

2016 Inflammatory Bowel Disease: Global view

Light and sound - emerging imaging techniques for inflammatory bowel disease

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Abstract

Patients with inflammatory bowel disease are known to have a high demand of recurrent evaluation for therapy and disease activity. Further, the risk of developing cancer during the disease progression is increasing from year to year. New, mostly non-radiant, quick to perform and quantitative methods are challenging, conventional endoscopy with biopsy as gold standard. Especially, new physical imaging approaches utilizing light and sound waves have facilitated the development of advanced functional and molecular modalities. Besides these advantages they hold the promise to predict personalized therapeutic responses and to spare frequent invasive procedures. Within this article we highlight their potential for initial diagnosis, assessment of disease activity and surveillance of cancer development in established techniques and recent advances such as wide-view full-spectrum endoscopy, chromoendoscopy, autofluorescence endoscopy, endocytoscopy, confocal laser endoscopy, multiphoton endoscopy, molecular imaging endoscopy, B-mode and Doppler ultrasound, contrast-enhanced ultrasound, ultrasound molecular imaging, and elastography.

Key words: Ulcerative colitis; Crohn's disease; Endoscopy; Chromoendoscopy; Autofluorescence endoscopy; Full-view full-spectrum endoscopy; Confocal endomicroscopy; Multiphoton endoscopy; High-definition endoscopy; Ultrasound molecular imaging; B-mode ultrasound; Doppler ultrasound

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Core tip: Patients with inflammatory bowel disease are known to have a high demand of recurrent evaluation for therapy and disease activity. Further, the risk of developing cancer during disease progression is growing from year to year. Especially, new physical imaging approaches utilizing light and sound waves have facilitated the development of endoscopic techniques. Within this article we highlight their potential for initial diagnosis, assessment of disease activity and surveillance of cancer development in established techniques and recent advances such as wide-view full-spectrum endoscopy, chromoendoscopy, auto-fluorescence endoscopy, endocytoscopy, confocal laser endoscopy, multiphoton endoscopy, molecular imaging endoscopy, B-mode and Doppler ultrasound, contrast-enhanced ultrasound, ultrasound molecular imaging, and elastography.

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INTRODUCTION

Inflammatory bowel disease (IBD) is a group of chronic inflammatory diseases seen in 1 of 200 to 500 individuals^[1]. The pathophysiology of the two major subtypes, Crohn's Disease and ulcerative colitis, is still not completely understood^[2]. The course of disease is marked by relapses of chronic inflammation and accompanied by severe symptoms, like bloody stool, abdominal pain and weight loss^[3]. The assessment of disease extent is still a substantial challenge for clinicians, but it is crucial for successful treatment. The absence of endoscopic activity, *e.g.*, mucosal healing or histologic remission, might even better guarantee long-term success compared to conventional clinical outcome measures^[4-6]. Studies demonstrated that higher rates of mucosal healing might be achieved with higher frequency of assessment of endoscopic disease activity and adjustments to medical therapy^[7,8]. It is still questionable, if patients adhere to intensive invasive endoscopic procedures^[9]. Facing a high economic burden^[10] together with globally increasing rates of pediatric IBD^[11] raising concerns for potential risks and harmful procedures^[12], we urgently need modalities to easily and quickly assess the extent of disease. Furthermore, these modalities need to account and detect precursor lesion in these patients knowing to bear an increasing risk of colitis associated cancer development^[13,14]. As light and sound are very different waves in their physical behavior, both can be used to generate new insights into a bright variety of diseases. We provide a review focused on recent

imaging advances based on sound and light wave technologies, which are already or are about to be translated into routine clinical use for inflammatory bowel disease.

RECOMMENDATIONS AND STATE-OF-THE-ART

International consensus guidelines and recommendations for inflammatory bowel disease, including its surveillance and management of dysplasia, point out important aspects concerning imaging are summarized in Table 1^[15-18].

Initial diagnosis, follow-up and surveillance are the major keys for clinical management of IBD. Up to now, endoscopy is representing the major backbone to compete in all disciplines. New imaging modalities are lining up to complement this technique with easy applicable, non-invasive and quantitative approaches, to individually improve patients' care.

MACROSCOPIC ENDOSCOPIC TECHNOLOGIES

Since the first endoscopy was performed by Kussmaul A in 1868, its technique and application has greatly expanded. Especially during recent years, new technological developments are further improving the diagnostic accuracy for wide-spread (pre-)clinical applications. Some of the most important techniques will be shortly described in this section:

High-definition endoscopy

Standard definition (SD) endoscopy offers images in a 4:3 aspect ratio, reaching up to 270000 to 410000 pixels, while high definition (HD) or high resolution endoscopy presents images with 850000 to 1 million pixels. It is clear that high resolution endoscopy results in visualization of a more detailed mucosa^[19].

Wide-view full-spectrum endoscopy

Usually, standard forward-viewing colonoscopes visualize the intestinal surface using an optical system from tip with an angle of view up to 170°. The wide-view full-spectrum endoscopy provides an extended view with a 330° angle. This platform was first tested in an *in vitro* model, suggesting better detection rates for polyps^[20]. Further, its applicability was also verified in small cohorts to show feasibility, performing at a 100% caecal intubation rate and providing high evaluation scores from patients and endoscopists^[21].

Chromoendoscopy

Chromoendoscopy uses various dyes, endoscopic optical and computer-based software to enhance image quality and to visualize the mucosal architecture. One first approach was reported by Tada *et al.*^[22] and since

Table 1 Recommendations and state-of-the-art in inflammatory bowel disease imaging according to international guidelines^[15-18]

Initial diagnosis and follow-up	<p>Colonoscopy with ileoscopy is recommended for the initial evaluation of inflammatory bowel disease (IBD) and for the differentiation IBD subtypes</p> <p>Sampling of mucosal biopsy specimens from multiple sites during the initial endoscopic evaluation of IBD is recommended</p> <p>Flexible sigmoidoscopy should be performed in patients with IBD when colonoscopy is contraindicated</p> <p>Radiological imaging techniques are complementary to endoscopic assessment. Cross-sectional imaging offers the opportunity to detect and stage inflammatory, obstructive and fistulizing Crohn's disease (CD) and is fundamental at first diagnosis to stage disease and to monitor follow-up</p> <p>Ultrasound (US) is a well-tolerated and radiation-free imaging technique, particularly for the terminal ileum and the colon. Examinations are impaired by gas-filled bowel and by large body habitus</p> <p>US is able to detect signs of Crohn's disease and has high and comparable diagnostic accuracy at the initial presentation of terminal ileal CD</p> <p>US can be used to assess disease activity in Crohn's disease of the terminal ileum</p> <p>US imaging is an adjunct to endoscopy for diagnosis of colonic IBD</p> <p>Transabdominal US has a high accuracy for assessing the activity and severity of Crohn's colitis; the performance in UC is less clear; the accuracy of monitoring therapy in colonic Crohn's disease is not well defined</p>
Surveillance and management of dysplasia	<p>It is recommended that all patients with UC or CD colitis undergo a screening colonoscopy 8 yr after disease onset to re-evaluate extent of disease and initiate surveillance for colorectal neoplasia</p> <p>It is recommended to perform surveillance colonoscopy every 1 to 3 yr beginning after 8 yr of disease in patients with UC with macroscopic or histologic evidence of inflammation proximal to and including the sigmoid colon and for patients with Crohn's colitis with greater than one-third of colon involvement</p> <p>If white-light colonoscopy is performed in case of surveillance, high definition (HD) is recommended rather than standard definition (SD)</p> <p>If surveillance is performed with SD colonoscopy, chromoendoscopy is recommended rather than white-light</p> <p>If performing surveillance with HD colonoscopy, chromoendoscopy is suggested rather than white-light colonoscopy</p> <p>If performing surveillance with SD colonoscopy, narrow-band imaging (NBI) is not suggested in place of white-light</p> <p>If performing surveillance with high-definition colonoscopy, NBI is not suggested in place of white-light</p> <p>If performing surveillance with image-enhanced HD colonoscopy, NBI is not suggested in place of chromoendoscopy</p>
Management of dysplasia discovered on surveillance colonoscopy	<p>After complete removal of endoscopically resectable polypoid dysplastic lesions, surveillance colonoscopy is recommended rather than colectomy</p> <p>After complete removal of endoscopically resectable nonpolypoid dysplastic lesions, surveillance colonoscopy is suggested rather than colectomy</p> <p>For patients with endoscopically invisible dysplasia (confirmed by a gastrointestinal pathologist), referral is suggested to an endoscopist with expertise in IBD surveillance using chromoendoscopy with high-definition colonoscopy</p>

then, different agents for topic application have been approved (methylene blue, toluidine blue, and cresyl violet, indigo carmine, acetic acid, Congo red, phenol red)^[23]. By using this technique, an enhancement of the mucosal surface could be achieved to augment superficial patterns and the contrast of pathologic versus normal mucosa^[24]. In order to further improve the visualization high-definition resolution was additionally introduced to this technique.

Narrow-band imaging (NBI) or virtual chromoendoscopy, is a comparable software based approach utilizing light of specific wavelength in green and blue spectra to enhance the vascular pattern of the mucosa. As hemoglobin is known to have a peak light absorption at these wavelengths, an optical filtered image can then display the capillaries on the surface and in the submucosa in different colors^[25,26].

Autofluorescence endoscopy

Depended on the biochemical composition of the visualized tissue, this technique utilizes intensity laser light to induce and generate autofluorescent light spectra^[27]. Strong endogenous fluorochromes such as collagen, elastin, nicotinamide adenine dinucleotide (NAD), flavin adenine dinucleotide (FAD), lipofuscin, tryptophan, and keratin can be detected^[28]. Most studies used 370 nm excitation light and col-

lected fluorescence in the range 400-700 nm^[29,30]. Fluorescence imaging is able to identify suspect lesion with high sensitivity, especially when it is used in the detection of suspect polyps^[31,32].

MICROSCOPIC ENDOSCOPIC TECHNOLOGIES

Whereas wide-field endoscopy enables the identification of suspect lesions or inflamed areas of the mucosa during the endoscopic procedure, microscopic evaluation of tissue samples is still required for a definitive diagnosis. As this can delay a definitive treatment up to several days, the development of *in vivo* endomicroscopic imaging techniques has been one of the major aims of endoscopic research during recent years. Whereas some techniques are already used in clinical practice, others are still in development as subsequently described.

Endocytoscopy

Endocytoscopy (EC) is based on contact light microscopy to the superficial layer of the mucosa. The technology uses fixed-focus and high-power objective lenses^[33]. In order to prepare an ideal environment for imaging, washing the surface together with

N-acetylcysteine for mucolysis is recommended^[34]. EC requires prestaining with absorptive topic agents like the combination of crystal violet and methylene blue^[35]. For example, EC was used to examine esophageal tissue to identify superficial esophageal carcinomas^[36] or bladder cancer cells^[37].

Confocal laser endoscopy

Confocal laser colonoscopy (CLE) is either based on the integration of a confocal laser microscope into the distal tip (ISC-1000/EC3870CIK, Pentax Corporation, Tokyo, Japan) or the utilization of a small probe, which can be introduced through the working channel (Cellvizio, Mauna Kea Technologies, Paris, France). During the procedure, a laser is delivering the excitation light to the surface of the mucosa providing *in-vivo* histology at a magnification of 1000-fold^[38]. As compared to chromoendoscopy, CLE also relies on the topic or systemic application of fluorescence agents^[39]. Kiesslich *et al.*^[38] demonstrated that this technique may be helpful to avoid repeated colonoscopies, because target lesions could be analyzed more rapidly *in vivo* during colonoscopy. As a side note: Pentax has already discontinued its product.

Multiphoton endoscopy

Multiphoton microscopy (MPM) has been widely used as an *in vivo* imaging technique for basic research. In comparison with single photon excitation during confocal microscopy, MPM provides a superior effective resolution in thick tissue samples and an increased penetration depth^[40]. Fluorescence imaging is therefore based on the molecular absorption of 2 infrared photons at the same time. First, by generating a second harmonic generation, a nonlinear scattering effect, fibers of collagen-I could be imaged. Second, autofluorescence can be detected from NADH-rich epithelial cells or FAD bearing immune cells. Because this effect is only occurring in a small volume of the focus images could be easily combined to a 3D-image stack^[41]. Compared to confocal laser endomicroscopy, this technique is not restricted by the detection of exogenous fluorophores and can easily visualize the subcellular level of gastrointestinal diseases^[41]. Until now, there is no MP-endoscope developed for clinical use, but pre-clinical systems have been already described^[42].

Molecular imaging endoscopy

To further improve the quality of endoscopic imaging, subcellular/molecular information were acquired by adding molecular targeted compounds such as antibodies, peptides or nano particles for specific detection^[43]. Liu *et al.*^[44] could show that a specific octapeptide conjugated with Cy5.5 excited at 671 nm allowed near infrared (NIR) fluorescence detection at 696 to 736 nm, which was supposed to be specific for colonic adenomas and achieved sub-cellular resolution

images. This general concept was also applied to adenomas/polyps, which are known to highly express the signaling molecule VEGF-A, which is supposed to be involved in vascular growth and maturation as well as tumor growth^[45,46]. The feasibility to visualize small tumors in real time during colonoscopy could be demonstrated using NIR fluorescence endoscopy^[47]. An overview of all described technologies for endoscopic imaging is given in Figure 1.

ULTRASOUND TECHNOLOGIES

Ultrasound (US) has an important role and great potential in imaging the intestine in children and adults^[48]. In some countries, *e.g.*, the United States, it is still far less important than CT imaging, which faces a relative increase of 47.3% from 2007-2010 for non-head application^[49]. Compared to US, CT provides the rapid evaluation of bowel and mesentery as well cross-sectional assessment of abdominal and pelvic organs including major vessels^[50]. In contrast, US is non-invasive, low cost, easily repeatable and does not rise concerns about radiation exposure in children and young adults^[51].

B-mode and Doppler ultrasound

US is a non-invasive, not radiant, and well tolerated modality. The window of imaging is limited by intestinal air or deep organs; therefore, fasting before imaging may be helpful^[52]. US for IBD imaging requires the use of high-frequency (5-17 MHz) linear transducers in order to increase spatial resolution and to allow adequate assessment of bowel diameter and of different intestinal layers^[53]. Authors recommend a systematic approach to visualize sites of inflammation including the upper and lower, right and left abdominal quadrants^[51]. Usually the transabdominal imaging is less invasive, but endoscopic or endosonographic approaches have also been described in pre-clinical^[54] and clinical settings^[55].

Contrast-enhanced ultrasound

Contrast-enhanced ultrasound utilized gas-filled coated microbubbles to image vascularity. Currently, its major domain is focal liver lesion diagnostics^[56] and it is also frequently applied to vascular or cardiac diagnostics^[57,58].

Due to its fast liver and renal independent pulmonary clearing, these microbubbles have superior pharmacologic profile in patients with a complicated medical history^[59,60]. Diagnostic accuracy^[56,61-64], pharmacological safety^[65], and cost efficiency in comparison to other conventional imaging modalities^[66] has been widely proven. Further, quantitative parameters could be easily derived by secondary software quantification^[67,68]. This technique was already applied in the follow-up of anti-vascular treatments in renal cell carcinoma^[69], hepatocellular carcinoma^[70,71] or

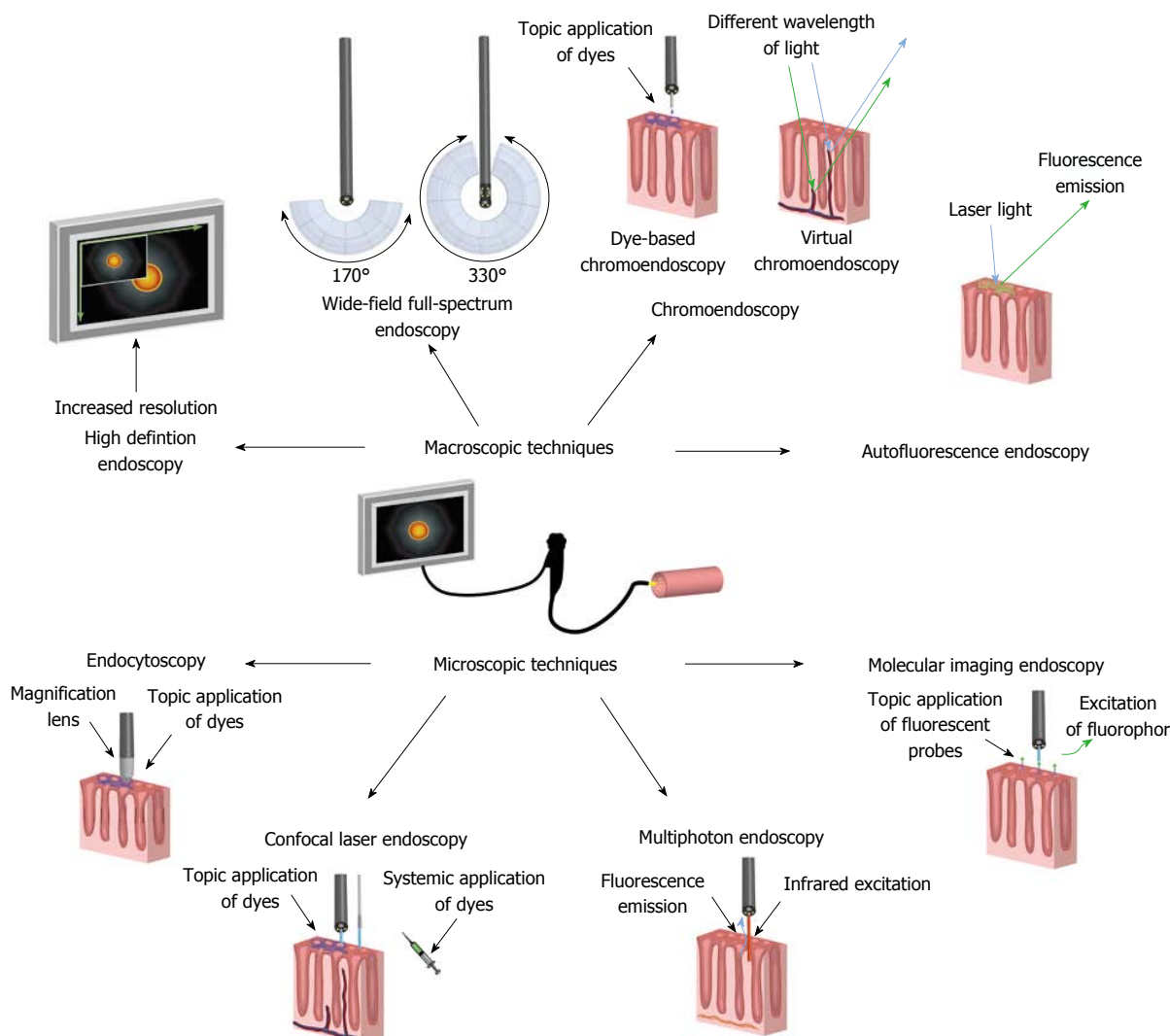


Figure 1 Overview of existing and emerging endoscopic technologies to visualize macroscopic or microscopic features of the intestine. Macroscopic technologies include: high-definition endoscopy, wide-view full-spectrum endoscopy, chromoendoscopy, and autofluorescence endoscopy. Microscopic technologies include: endocytoscopy, confocal laser endoscopy, multiphoton endoscopy, and molecular imaging endoscopy. A detailed description for each modality is given in the text.

cholangiocellular carcinoma^[72].

Ultrasound molecular imaging

A further evolution of the aforementioned technique is ultrasound molecular imaging (UMI) or targeted molecular ultrasound. Both, CEUS and UMI, have in common that they use small gas-filled microbubbles to image vascularization. Further, UMI contrast agents have coupled a ligand to their outer shell to target specific endothelial molecules of interest^[73]. Pre-clinical systems have been applied to detect cancer neovascularization in prostate using VEGFR-2^[74] or P- and E-selectins in acute myocardial ischemia^[75]. Until now, a clinical translation has not been achieved yet.

Elastography

Another “contrast-agent-free” modality is ultrasound elastography. It is a non-invasive imaging approach to evaluate tissue hardness^[76,77]. A transducer generates forced push pulses to displace targeted tissues at a

specified depth. This displacement causes orthogonal shear waves, which can be detected as they propagate through the tissue of interest^[77]. The distance traveled by the generated shear and the time provides an estimate of shear wave velocity and tissue hardness (m/s)^[78]. The shear wave velocity corresponds to the tissues’ ability to resist deformation and increases with increasing tissue hardness^[77]. This has been exemplary studied in liver fibrosis^[79], focal liver lesions^[80], and thyroid nodules^[81]. An overview all described technologies for ultrasound imaging is given in Figure 2.

CLINICAL EVIDENCE AND TRANSLATION OF ENDOSCOPIC TECHNIQUES

First diagnosis of IBD

The identification of distinct patterns of mucosal inflammation has been one part of the initial diagnosis of IBD for decades. Whereas inflammation in Crohn’s disease (CD) presents with aphthous ulcers, cobble stoning,

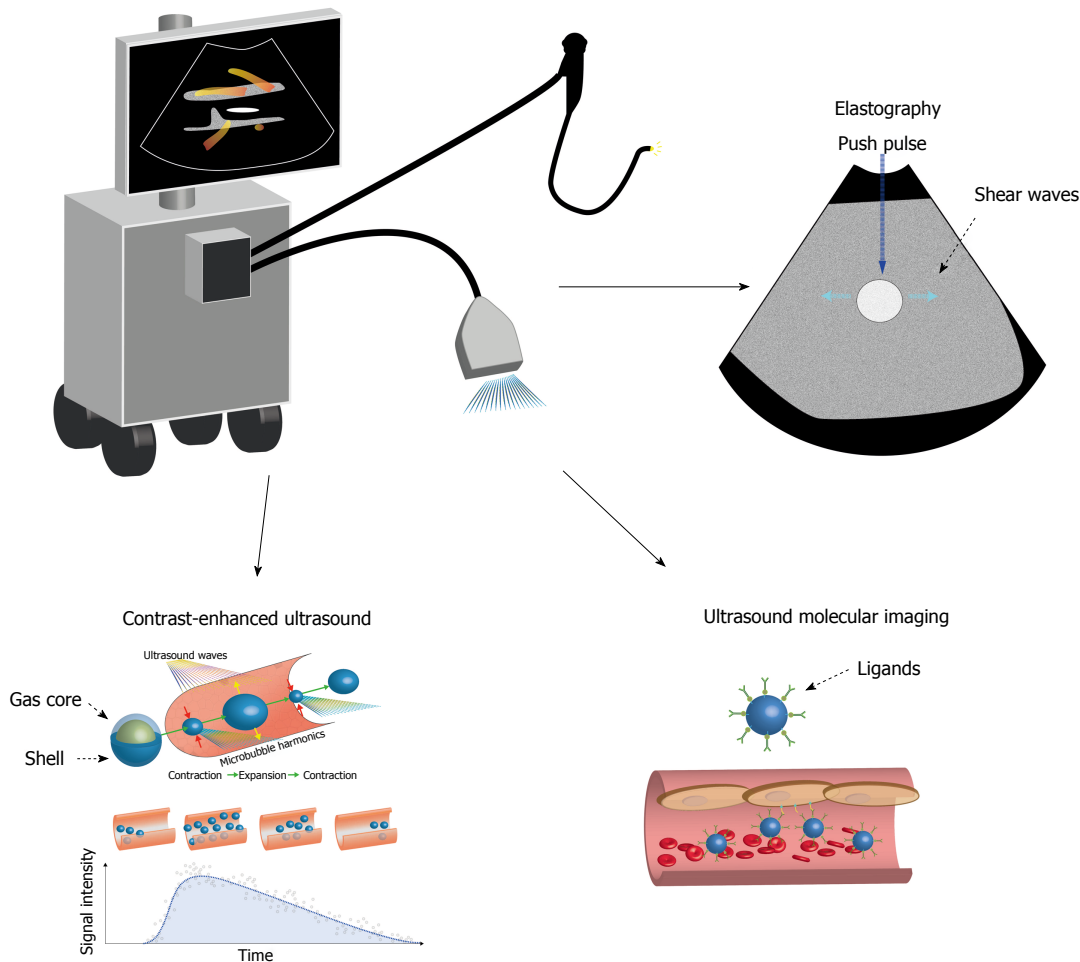


Figure 2 Overview of existing and emerging ultrasound transabdominal and endoscopic technologies for visualizing the intestine. Besides B-mode and Doppler, technologies include: contrast-enhanced ultrasound, ultrasound molecular imaging, and elastography. A detailed description for each modality is given in the text.

serpiginous ulcers, and the possibility of strictures in the terminal ileum; erythema, edema, bleeding and increased granularity of the colonic mucosa can be observed in UC. Despite these characteristic signs, endoscopy alone does not allow the definitive diagnosis of CD or UC and therefore relies on additional signs in microscopy such as granuloma formation in CD or crypt abscesses in UC. Despite the above-mentioned technological advantages of wide-field endoscopy during recent years, none of these technologies, including the techniques described above, have so far been shown to improve the initial diagnosis of IBD alone. However, first results show some advantage for the additional usage of confocal endomicroscopy. Although limited by its penetration depth, it is capable of visualizing disease-specific microscopic patterns, known from histopathology, to differentiate between UC and CD^[82]. Findings in CD showed significantly more discontinuous inflammation, increased focal cryptitis, and discontinuous crypt architectural abnormality compared to UC, which was associated with severe, widespread crypt distortion, decreased crypt density, and frankly irregular surface^[82]. In

addition to CLE, also EC has been used for the microscopic evaluation of IBD. However, although EC was able to reliably distinguish between single inflammatory cells, it is not clear, whether it can be used for the initial diagnosis and differentiation of IBD subtypes^[83]. In conclusion, microscopic endoscopic techniques still lack in clear evidence to be able to visualize distinct disease patterns such as granulomas in CD.

Assessment of disease activity

In contrast to the initial diagnosis of IBD, more data are available regarding the use of new endoscopic imaging techniques for monitoring disease activity in IBD patients. Based on a prospective randomized trial, chromoendoscopy showed a higher diagnostic performance to assess the extent and severity of the inflammatory activity in UC when compared to conventional colonoscopy^[84]. For NBI, Kudo *et al.*^[85] found that mucosal vascular patterns in UC presenting with obscure configuration showed significantly more inflammatory cell infiltrates, increased goblet cell depletion, and basal plasmacytosis. This group

Table 2 Assessment of disease activity with advanced endoscopic imaging in the context of clinical trials

Ref.	Technique	No. of patients	Findings
Kiesslich <i>et al</i> ^[84] , 2003	CE	165	Agreement with histology: 84.5% (72 of 84) <i>vs</i> 60% (49 of 81)
Kudo <i>et al</i> ^[85] , 2009	NBI	30	Obscure mucosal vascular pattern is associated with inflammatory cell infiltrates (26% <i>vs</i> 0%), goblet cell depletion (32% <i>vs</i> 5%), and basal plasmacytosis (2% <i>vs</i> 21%)
Danese <i>et al</i> ^[87] , 2010	NBI	14	Positive appearance on NBI correlated with increase in angiogenesis or vessel density
Neumann <i>et al</i> ^[88] , 2013	Virtual CE (i-Scan)	78	Inflammatory extent and activity accordance with the histological results: 48.71% and 53.85% (white-light) and 92.31% and 89.74% (i-Scan)
Watanabe <i>et al</i> ^[89] , 2008	CLE	17	Distinct alterations in active and non-active UC patients compared to histology
Li <i>et al</i> ^[90] , 2010	CLE	73	Crypt architecture and fluorescein leakage with CLE correlate with histological results
Neumann <i>et al</i> ^[92] , 2012	CLE	54	CDEAS consisting of six parameters: crypt number, crypt distortion, micro erosions, cellular infiltrate, vascularity, and number of goblet cells Strong correlation of CDEAS and CRP

CE: Chromoendoscopy; NBI: Narrow-band imaging; CLE: Confocal laser endomicroscopy.

also described the key features of different stages of activity in UC imaged with NBI^[86]. In a small pilot study the concept of angiogenesis in IBD was also assessed to demonstrate that positive appearance on NBI showed increase in angiogenesis or vessel density^[87]. By using the principle of digital post-processing in real-time (virtual chromoendoscopy, i-Scan), inflammatory extent and activity compared with histology showed an overall agreement of 48.71% and 53.85% (white-light) and 92.31% and 89.74% (i-Scan)^[88]. Also endomicroscopic techniques have been tested to grade activity in IBD. For instance, CLE is able to provide information equivalent to conventional histology, showing distinct alterations in active and non-active UC patients compared to normal controls^[89]. Li *et al*^[90] demonstrated that a classification based on crypt architecture and fluorescein leakage with CLE showed good correlations with histological results in UC. The strong ability of visualizing abnormalities on a cellular level, underling the possibility to assess mucosal healing, was demonstrated by showing distinct vascular and tissue alterations in even endoscopically (magnified) normal appearing colonic mucosa in patients with UC in the state of remission^[91].

For CD, a CD Endomicroscopic Activity Score (CDEAS) was proposed, which is consisting of six parameters: crypt number (increased or decreased), crypt distortion, micro erosions, cellular infiltrate, vascularity, and number of goblet cells (increased or decreased)^[92]. Interestingly, the authors found a strong correlation of CDEAS and CRP to underline the potential as a disease activity predictor in CD^[92]. EC is also capable to visualize different histopathological features. In a pilot trial Neumann *et al*^[92] found a concordance with histopathology for grading intestinal disease activity reaching to 100%^[83]. In order to visualize histology in real-time without the use of dyes a comparable approach might be achieved with MPM^[41]. The implementation into an endoscopic device shall be a helpful to create images of tissue in subcellular resolution^[42,93,94]. An overview of selected studies is given in Table 2.

Prediction of therapeutic response

In addition to monitoring disease activity, CLE techniques have also been used to predict the response to biological therapy in IBD. In a recent pilot study performed by Atreya *et al*^[95], molecular-targeted confocal endomicroscopy prior to the initiation of anti-tumor necrosis factor (TNF) alpha therapy was used to evaluate the subsequent therapeutic response in 25 CD patients. The authors used a topical fluorescent anti-TNF-antibody to visualize membrane-bound TNF^[95]. It was shown that patients with high numbers of membrane-bound TNF on inflammatory cells show higher short-term response rates, higher rates of mucosal healing and lower inflammatory scores during anti-TNF-therapy even after one year. This molecular targeted approach demonstrates an ideal example how personalized medicine, including innovative imaging strategies and targeted therapies, could be applied to IBD^[6].

Surveillance, detection of precursor lesions and colon cancer

One main focus of the majority of new techniques is set to surveillance and detection of dysplasia in IBD. It is very well established that HD endoscopy is superior to SD endoscopy in detecting dysplastic lesions and cancer. In fact, a 3-fold higher detection rate with HD endoscopy was observed when compared to SD endoscopy in IBD^[96].

Displaying an ever bigger field of view in high-resolution wide-view full-spectrum endoscopy could perform at an adenoma miss rate significantly lower compared to standard forward-viewing endoscopy: 5/67 (7%) *vs* 20/49 (41%) ($P < 0.0001$)^[97]. By almost doubling the displayed window and reducing blind corners, this approach might also help to improve visualization of inflammation mucosa and suspects lesions in IBD. However, this approach is also not yet implemented for IBD and the greatest benefit is by now still attributed to chromoendoscopy in the setting of surveillance. In fact, chromoendoscopy allows the discrimination of hyperplastic/non-adenomatous

polyps from adenomatous polyps at a sensitivity and specificity of 93% and 95% respectively^[98]. A meta-analysis from six trials could show that dye-based chromoendoscopy has medium to high sensitivity and high diagnostic accuracy for detection of dysplastic lesions in UC^[99]. This has led to the recommendation that this procedure together with targeted biopsies is preferred as a surveillance procedure in IBD patients in US and European guidelines^[100-103].

In contrast, virtual chromoendoscopy (such as NBI) could not show any advantage to standard white-light endoscopy in terms of improved adenoma detection rate, *e.g.*, authors concluded that this technique likely will not contribute to a reduction in adenoma miss rates^[25]. On the other hand, NBI may improve pathology diagnosis for diminutive colorectal polyps were 92.8% (95%CI: 90.4%-94.8%) and patients could be already informed of the results at discharge^[26]. Comparing this to dye-based techniques, NBI was found to have a lower dysplasia detection rate^[15]. This is the reason why dye-based approaches still remain recommend by international guidelines^[100-103]. Suspect polyps presented with different characteristics in autofluorescence endoscopy: they showed fluorescence intensity maxima at approximately 460 nm, while normal colon was found to have larger fluorescence intensity compared to adenoma by a factor varying between 2-9 \times ^[29,30]. As demonstrated in patients with Barrett's esophagus, CLE is highly capable in detecting intraepithelial neoplasia^[104] 21741642. This approach combined with chromoendoscopy leads to an increase of 4.75-fold in detecting neoplasias while 50% fewer biopsy specimens ($P = 0.008$) were required in the colon^[105]. As stated for wide-view full-spectrum endoscopy these techniques are not (yet) translated into clinical routine use; especially for patients with IBD.

CLINICAL EVIDENCE AND TRANSLATION OF ULTRASOUND TECHNIQUES

Assessment of disease activity

In contrast to endoscopic imaging techniques, other imaging techniques including CT, MRI, scintigraphy and US are mainly used to evaluate the extend of disease and disease activity in IBD patients. All imaging strategies are based on the identification of distinct morphological characteristics. These include the assessment of mucosal alterations, transmural involvement and extra intestinal manifestations.

So far, no single imaging technique is considered as diagnostic gold standard^[51]. Even if MRI seems to perform at a better sensitivity, US is a useful, non-invasive radiation free imaging technique for the initial diagnostic if IBD is suspected^[106,107]. If ultrasound is compared to X-ray or endoscopic results by disease localization it shows higher diagnostic performance for inflammatory conditions of the ileum and sigmoid/

descending colon than in the rectum, duodenum and proximal jejunum^[108]. There are no data published, but it has been estimated that approximately 6 mo and 100 examinations are needed to gain proficiency in performing bowel US^[106,109]. A meta-analysis on different modalities for the diagnosis of IBD on a per-patient basis showed high sensitivity and specificity for US, MRI, scintigraphy, and CT as well^[110]. In fact, the authors could not show significant differences in diagnostic accuracy among the imaging techniques and concluded that a diagnostic modality without ionizing radiation should be preferred if possible. By measuring the wall thickness and longitudinal extent of pathologically altered bowel segments it was found that US is not strictly associated with clinical activity^[111]. In contrast, Limberg demonstrated that assessment with color Doppler/Duplex ultrasonography is helpful and offers a noninvasive and indirect mean of assessing disease activity in intestinal inflammation^[112]. Active CD lesions were found to have increased blood flow on preoperative color Doppler US correlating with greater vascularity and numbers of inflammatory leukocytes upon histology^[113]. The authors concluded that Doppler US is capable of characterizing the inflammatory activity of CD small-intestinal lesions. The same was shown in children, where mucosal or transmural hypervascularity was not specific and color Doppler sonography could be correlated with different etiological inflammatory bowel processes^[114]. Taken away the advantage of being a transabdominal and non-invasive technique, but being closer to the mucosa, ultrasound can also be used to image from inside the body. In this way, endosonography was able to differentiate UC from CD by a sensitivity of 92.3% showing a good correlation with histological inflammation scores (UC: $r = 0.43$; CD: $r = 0.69$)^[55].

Romanini *et al.*^[115] used a quantitative approach after ultrasound contrast application in order to visualize vascular changes and to correlate disease activity with histologic vascular density. The group described cut-off values to distinguish between active and inactive disease, such as peak enhancement ($> 40.5\%$) or regional blood flow (> 54.8 mL/min)^[115]. Further, perfusion analysis one month after starting treatment can provide prognostic information regarding treatment efficiency in CD^[116]. The major advantage of CEUS is that the use of this technique is already approved so it can already be used.

Furthermore, CEUS can be used for molecular targeted imaging, possibly allowing additional information regarding disease activity. Up to now, molecular approaches are limited to pre-clinical settings. Deshpande *et al.*^[117] could show that targeted contrast-enhanced US imaging enables noninvasive *in vivo* quantification and can be used for monitoring P-selectin expression in mice with induced chemical colitis. As selectins are glycoproteins expressed during the first phase of leukocyte adherence, it seems a favorable marker for detection of early inflammatory

processes^[118]. Consequently, it has been shown that this approach might be a promising modality for assessing and monitoring active inflammation in IBD^[119], both in early and chronic IBD models. The introduction of antibodies targeting $\alpha_4\beta_7$ -integrin leukocyte trafficking has now also become a new major target in IBD therapy^[120]. That is why this approach seems to be an ideal tool to assess endothelial expression of emerging molecular targets aiming leukocyte trafficking in IBD therapy.

Assessment of tissue fibrosis

As ongoing inflammation drives intestinal fibrosis^[121], ultrasonic electrography might have a valuable role in this scenario. As demonstrated in a rat model elastography, is feasible able to distinguish acutely inflamed from fibrotic intestine^[78,122]. This has been translated to human *ex vivo* tissue^[123] and clinical observations^[124,125], which found that increased shear wave velocity corresponds to increase in tissue fibrosis and stricturing disease. In a pilot study in children, this modality combined with hydrosonography appears to be able to predict the presence of complications or increased disease activity^[126].

CONCLUSION

In the recent decade the utilization of light and sound waves has greatly expanded in imaging modalities for the evaluation of IBD. Many of them are still waiting to gain entrance into clinical studies and applications. If the focus has been initially set to detection of dysplastic lesions, now new modalities are coming up to also assess initial presentation of the disease or its activity in follow-up. Interestingly, more and more morphological approaches are silently replaced by functional or molecular imaging modalities, which resemble more closely the pathophysiology and therapeutic interventions in IBD.

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