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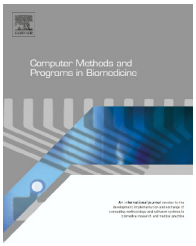

Use of shape-from-shading to estimate three-dimensional architecture in the small intestinal lumen of celiac and control patients

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ABSTRACT

Background: As measured from videocapsule endoscopy images, the small intestinal mucosa of untreated celiac patients has significantly greater and more varied texture compared to normal patients. Three-dimensional modeling using shape-from-shading principles may further increase classification accuracy.

Methods: A sequence of 200 consecutive videocapsule images acquired at a $2\,s^{-1}$ frame rate and 576×576 pixel dimension, were obtained at four locations in the small intestinal lumen of ten patients with biopsy-proven celiac disease and ten control patients. Each two-dimensional image was converted to a three-dimensional architectural approximation by considering the 256 grayscale level to be linearly representative of image depth. From the resulting three-dimensional architecture, distinct luminal protrusions, representative of the macro-architecture, were automatically identified by computer algorithm. The range and number of protrusions per image, and their width and height, were determined for celiacs versus controls and tabulated as mean ± SD.

Results: The mean number of villous protrusions per image was 402.2 ± 15.0 in celiacs versus 420.8 ± 24.0 in controls ($p < 0.001$). The average protrusion width was 14.7 pixels in celiacs versus 13.9 pixels in controls ($p = 0.01$). The mean protrusion height was 3.10 ± 2.34 grayscale levels for celiacs versus 2.70 ± 0.43 grayscale levels for controls ($p < 0.001$). Thus celiac patients had significantly fewer protrusions on the luminal surface of the small intestine as compared with controls, and these protrusions had greater dimensions, suggesting they are indicative of a mosaic (cobblestone) macro-architectural pattern which is common in celiacs.

Conclusions: Shape-from-shading modeling is useful to explore luminal macro-architecture and to detect significant differences in luminal morphology in celiac versus normal patients, which can increase the usefulness of videocapsule studies.

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1. Background

The mucosal surface of the small intestine is characterized by folds and villi which are approximately 0.5 mm long and 0.1 mm in diameter in healthy human patients [1]. In health, epithelial cells lining the villi transport nutrients from the intestinal lumen to the bloodstream [2]. In celiac disease, as a result of an immune reaction to dietary gluten, the mucosa becomes inflamed and villi become shortened (villous atrophy), and malabsorption of nutrients occurs [3]. At the microscopic level, villous projections become small or nonexistent [3,4]. Endoscopically, the mucosal appearance has visible fissuring that frequently displays a mosaic or cobblestone appearance. The mucosal folds when viewed side-on may appear scalloped. These structural changes are likely to be reflected quantitatively as alterations in the three-dimensional mucosal architecture.

While endoscopic visualization of the small intestinal mucosal surface using video endoscopic techniques is the standard method of assessing the mucosal surface and allows biopsy for the diagnosis of celiac disease, other methods are also available. These include contrast-enhanced magnetic resonance (MR) imaging as a way to show the mucosal changes in celiac disease [5]. Another novel diagnostic technique is endocytoscopy, which enables real-time visualization of the intestinal mucosa at 450× magnification, so that intestinal villi dimensions can be determined [6]. Moreover, irregular and abnormal peristalsis is present in most untreated celiac patients and can be evaluated by means of ultrasound using a combination of signs [7]. Computed tomography can also be implemented to discriminate celiac disease from other maladies, but has thus far been limited to visual analyses [8]. Any imaging method to detect pathology throughout the small intestinal lumen in celiac patients should be able to assess not only the typical endoscopic markers including a reduction or absence of duodenal folds, scalloping of the duodenal folds, mosaic or cobblestone appearance of the mucosal surface, and mucosal fissures, crevices or grooves, but also to directly assess whether villous atrophy is present [9].

Videocapsule endoscopy can be used to acquire high-resolution images from the entire small intestinal mucosa [4,10,11]. In previous work, it was shown that differences in mucosal architecture related to villous atrophy can be detected by measuring videocapsule image texture [4,10,11]. Texture can be defined as the variation in image brightness at scales smaller than the region of interest, and can be measured as the standard deviation from the mean [12]. Using this measurement for comparison of celiac versus control videoclips, texture was found to be significantly greater in celiacs [4,10,11]. It was hypothesized that the increased texture was correlated to abnormal macroscopic image features, which are in turn related to villous atrophy at the microscopic level. However, this textural measurement is not indicative of the three-dimensional profile of mucosal architecture. If there were a way to encode for three-dimensional structure, it could be useful to detect additional features of abnormal mucosa. The shape-from-shading transformation from two to three dimensions can provide information regarding object depth, and it is useful for correction of tissue area estimates [13]. In the current study, we sought to construct a three-dimensional rendering of two-dimensional videocapsule images using shape-from-shading principles. This was done, as a first approximation, by linearly converting grayscale level to image depth. In so doing, abnormalities in celiac small intestinal mucosa could be measured as alterations in three-dimensional architecture. The objective of the study was to characterize the three-dimensional architecture of the small intestinal surface using a particular syntax, which as we shall show, is useful for distinguishing celiac from control videoclips.

1.1. *Acquisition and preprocessing of clinical data*

For quantitative analysis, videocapsule endoscopic images were obtained from patients who had provided informed consent prior to endoscopy. Indications for this procedure include suspected celiac disease, suspected Crohn's disease, obscure bleeding, iron-deficient anemia, and chronic diarrhea. Patients under 18 years of age, pregnant women, and those with a history of intestinal obstruction, presence of a pacemaker, or chronic use of non-steroidal anti-inflammatory drugs (NSAIDs) were excluded. Only complete videocapsule endoscopy studies, reaching the colon, were used for analysis. Retrospective analysis of videocapsule endoscopy data was approved by the Internal Review Board at Columbia University Medical Center.

The PillCamSB2 videocapsule (Given Imaging, Yoqneam, Israel) was used to obtain small bowel images. The system consists of a recorder unit, real-time viewer, battery pack, antenna lead set, recorder unit cradle and harness, battery charger, and real-time viewer cable. The capsule is 26 mm × 11 mm in size. A light source illuminates the luminal wall in line with the camera direction. All subjects swallowed the PillCam SB2 videocapsule with radio transmitter after a 12 h fast and wore a small portable recording device. The recorder received radioed images via a sensor array that was transmitted by the videocapsule as it passed through the GI tract. The procedure began in early morning by swallowing the capsule with approximately 200 ml of water, and investigation was terminated either upon arrival of the capsule in the cecum, or after 8 h. Subjects were allowed to drink water 2 h after ingesting the capsule, and to eat a light meal after 4 h. Videos were reviewed and interpreted by an experienced gastroenterologist using a HIPAA-compliant PC-based workstation equipped with Given Imaging analysis software that was also used to export videos for further analysis.

Retrospective data were obtained from 10 celiac patients on a regular diet or within 3 months of starting a gluten-free diet. In these patients the diagnostic biopsy revealed Marsh grade II–IIIC lesions [14]. All patients were evaluated at Columbia University Medical Center, New York, from May 1, 2008 to July 31, 2009. The celiac cohort consisted of 5 female and 5 male patients (mean ages 50.5 and 44.0 years, respectively), and a control group 6 female and 4 male patients (mean ages 50.0 and 51.5 years, respectively). The videocapsule frame rate was set to acquire two digital images per second with the image dimension being 576 × 576 pixels.