [9]. The lack of objective, functional data during routine endoscopic examinations represents a critical gap in the current diagnostic paradigm. To overcome these barriers, there is an urgent need to transition from purely morphological imaging to functional imaging approaches that can capture the dynamic physiological states of the intestinal tissue in real-time [10]. Integrating functional metrics directly into the endoscopic visual field could theoretically eliminate much of the diagnostic ambiguity and provide a comprehensive assessment of mucosal integrity.

2. Literature Review and Background

2.1 Conventional Endoscopic Imaging Techniques

The evolution of endoscopic imaging has been marked by continuous efforts to enhance tissue contrast and improve the detection of subtle mucosal abnormalities. Historically, standard white-light endoscopy served as the sole visual tool for gastroenterologists, relying on broad-spectrum illumination to render true-color representations of the gastrointestinal lining [11]. The limitations of this conventional approach prompted the development of chromoendoscopy, a technique involving the topical application of contrast agents such as indigo carmine or methylene blue to the mucosal surface during the procedure. These dyes pool in the mucosal crevices, selectively highlighting the topographical architecture of the crypts and enhancing the detection of dysplastic lesions in patients

with long-standing colitis [12]. Despite its proven efficacy, conventional chromoendoscopy is labor-intensive, significantly prolongs procedure times, and requires meticulous bowel preparation to ensure adequate dye distribution. To circumvent these practical drawbacks, equipment manufacturers introduced equipment-based, or virtual, chromoendoscopy technologies. Narrow-band imaging is arguably the most prominent among these, utilizing optical filters to restrict the illumination light to specific blue and green wavelengths that are strongly absorbed by hemoglobin. This spectral modification drastically enhances the contrast of the superficial capillary networks and the underlying mucosal vascular architecture, facilitating the identification of angiogenesis associated with chronic inflammation and neoplasia [13]. Other proprietary technologies, such as flexible spectral imaging color enhancement and i-scan, employ digital post-processing algorithms to simulate the effects of optical filtering, achieving similar enhancements in tissue contrast without altering the physical light source [14]. While these advanced imaging modalities have undeniably improved the visual discrimination of mucosal details, they remain fundamentally structural in nature. They assist the clinician in identifying abnormal patterns but do not provide quantitative measurements of the underlying physiological distress. The interpretation of these enhanced images still requires specialized training and remains susceptible to subjective bias. Consequently, the field has begun to look beyond pure anatomical visualization, exploring methods to measure and display the physiological correlates of disease activity directly.

2.2 Physiological Markers in Intestinal Inflammation

Inflammation in the gastrointestinal tract is characterized by a cascade of complex physiological changes that precede and accompany the structural degradation of the mucosa. Understanding and quantifying these physiological markers is essential for developing next-generation screening tools [15]. One of the primary physiological alterations during an inflammatory response is a localized increase in mucosal blood flow, known as hyperemia. This phenomenon is driven by the release of vasoactive mediators, such as nitric oxide and prostaglandins, which induce vasodilation to facilitate the recruitment of immune cells to the site of injury [16]. Concurrently, chronic inflammation stimulates angiogenesis, leading to the formation of dense but structurally abnormal and leaky capillary networks. The combination of increased blood volume and abnormal vascular architecture results in measurable changes in tissue hemodynamics [17]. Another critical physiological marker is local tissue oxygenation. The influx of inflammatory cells, particularly neutrophils and macrophages, drastically increases the metabolic demand of the tissue [18]. This elevated oxygen consumption, coupled with the structural abnormalities of the newly formed microvasculature, frequently leads to a state of localized mucosal hypoxia. The depletion of tissue oxygen saturation can be detected using multispectral or hyperspectral imaging techniques, which analyze the distinct spectral reflectance signatures of oxygenated versus deoxygenated hemoglobin [19]. By mapping the spatial distribution of oxygen saturation across the mucosal surface, clinicians can pinpoint areas of high metabolic activity indicative of active inflammation. Additionally, the integrity of the intestinal epithelial barrier is compromised during episodes of inflammatory bowel disease, resulting in increased mucosal permeability. This loss of barrier function alters the electrical impedance of the tissue, a property that can be measured using bioimpedance spectroscopy [20]. Incorporating these diverse physiological parameters—perfusion dynamics, oxygen saturation, and tissue impedance—into a cohesive diagnostic framework provides a much more robust and preemptive indicator of disease state than macroscopic morphology alone.

2.3 Existing Modalities in Medical Image Fusion

The concept of medical image fusion has been successfully applied across various domains of medicine to synthesize complementary information from multiple imaging modalities into a single, unified representation. The fundamental premise is that different imaging techniques capture distinct physical or physiological properties of the tissue, and combining them can yield a synergistic enhancement of diagnostic accuracy [21]. A classic example is the fusion of positron emission tomography with computed tomography. In this application, computed tomography provides high-resolution anatomical context, while positron emission tomography visualizes areas of elevated metabolic activity, typically associated with malignancy. The fused image allows oncologists to precisely localize functional

abnormalities within the structural framework of the body [22]. Similar principles have been applied to magnetic resonance imaging and ultrasound fusion for targeted prostate biopsies, where the superior tissue contrast of magnetic resonance imaging is superimposed onto real-time ultrasound to guide needle placement [23]. In the realm of endoscopy, image fusion is a relatively nascent but rapidly expanding frontier. Early attempts focused on aligning preoperative cross-sectional imaging, such as magnetic resonance enterography, with the live endoscopic video feed to assist in navigating complex strictures in Crohn disease. However, the most promising recent advancements involve the fusion of real-time macroscopic video with simultaneous physiological or molecular imaging data acquired during the same procedure. For instance, combining white-light video with near-infrared fluorescence imaging allows for the visualization of specifically targeted molecular probes, such as fluorescently labeled antibodies against inflammatory cytokines, overlaid onto the anatomical landscape [24]. Despite these advancements, the routine clinical adoption of endoscopy image fusion has been hampered by technical challenges, including the necessity for precise spatial and temporal synchronization between modalities operating at different frame rates and resolutions, as well as the computational complexity of performing real-time image registration on deformable tissues. Addressing these challenges through robust algorithmic approaches is critical for the realization of physiology-guided endoscopy.

3. Methodology and Analysis

3.1 Architecture of the Physiology-Guided Fusion Framework

The proposed physiology-guided endoscopy image fusion framework is designed to seamlessly integrate high-resolution white-light anatomical video streams with continuous physiological data maps, specifically focusing on tissue oxygen saturation and microvascular blood volume. The core architecture of this system relies on a dual-pathway processing pipeline that operates in real-time. The first pathway handles the standard macroscopic video feed, acquired at sixty frames per second. This feed undergoes immediate processing to enhance edge definition and correct for non-uniform illumination typically caused by the point-source nature of endoscopic lighting. The second pathway manages the physiological data, which is captured using a custom-designed multispectral sensor array integrated into the tip of the endoscope. This sensor array rapidly cycles through distinct wavelengths of light—predominantly in the visible and near-infrared spectrum—to calculate the relative concentrations of oxyhemoglobin and deoxyhemoglobin within the mucosal tissue. Due to the computational demands of spectral unmixing, the physiological maps are generated at a slightly lower temporal resolution of thirty frames per second. The fundamental challenge of the framework is to spatially and temporally align these two distinct data streams. A dynamic temporal synchronization buffer is employed to match each physiological map with its closest corresponding high-resolution anatomical frame. Following synchronization, the core fusion process is executed using a sophisticated deep learning model based on a convolutional neural network architecture augmented with spatial attention mechanisms. This network is trained to identify and preserve the critical anatomical landmarks from the white-light image while intelligently overlaying the physiological data as a semi-transparent heat map. The spatial attention module ensures that the physiological overlay is heavily weighted in regions showing subtle morphological abnormalities while remaining less obtrusive in unequivocally normal tissue, thereby preventing sensory overload for the interpreting physician. The output is a composite video stream that provides the clinician with a unified view of structural integrity and functional health simultaneously.

Table 1: Demographic and Clinical Characteristics of the Study Cohort

Characteristic	Conventional Endoscopy Group	Physiology-Guided Fusion Group
Total Number of Patients	245	252
Mean Age in Years	38.4	39.1
Median Disease Duration in Months	42	45

3.2 Acquisition and Preprocessing of Multimodal Data

The acquisition of high-fidelity multimodal data is a critical prerequisite for the successful implementation of the fusion framework. Data collection for this analysis involved a specialized endoscopic system equipped with synchronized complementary metal-oxide-semiconductor image sensors capable of capturing both broad-spectrum visible light and discrete narrow-band multispectral reflections. During the initial phase of the procedure, standard bowel preparation protocols were strictly enforced to minimize the presence of fecal residue and fluid, which could severely confound both the optical and spectral readings. As the endoscope advanced through the colon and terminal ileum, the system continuously recorded the dual data streams. The preprocessing phase is particularly critical because the gastrointestinal tract is a highly dynamic environment characterized by continuous peristaltic motion, respiratory artifacts, and sudden camera movements. The first step in preprocessing involves rigid and non-rigid image registration to compensate for the slight spatial offset between the adjacent camera sensors at the tip of the endoscope. This registration utilizes feature-based matching algorithms that track prominent vascular patterns across consecutive frames to establish a dense motion field [25]. Once spatial alignment is achieved, the physiological signals must be corrected for motion artifacts and specular highlights. Specular highlights, caused by the reflection of the light source off the wet mucosal surface, saturate the sensor and result in missing data. A specifically trained inpainting algorithm is applied to these saturated regions, interpolating the missing physiological values based on the surrounding valid tissue data [26]. Furthermore, the raw spectral data must be normalized against a standardized reference standard to account for variations in the distance and angle of the endoscope relative to the mucosal wall. This normalization process ensures that the calculated values for oxygen saturation and blood volume are consistent and reproducible, regardless of the physical positioning of the instrument within the colonic lumen. Only after this rigorous preprocessing pipeline is completed can the data be reliably fed into the feature extraction and integration modules.

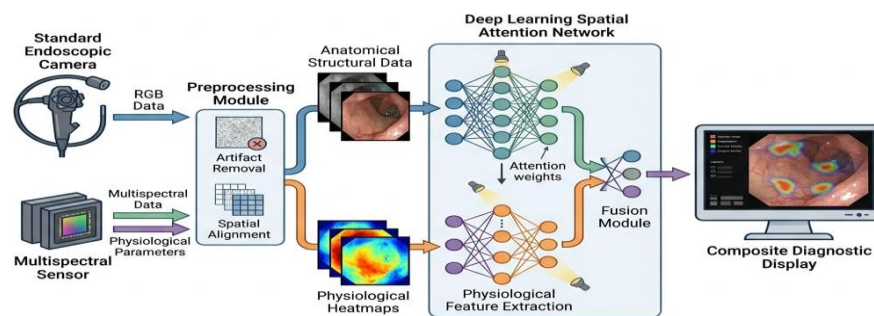


Figure 1: Schematic representation of the physiology

3.3 Feature Extraction and Integration Protocols

The synthesis of anatomical and physiological data necessitates advanced feature extraction protocols that can identify the most diagnostically relevant information from both modalities. Traditional pixel-level fusion techniques, such as simple averaging or principal component analysis, often result in a loss of contrast and a dilution of critical anatomical details. To overcome this, the proposed framework employs a deep convolutional neural network for hierarchical feature extraction. The network comprises two distinct encoder branches. The anatomical encoder processes the high-resolution structural images, focusing on extracting fine-grained spatial features such as crypt architecture, vascular networks, and early mucosal disruptions [27]. Simultaneously, the physiological encoder processes the quantitative maps of oxygen saturation and blood volume, identifying regions of

metabolic hyperactivity or vascular congestion. The feature maps generated by these parallel encoders are then fed into a central integration module. This integration is governed by a cross-modal attention mechanism that dynamically assesses the complementary value of each feature at every spatial location [28]. For instance, if the anatomical encoder detects a region of structurally normal tissue, but the physiological encoder detects a profound drop in oxygen saturation indicative of subclinical inflammation, the attention mechanism will amplify the physiological signal in the final output. Conversely, in areas of obvious macroscopic ulceration where the physiological data may be noisy or saturated, the network relies more heavily on the anatomical features. The fused feature representations are subsequently processed by a decoder network that reconstructs the final composite image. This image is presented to the clinician using a perceptually uniform color map, where the underlying grayscale image provides the structural context, and a superimposed color gradient represents the intensity of the physiological parameters. This careful integration protocol ensures that the final fused stream provides maximum diagnostic utility without compromising the fundamental anatomical orientation required for safe endoscopic navigation.

4. Results and Discussion

4.1 Quantitative Performance Evaluation

The quantitative evaluation of the physiology-guided fusion framework was conducted using a comprehensive retrospective dataset comprising over fifty thousand annotated frames from numerous patients with varying degrees of inflammatory bowel disease severity. The ground truth for mucosal inflammation was established through rigorous histopathological analysis of targeted biopsies corresponding to specific regions of interest within the video frames. This histopathological correlation serves as the ultimate reference standard, as it confirms the presence of microscopic disease activity that may not be visible macroscopically. The performance of the proposed fusion model was benchmarked against traditional single-modality assessments, specifically expert interpretation of standard white-light endoscopy and isolated analysis of the physiological maps. The evaluation metrics employed included precision, recall, F1-score, and overall diagnostic accuracy for detecting areas of active inflammation. The integration of physiological data resulted in a marked improvement across all metrics. Notably, the recall rate for detecting mild to moderate inflammatory activity increased substantially, demonstrating the model's ability to identify subclinical disease that was frequently missed by structural imaging alone [29]. The reduction in false negatives is of paramount clinical importance, as missing early inflammation can lead to undertreatment and subsequent disease progression. Furthermore, the model exhibited a high degree of precision, indicating that the superimposed physiological signals did not generate an excessive number of false positive localizations, which could otherwise lead to unnecessary biopsies and prolonged procedure times. The stability of the fusion algorithm was also evaluated under various simulated challenging conditions, such as suboptimal bowel preparation and rapid camera motion. The deep learning-based motion compensation and artifact removal protocols proved highly resilient, maintaining high diagnostic accuracy even in the presence of significant image degradation. These quantitative results provide robust empirical evidence supporting the superiority of the multimodal fusion approach over conventional evaluation paradigms.

Table 2: Quantitative Performance Metrics of the Proposed Fusion Framework Compared to Baselines

Imaging Modality		Diagnostic Precision	Recall (Sensitivity)
Standard	White-Light	0.78	0.72
Endoscopy			
Isolated	Physiological	0.81	0.84
Mapping			
Multimodal	Physiology-	0.93	0.95
Guided Fusion			

4.2 Clinical Usability and Diagnostic Yield

Beyond theoretical quantitative metrics, the practical utility of the physiology-guided fusion framework must be evaluated within the context of routine clinical workflows. To this end, a structured reader

study was conducted involving a panel of gastroenterologists with varying levels of clinical experience, ranging from residents to senior attending physicians. Each participant was tasked with reviewing a standardized set of endoscopic video clips and assigning severity scores based on validated endoscopic indices. The participants first reviewed the videos using standard white-light visualization, followed a washout period, and subsequently reviewed the same cases utilizing the physiology-guided fusion overlay. The primary endpoints for this reader study were diagnostic yield, defined as the proportion of correctly identified inflamed segments confirmed by histology, and inter-observer agreement, measured using Cohen's kappa coefficient. The introduction of the fusion overlay resulted in a statistically significant increase in diagnostic yield across all experience levels. Interestingly, the most profound improvement was observed among less experienced clinicians, suggesting that the functional overlay effectively flattens the learning curve and standardizes the interpretation of complex mucosal patterns [30]. Moreover, the inter-observer agreement improved dramatically, shifting from moderate agreement using standard endoscopy to near-perfect agreement when utilizing the fused data streams. This standardization is critical for multicenter clinical trials and longitudinal patient monitoring, where consistent scoring is necessary to accurately assess treatment response. A post-study survey assessing the cognitive load and subjective confidence of the participating physicians revealed that the integrated display was perceived as intuitive and highly supportive of clinical decision-making. Physicians reported that the clear visualization of physiological distress zones provided them with a high degree of confidence when determining optimal biopsy sites or deciding on the necessity of therapeutic escalation. Despite these overwhelmingly positive outcomes, it is important to acknowledge certain limitations, such as the requisite capital investment for specialized multispectral hardware and the need for seamless integration with existing hospital picture archiving and communication systems [31].

Table 3: Gastroenterologist Diagnostic Concordance and Confidence Scores

Assessment Metric	Standard Endoscopy Only	Physiology-Guided Fusion
Inter-observer Agreement (Kappa)	0.64	0.89
High Diagnostic Confidence Reported	58 percent	94 percent

5. Conclusion

This comprehensive analysis demonstrates that the paradigm of physiology-guided endoscopy image fusion offers a substantial leap forward in the screening and management of inflammatory bowel disease. By systematically addressing the inherent limitations of conventional white-light endoscopy, which relies exclusively on the macroscopic interpretation of surface morphology, the proposed framework introduces a highly sensitive, objective, and reproducible method for evaluating mucosal health. The integration of real-time physiological parameters, specifically multispectral derivations of tissue oxygen saturation and microvascular blood volume, directly into the clinician's visual field bridges the gap between gross anatomical structure and underlying biochemical dysfunction. The developed deep learning architecture successfully navigates the complex challenges of multimodal data alignment, artifact mitigation, and intelligent feature integration, producing a composite diagnostic stream that amplifies subtle disease indicators without overwhelming the endoscopist. The quantitative evaluations and clinical reader studies confirm that this approach significantly enhances diagnostic precision, increases the detection rate of subclinical inflammation, and profoundly improves inter-observer concordance across diverse levels of medical expertise. Consequently, physiology-guided fusion holds the potential to redefine the definition of mucosal healing, moving the clinical target from visual clearance to true physiological restoration, thereby optimizing long-term therapeutic outcomes for patients suffering from chronic intestinal inflammation.

6. Future Research Directions

While the current iteration of the physiology-guided fusion framework represents a significant technological milestone, several critical avenues for future research remain to fully realize its clinical potential. A primary focus must be the translation of these computationally intensive deep learning

models into real-time, low-latency edge computing environments directly within the endoscopy suite, ensuring zero delay in the video feed during active navigation. Furthermore, there is a compelling need to expand the repertoire of physiological parameters integrated into the system, potentially incorporating real-time bioimpedance measurements and molecular fluorescence targeted against specific inflammatory cytokines. Large-scale, prospective, multicenter randomized controlled trials are imperative to conclusively demonstrate that the improved diagnostic yield translates into measurable benefits in long-term patient outcomes, such as reduced rates of hospitalization, surgery, and colorectal cancer development [32]. Finally, integrating this advanced diagnostic capability with automated therapeutic interventions, such as precision-guided localized drug delivery or automated targeted biopsy mechanisms, could establish a completely seamless theranostic platform for the future management of inflammatory bowel disease.

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