Surface Visualization at 3D Endoluminal CT Colonography: Degree of Coverage and Implications for Polyp Detection

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Background & Aims: **Effective colonoscopic screening for polyps, whether by optical or virtual means, requires adequate visualization of the entire colonic surface. The purpose of this study was to assess prospectively the degree of surface coverage at 3-dimensional (3D) endoluminal computed tomography colonography (CTC) after retrograde fly-through, combined retrograde–antegrade fly-through, and review of remaining missed regions.** ***Methods:*** **The study group consisted of 223 asymptomatic adults (mean age, 57.8 ± 7.2 y; 111 men, 112 women) undergoing primary CTC screening. CTC studies were interpreted by experienced readers using a primary 3D approach. The CTC software system that was used continually tracks the percentage of endoluminal surface visualized. The degree of coverage was assessed prospectively after retrograde and combined retrograde–antegrade navigation. The added effect of reviewing missed regions was also assessed prospectively.** ***Results:*** **The mean surface coverage after only retrograde 3D endoluminal fly-through from rectum to cecum was 76.6% ± 4.8% (range, 63%–92%); coverage was 80% or less in 181 (81.2%) patients. Antegrade navigation back to the rectum increased the overall coverage to 94.1% ± 2.3% (range, 84%–99%; $P < .0001$). A review of missed regions 300 mm^2 or larger increased coverage to 97.9% ± 1.1% (range, 93%–99%; $P < .0001$) and added 21.4 ± 11.4 seconds to the interpretation time (range, 3–67 s).** ***Conclusions:*** **Combined bidirectional retrograde and antegrade 3D navigation, supplemented by rapid review of missed regions, effectively covers the entire evaluable surface at CTC. Unidirectional retrograde 3D fly-through typically excludes 20% or more of the endoluminal surface, which may provide insight into potential limitations at optical colonoscopy.**

Effective screening for colorectal polyps with structural examinations such as optical colonoscopy (OC) and computed tomography colonography (CTC) requires adequate visualization of the entire endoluminal surface. CTC, also known as *virtual colonoscopy*, represents a diagnostic technique that is not limited by the physical constraints of conventional endoscopy.[1] As such, 3-dimensional (3D) endoluminal evaluation at CTC is possible in any direction, including both retrograde (rectum to cecum) and antegrade (cecum to rectum) directions. With OC, unrestricted bidirectional evaluation is not possible, even with dedicated withdrawal techniques. The CTC software system we use documents endoluminal surface visualization as a percentage of the total surface during real-time visualization. If the entire endoluminal surface is evaluated adequately by 3D CTC, polyp detection may be improved over primary 2-dimensional (2D) evaluation.[2] Our study sought to assess prospectively the degree of surface coverage during routine CTC interpretation. Because retrograde CTC fly-through roughly simulates the available view at conventional endoscopy, surface coverage at this point may serve as a rough estimate of readily visualized mucosa at standard OC examination.

Materials and Methods

The study group was derived from 240 consecutive asymptomatic average-risk adults undergoing primary CTC screening at our institution over a 2-month period from April to June 2005. Studies from 17 patients were excluded owing to either inclusion of portions of small bowel or exclusion of colon with the automated segmentation model performed by the CTC system, which would have resulted in aberrant estimates for the total colonic endoluminal surface in those cases. The final study group therefore was composed of 223 patients (mean age, 57.8 ± 7.2 years; 111 men, 112 women). Our CTC screening program operates under an institutional review board–approved protocol that allows for prospective and retrospective data analysis. The specific methods used for colonic preparation, colonic distention, CT scanning, and CTC interpretation are outlined below.

Colonic preparation consisted of a combination of oral sodium phosphate (45 mL), dilute 2% barium (250 mL), and

Abbreviations used in this paper: CTC, computed tomography colonography; OC, optical colonoscopy; 3D, 3-dimensional; 2D, 2-dimensional.

0016-5085/06/$32.00
doi:10.1053/j.gastro.2006.01.044

water-soluble iodinated contrast material (diatrizoate, 60 mL) taken in succession as single doses the evening before the colonic examination, in conjunction with a clear liquid diet.[3] Dilute barium and water-soluble oral contrast are administered for the purposes of tagging any residual colonic stool and fluid, respectively.[4] This preparation protocol has been refined and simplified from our initial approach[1] and generally results in scant or minimal tagged residua. Colonic distention is obtained with automated continuous carbon dioxide delivery, which we have found provides more reliable distention and less postprocedural discomfort compared with insufflation of room air.[5]

Breath-hold supine and prone CT acquisitions were obtained on 8- and 16-channel multidetector scanners (GE LightSpeed Series; General Electric Medical Systems, Milwaukee, WI). The CT technique entails 1.25-mm collimation, 1-mm reconstruction interval, and low-dose technique (120 kVp and 50–75 mAs). An individualized increased technique often is needed for morbidly obese patients. The CT datasets then are networked to a CTC software system (V3D Colon; Viatronix, Stony Brook, NY) and immediately interpreted by an experienced abdominal imager (P.J.P., A.J.T.). Final results are communicated to patients within 2 hours, until which time they remain in a fasting state to allow for same-day polypectomy at OC, if needed. This approach avoids the need for repeat colonic preparation if a large polyp is found at CTC.[6]

The CTC software system extracts the gas-filled colon by an automated segmentation step, which generates a 3D model that includes a centerline path for automated navigation. Our routine primary 3D CTC interpretation consists of complete antegrade and retrograde 3D endoluminal fly-through for initial polyp detection, performed on both supine and prone colon models.[7] Navigation along the centerline is interspersed with manual mouse-driven detours as needed for suspicious findings. The opacified residual luminal fluid can be subtracted digitally but we no longer find this step to be advantageous for the following reasons: (1) this process can introduce artifacts, (2) the complementary supine and prone views are both evaluated in all patients, and (3) the high fidelity of our current preparation results in only minimal residual fluid.[3]

The main objective for CTC screening at our program is the detection of colorectal polyps that are of potential clinical significance. Lesions of potential significance are defined as polyps measuring more than 5 mm in size. Diminutive lesions are not reported, which greatly increases our time efficiency and accuracy for interpretation.[1] With our interpretive approach, most polyps initially are detected on the 3D view during endoluminal fly-through navigation. Focused review of the 2D multiplanar reformatted images is performed for confirmation of all suspected polyps detected on the 3D display, but the 2D display also is used for secondary polyp detection. We believe that this biphasic CTC interpretation optimizes the complementary nature of the 2D and 3D displays. Recent software improvements, including a doubling of the maximum 3D flight speed, allow for typical combined 2D–3D interpretation times of 10–15 minutes or less.[7]

The CTC software system automatically tracks and continually updates the surface voxels that are visualized during real-time 3D fly-through examination, which is reported as a percentage of the total endoluminal surface.[8] The seen and unseen colonic surfaces can be depicted easily on the diagnostic view station by painting with a distinct color on the 3D endoluminal view (Figure 1). This also can be depicted on the colonic map that is generated for purposes of localization and quality assurance (Figure 1). Volume-rendered surfaces greater than 6 cm from the viewer's vantage point are not yet considered to be visualized to avoid an overestimation of adequate diagnostic evaluation. In addition, the field of view is restricted to 90° in both the vertical and horizontal planes (127° from corner to corner) to allow more focused evaluation and to decrease distortion. After bidirectional (ie, retrograde and antegrade) 3D endoluminal fly-through is completed, the reader has the option to review the remaining patches of nonvisualized colonic surfaces in descending order of cross-sectional area.[8] We will refer to this function as the *missed region tool*. Missed regions measuring more than 1000 mm^2 in surface area are considered large and regions measuring 300–1000 mm^2 are considered small for the purposes of this study. From a practical standpoint, we generally do not perform a review of missed patches measuring less than 300 mm^2 in surface area (Figure 1).

The degree of surface coverage was recorded during prospective CTC evaluation using our standard primary 3D interpretive approach to reflect actual clinical practice. Because of the logistical time constraints involved with prospective real-time interpretation of CTC studies at our center, which require rapid supine–prone evaluation in case polypectomy is necessary, surface coverage data were recorded for only the initial 3D dataset evaluated (per routine, the other dataset was interpreted in all patients but the coverage numbers were not recorded). In our experience, similar results would be expected for the remaining dataset. The percentage of surface visualization was tracked for 3 main end points: (1) after unidirectional retrograde 3D fly-through from rectum to cecum, (2) after combined retrograde–antegrade fly-through, and (3) after the additional review of missed regions measuring 300 mm^2 or more in surface area. Results primarily are reported as a mean percentage ± 1 SD. Statistical testing for significance between the 3 groups was performed using the Student *t* test. The number of large (>1000 mm^2) and small (300–1000 mm^2) missed regions was recorded, as was the total additional time required to review it.

Results

For the 223 patients in the study group, the supine dataset was used for initial diagnostic interpretation and surface coverage evaluation in 164 patients and the prone dataset served as the initial 3D display mode for the remaining 59 patients. Surface coverage for the alternate display mode (prone or supine) generally was similar to the initial display mode in each patient but

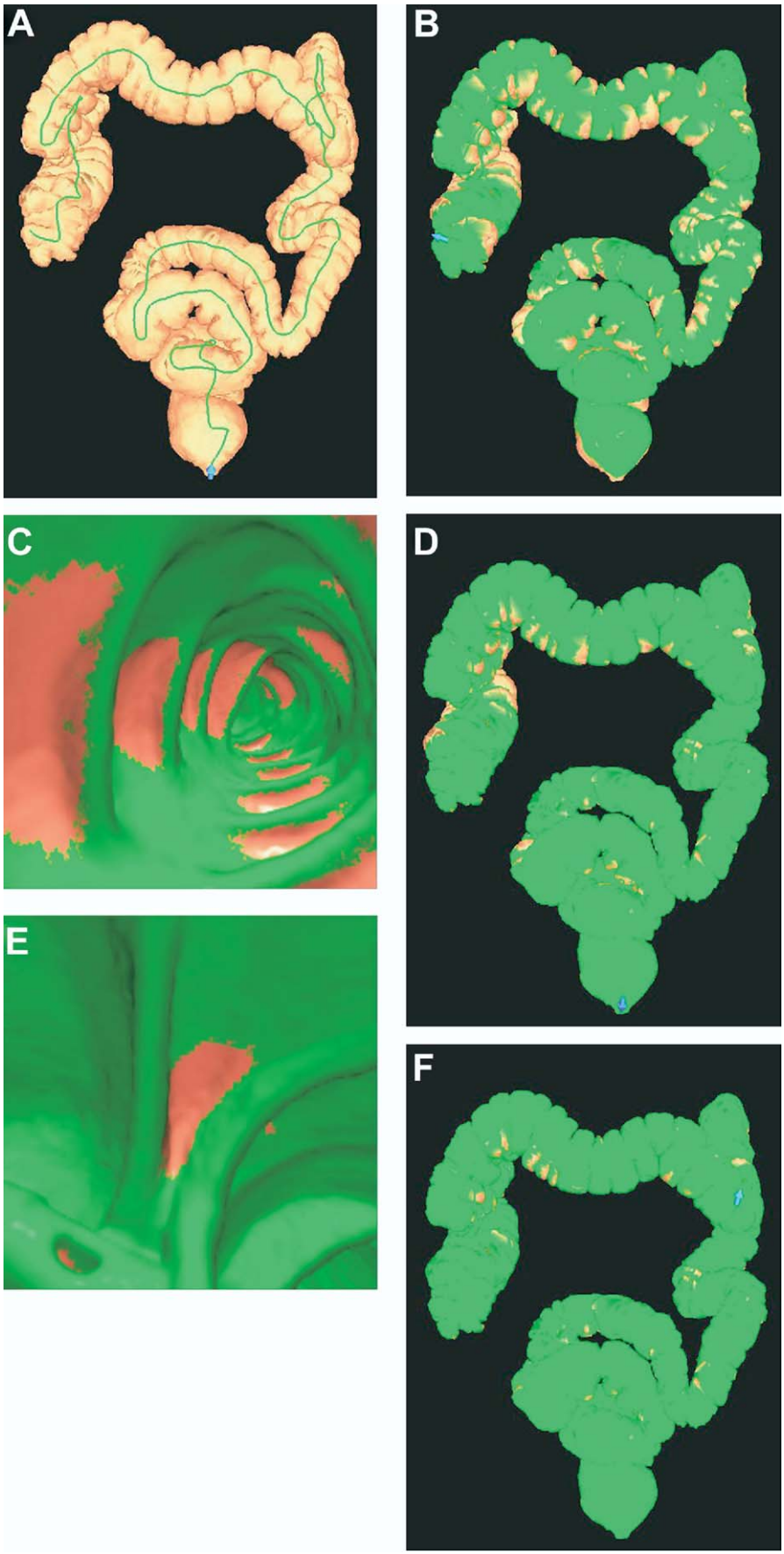

Figure 1. Screening CTC in an asymptomatic average-risk 50-year-old man. (*A*) Supine 3D colon map extracted from the CT dataset by an automated segmentation step performed by the CTC software system before review. This map is useful for assessing the quality of colonic distention, depicting real-time position during endoluminal navigation, and for showing the location of positive findings. The green line represents the automated centerline for endoluminal fly-through. (*B*) 3D colon map after retrograde navigation from rectum to cecum depicts the regions of visualized endoluminal surface (painted green). The degree of coverage at this point of the examination was 71% of the total endoluminal surface. (*C*) The 3D endoluminal view facing in the antegrade direction (toward the rectum) shows the regions of mucosal surface not visualized after unidirectional fly-through in the opposite direction. These areas behind colonic folds represent relative blind spots at OC and are the reason for performing bidirectional evaluation at CTC. (*D*) The 3D colon map after combined retrograde–antegrade navigation shows the interval increase in the degree of endoluminal coverage (now at 93% in this case). (*E*) The 3D endoluminal view obtained during use of the missed region tool shows a typical surface patch not seen after routine bidirectional navigation. Most missed patches are located between folds, particularly at the inner turn of flexures. Note that the inner aspect of the adjacent diverticulum also evaded visualization at routine evaluation. (*F*) The 3D colon map shows the effect of rapid review of all missed patches 300 mm^2 or larger in surface area that were not seen after the initial bidirectional fly-through, which increased the overall surface coverage to 98%. The use of the missed region tool added 20 seconds to the interpretation of this case.

was not recorded to expedite the prospective clinical reading.

The mean surface coverage after unidirectional retrograde 3D endoluminal fly-through from rectum to cecum in these 223 patients was 76.6% ± 4.8%, ranging from a low of 63% to a high of 92% (Figure 1). The degree of coverage was 80% or less in 181 (81.2%) of 223 and was less than 90% in all but 1 patient (99.6%). Antegrade fly-through back to the rectum increased overall coverage to 94.1% ± 2.3%, with a range of 84%–99% (Figure 1). The difference in coverage between retrograde only and combined retrograde–antegrade navigation was highly significant ($P < .0001$). The degree of surface coverage from combined retrograde–antegrade fly-through was 90% or greater in 215 (96.4%) of 223 patients.

A review of all missed regions measuring 300 m^2 or more increased the overall colorectal surface coverage to 97.9% ± 1.1%, with a range of 93%–99%. The differences in coverage between this final step and the 2 previous steps were highly significant ($P < .0001$). The surface coverage was 98% or greater in 164 (73.5%) of 223 patients. The additional interpretation time to review these missed regions averaged 21.4 ± 11.4 seconds (range, 3–67 s). The added time was 20 seconds or less in 135 (60.5%) of 223 patients and was less than 1 minute in all but 4 patients (98.2%). The mean number of large missed regions (>1000 mm^2) after combined retrograde–antegrade fly-through was 3.6 ± 2.8, ranging in number from 0 to 18 (Figure 1). The number of large missed regions was less than 10 in all but 8 patients (96.4%). The mean number of small missed regions (300–1000 mm^2) was 15.5 ± 8.5, with a range of 1–65 regions. The number of small missed regions was less than 30 in all but 12 patients (94.6%). No additional polyps measuring 6 mm or more were identified with the missed region tool that were not seen with routine 3D or 2D CTC evaluation in this patient series. On occasion, a polyp seen during centerline fly-through on one 3D view (supine or prone) will be seen only with the missed patch tool on the other 3D view (Figure 2).

Polyps that measured 6 mm or greater were detected prospectively in 26 (11.7%) of the 223 patients in this series, which is similar to the overall CTC test-positive rate from the initial 2000 adults evaluated by our screening program. The largest CTC-detected lesion was medium sized (6–9 mm) in 15 patients and was large (≥10 mm) in 11 patients. The lesions were confirmed and removed at same-day OC in 17 (94.4%) of 18 patients evaluated; in 1 patient a 6-mm polyp detected at CTC was not found at OC. Eight of the 26 patients opted for short-term CTC surveillance of medium-sized lesions in lieu of OC according to our institutional review board–approved protocol.

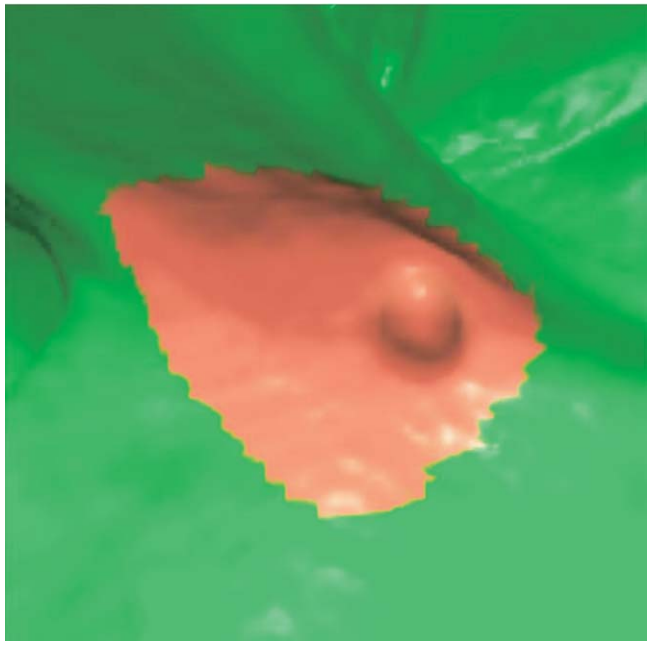

Figure 2. Screening CTC in an asymptomatic average-risk 55-year-old woman. The 3D endoluminal view from the prone dataset during use of the missed region tool shows a 6-mm polyp on the inner aspect of a flexure that was not seen during routine bidirectional navigation along the centerline. However, this lesion was seen during routine 3D centerline fly-through of the supine dataset. Several additional polyps measuring up to 10 mm also were identified (not shown).

Discussion

Our results show that colonic visualization with routine 3D endoluminal CTC typically covers about 98% of the total evaluable surface with our standard interpretive approach. Retrograde-only 3D fly-through from rectum to cecum, which roughly simulates conventional OC evaluation, typically excludes 20% or more of the endoluminal surface. After combined retrograde and antegrade navigation, rapid review of missed patches that potentially could harbor a significant polyp adds little to the overall interpretation time, yet increases diagnostic confidence. When the entire colonic surface is visualized adequately at 3D endoluminal CTC, Beaulieu et al[2] showed previously that polyp detection can be improved over primary 2D evaluation. We believe that primary 3D polyp detection, supplemented by obligatory 2D evaluation, is critical for CTC screening of average-risk adults.[1] Because our interpretive approach includes complete 3D evaluation of both supine and prone datasets, the degree of overlap between the 2 views is substantial. When combined with 2D evaluation, the overall redundancy that is built into this interpretive approach ensures that most polyps of significant size will be detected.[1]

A practical benefit of tracking which surfaces have been evaluated adequately at 3D CTC is that if a reader is interrupted during interpretation, it is easy to resume where the investigation left off. With CTC systems that do not track coverage, time-consuming re-evaluation of visualized areas may be necessary. In our clinical practice, the missed region tool rarely has uncovered a significant polyp because most are detectable readily on the initial bidirectional 3D fly-through evaluation. However, reviewing the larger missed patches requires very little additional interpretation time and increases overall diagnostic confidence. In the authors' experience with more than 3000 screening CTC examinations, we can recall several polyps ranging in size from 6–10 mm that were not seen on standard bidirectional 3D fly-through along the centerline but were identified with the missed region tool. However, lesions of this size generally will be detectable on either secondary 2D review or by standard 3D evaluation of the alternate dataset, which again shows the redundancy of this CTC system for polyp detection.

The high degree of surface coverage possible with 3D endoluminal CTC raises the question of whether a single acquisition (ie, supine or prone) would be adequate for interpretation. However, because of the complementary nature of the supine and prone displays in terms of distention, gravitational fluid shifts, and other anatomic factors, we believe that the redundancy provided by the use of both views, and the ability to confirm all suspected lesions seen on 1 view, mandate the continued used of both positions.

Earlier studies investigating the OC miss rate for large polyps were somewhat limited because OC itself was used as its own reference standard.[9,10] Recent studies that have used segmental unblinding of CTC results as the enhanced reference standard have shown increased OC miss rates for large polyps ranging from 12% to 17%.[11,12] The majority of lesions initially missed at prospective OC (but found on second look) were located behind colonic folds.[11] These miss rates approach the percentage of colonic surface not seen on retrograde-only 3D CTC, which could be considered a rough surrogate for standard OC evaluation. An estimated 4% of right-sided invasive cancers may be missed at OC,[13] which conceivably could relate to the more prominent haustral folds seen in the proximal colon or factors related to the increased distance the scope must traverse. Methods for improving visualization behind colonic folds at OC have been proposed.[14,15] Another factor worthy of consideration is withdrawal times at OC, which likely affect mucosal coverage and have been shown to influence polyp detection.[16]

In addition to 3D endoluminal volume rendering, which simulates the appearance at conventional endoscopy, several nonanatomic 3D volume visualization modes have been created for potential evaluation at CTC. One approach, referred to as *virtual dissection*, unfolds, fillets, and flattens the colon to simulate evaluation at gross pathology.[17] Although virtual dissection is an appealing concept for efficient interpretation, the versions that currently are available introduce significant artifacts that often distort even large polyps beyond recognition.[18] Another approach consists of an unfolded cube display that also attempts to increase simultaneous surface visualization.[19] Computer-aided detection for the purpose of polyp detection at CTC, although not directly related to 3D volume rendering, also relies on adequate coverage of the colonic surface.[20] Most other CTC software systems, which generally are not capable of efficient and effective primary 3D polyp detection, do not yet offer a tool for determining endoluminal surface visualization.[21] Given the usefulness of this tool for primary 3D evaluation, we anticipate that some form of it will become available on more systems in the future.

Since the completion of our validation trial for CTC screening,[1] several improvements in methodology have been realized that have both increased the study quality and decreased the interpretation time.[3,6,7] First, our colonic preparation has been simplified, with subjectively improved results at CTC. Second, our front-line method of colonic distention has switched from room air insufflation to automated carbon dioxide delivery, which results in both improved distention and decreased postprocedural discomfort.[5] Third, continued advances in the CTC software system have resulted in more efficient and effective evaluation. The combined effect of these improvements has led to CTC examinations that are of consistently higher quality, resulting in higher positive predictive values and significantly decreased interpretation times. The improvement in the positive predictive value of our current approach over that used in the multicenter screening trial[1] is reflected by the fact that CTC-detected polyps were confirmed at OC in 17 (94.4%) of 18 patients from the current series, which is similar to the overall experience of our screening program to date (unpublished data, submitted but not accepted).

The fact that 17 patients were excluded from the surface coverage analysis is a potential limitation. For the patients in whom portions of small bowel were not segmented properly from the colon, the degree of colonic surface coverage would have been underestimated erroneously because the included small-bowel luminal surface is included in the total calculated area. For patients

in whom portions of colon were excluded, the actual total surface is not accounted for by the coverage tool. Although the degree of coverage therefore is not reflected accurately, in reality these excluded segments still are evaluated by the radiologist using both 2D and 3D displays unless they are collapsed completely, which is rare in our experience. Therefore, although these 17 patients were excluded for technical reasons, their evaluation nonetheless was complete from a clinical standpoint in all cases.

In conclusion, bidirectional 3D CTC fly-through, supplemented by rapid review of missed regions, results in reliable coverage of the entire evaluable endoluminal surface. Unidirectional retrograde 3D fly-through typically misses 20% or more of the endoluminal surface, which may have implications for visualization at standard OC examination. Combined CTC evaluation of both supine and prone datasets provides significant redundancy for polyp detection. More widespread adoption of our clinically validated methods for CTC could hasten the acceptance of this promising screening tool.[22] The complementary nature of CTC and OC should ultimately result in overall improved detection of significant colorectal neoplasia.

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Received September 5, 2005. Accepted January 11, 2006.

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