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Improving the Accuracy of CT Colonography Interpretation: Computer-Aided Diagnosis

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Synopsis

Computer-aided polyp detection aims to improve the accuracy of the colonography interpretation. The computer searches the colonic wall to look for polyp-like protrusions and presents a list of suspicious areas to a physician for further analysis. Computer-aided polyp detection has developed rapidly over the past decade and in the laboratory setting and has sensitivities comparable to those of experts. Computer-aided polyp detection tends to help inexperienced readers more than experienced ones and may also lead to small reductions in specificity. In its currently proposed use as an adjunct to standard image interpretation, computer-aided polyp detection serves as a spellchecker rather than an efficiency enhancer.

Keywords

CT colonography; computer-aided detection; Observer performance; colonic polyps

Introduction

Computer-aided detection (CAD) for CT colonography (CTC) is a relatively new technology, having been introduced in the late 1990's. CAD has developed rapidly and early clinical trials of CAD are beginning to appear in the literature. This chapter presents a brief overview of the current clinical status of CT colonography CAD. The chapter concludes with a description of some advanced computerized display technologies that also assist CTC readings and may play an important role in improving the diagnostic efficacy of CTC.

Rationale for Computer-Aided Detection

It has been shown that perceptual error reduces the sensitivity of CT colonography by 14% for polyps 1 cm in size or larger¹. Given the multitude of images in a CTC study, the causes of perceptual error are not mysterious. Depending upon the reconstruction interval, there can be

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1,200 images or more to interpret. For example, images in the prone and supine positions must be interpreted. Some investigators examine the colon antegrade and retrograde and in lung and soft tissue windows. Three-dimensional virtual endoscopic views may also be needed for problem solving. Average interpretation times ranging from 15 – 25 minutes per study have been reported in the literature ^{2, 3}.

Interpretive errors can lead to substantial reductions in polyp detection sensitivity⁴. Polyps can be missed if they are located between or behind haustral folds, in areas of poor bowel preparation or inadequate distention or due to inconspicuousness due to flat shape. Factors affecting the ability to perceive abnormalities on large 2-D CT data sets and three-dimensional endoluminal fly-through images require further study⁵.

Effect of reader fatigue

There is as yet little or no information about the effect of reader fatigue on the diagnostic efficacy of CTC interpretation. Anecdotally, radiologists report an upper limit on the number of CTC cases they can interpret per day, typically less than 10. Because interpretation of the CTC data is complex and requires manipulation of different types of images and sustained concentration, it is likely that fatigue will be an issue. Also, without addressing the lengthy interpretive process, it is unlikely that costs for CT colonography can be substantially reduced. It is therefore likely that CAD implementations that reduce fatigue will be beneficial both for improving accuracy and reducing costs. While some benefits of CAD in improving radiologist performance have been proven, it has not yet been shown that these benefits accrue because of a reduction in fatigue. However, fatigue and perceptual errors are closely intertwined. More research will be needed in this area.

Performance of 1 reader vs. 2 readers (Single versus Double reading) without CAD

Double reading of medical images has been shown to increase sensitivity in certain settings, for example in interpretation of mammograms⁶. There has been relatively little work on double reading of CT colonography. In a study using three readers, Johnson et al. found that the per patient and per polyp sensitivities tended to be higher and the specificity lower with double reading than for some single readings⁷. However, there was considerable variability in the sensitivities of the three readers for polyp detection. In part, a hope is that CAD will provide a similar benefit to that of double reading but without the additional cost of the second human interpreter.

Principles of CAD

The purpose of computer-aided detection (CAD) is to locate possible polyps automatically and annotate the images or present a list of image locations. The radiologist reviews the output of the CAD and makes the final diagnosis.

The main function of the CAD software is to identify sites with features characteristic of polyps^{8–12}. Examples of useful features for CAD include surface shape and CT attenuation. Once these features are identified, the CAD software classifies sites of detection as potential polyps or false positive diagnoses. A suitable CAD system has high sensitivity for detection of clinically significant polyps (those over a size threshold, e.g. 0.5 or 1.0 cm) and a low number of false positive detections. All current CTC CAD systems produce on average at least one false positive detection per CTC examination. Hence, review of the CAD marks by a trained reader is still required to prevent unnecessary referrals for colonoscopic polypectomy.

Once potential polyps are detected by CAD, they must be shown to the radiologist who makes the final diagnosis. There are a number of ways to do this. One way is to label sites directly on CTC images to show the radiologist where the potential polyps may be found¹³. These labels can be turned on or off so that they do not obscure the original images. To save time, the radiologist can jump directly to the labeled images. Labels can be applied to both the 2-D cross-sectional and 3-D endoluminal images.

Common false positives

The most common CAD false positives are on the ileocecal valve, thick haustral folds, residual fecal matter and the rectal tube^{14–16}. It is possible to reduce the numbers of these false positives through various techniques. For example, the ileocecal valve can be identified because it tends to be large and contain fat leading to lower CT attenuation than that of polyps^{17, 18}. The rectal tube can be identified by its location in the rectum and by detecting its hollow channel^{19, 20}.

False positives due to residual fecal matter and thick haustral folds can be more difficult to eliminate. High-quality bowel preparation and adequate colonic distention can reduce these problems^{21–24}.

Reasons for false negatives

The most common reasons for CAD false negatives are flat polyps, inadequate colonic distention, residual fecal matter, adhering contrast medium, polyp at air-fluid boundary and small polyp size^{14, 15, 25}.

A flat polyp has a low elevation above the surface of the adjacent colonic mucosa. Flatter polyps are less conspicuous both to radiologists and CAD software^{26, 27}. Hyperplastic polyps tend to be flatter than adenomatous polyps making them less conspicuous and more difficult to diagnose^{28, 29}. The poorer sensitivity of CTC for detecting hyperplastic polyps may be beneficial by avoiding unnecessary colonoscopy and polypectomy for these lesions which have lower malignant potential³⁰.

Inadequate colonic distention can be prevented by careful technique and the use of carbon dioxide insufflators^{23, 24}. Quality assessment software can identify poor colonic distention in real time and allow correction before the patient leaves the examination room^{21, 22}.

Residual fecal matter and fluid can cover polyps and obscure them. Fecal and fluid tagging with barium- and iodine-based contrast materials enable visualization of such polyps².

The CT attenuation of polyps adjacent to endoluminal contrast material can be artificially increased. This phenomenon, known as pseudoenhancement, can prevent polyp detection since the inflated CT values may greatly exceed typical soft tissue attenuation values. Software corrections can greatly improve the sensitivity for detecting such polyps, particularly those submerged under contrast-enhanced fluid^{31–33}.

Contrast material can adhere to some polyps³⁴. CAD software must be able to identify such polyps. Software that identifies polyps with adherent contrast material is under development³⁵.

Polyps at the air-fluid boundary can be difficult to detect whether or not the fluid is tagged with contrast material. Software that improves electronic fluid subtraction at the air-fluid boundary may enable detection of such polyps^{36, 37}.

CAD performance tends to fall off for smaller polyps¹⁴. Polyps from 6 to 9 mm in size are of particular interest since patient management (surveillance versus immediate polypectomy)

may depend on whether polyp size is at the high or low end of this range³⁸. Even with the use of modern thin-section CT scanners, it is likely that CAD sensitivity for six and 7 mm polyps is substantially less than that of eight and 9 mm polyps although these size subcategories are usually not reported separately.

Current Status of CTC CAD

CT colonography computer-aided detection is in an advanced stage of development³⁹. Several small clinical trials have been published. A number of commercial and pre-commercial CAD systems have been developed and have undergone or are undergoing regulatory review. In “stand alone” CAD trials in the computer laboratory, as opposed to observer studies in which the performance of radiologists with CAD assistance is evaluated, the baseline sensitivities for detecting large (≥ 10 mm) polyps are as high as 85 – 100% with less than 10 false positives per patient^{10, 12, 14, 40–42}. These sensitivities reach or exceed those achieved by radiologists.

CAD has not yet been developed to handle the problem of extracolonic findings^{43–46}. The multiplicity of potential sites and types of extracolonic findings makes it particularly difficult to develop a CAD system to detect them all.

Stand alone CAD Trials – Baseline Performance of CAD in the Laboratory

In 2005, Summers et al. published the results of a large stand alone CAD trial¹⁴. The authors trained their CAD system on 394 patients’ CTC datasets and tested on 792 datasets, both sets taken from the Department of Defense screening CTC dataset reported earlier by Pickhardt et al.². The reference standard was segmentally-unblinded optical colonoscopy. For the test set, per-polyp and per-patient sensitivities for CAD were both 89.3% (25 of 28 polyps) for detecting retrospectively identifiable adenomatous polyps at least 1 cm in size. The false-positive rate was 2.1 per patient. The CAD system detected one cancer originally missed by the colonoscopists. At both 8-mm and 10-mm adenoma size thresholds, the per-patient sensitivities of CAD (85.4% and 89.3%, respectively) were not significantly different from those of optical colonoscopy before segmental unblinding.

Halligan et al. published an external validation of a CAD system for CTC⁴⁷. External validation refers to the assessment of CAD applied to data different from that on which the CAD software was trained. The results of the external validation provide information about the generalizability of the CAD to different patient populations. The per polyp sensitivity of their CAD system was 94% for detecting polyps 6 mm or larger, indicating good generalizability. The false positive rates ranged from 14 to 43 depending on the settings of a “sphericity filter”.

Summers et al. reported an external validation study of their CAD system¹⁵. Their CAD system had per polyp sensitivities of 91.5% for adenomas 10 mm or larger and 82.1% for adenomas 6 to 9 mm. The per patient sensitivities were 97.6% and 82.4%, respectively. The mean and median false positive rates were 9.6 and 7.0 per patient, respectively.

Van Ravesteijn et al. reported CAD sensitivities for polyps 6 mm or larger ranging from 85 to 100% with between four and six false positives per scan⁴⁸. They applied their CAD system to four different data sets. They also performed a cross-center external evaluation and found that the trained CAD system generalized to data from different medical centers and with different patient preparations.

Lee et al. reported the sensitivity of three different CAD systems for detecting simulated polyps in an anthropomorphic colonic phantom²⁵. For polyps 6 mm or larger, the differences in the per polyp sensitivities amongst the three CAD systems were not statistically significant. Sensitivities were lowest for flat polyps, intermediate for sessile polyps and greatest for

pedunculated polyps. The false positive rates ranged from 2.6 to 4.6 per scan and were not statistically different but the distribution of causes of false positives did differ amongst the three CAD systems.

Effect of CAD on observer performance; CAD as a First, Concurrent or Second Reader

The standalone performance of CAD software in the laboratory described in the previous section describes the theoretical best performance achievable. However, when used in the clinic, CAD software rarely achieves its full potential. To assess the likely clinical benefit of CAD, researchers conduct observer performance experiments in which radiologists use CAD to read unknown cases. The experiments are typically conducted in a simulated clinical setting and to date have not been prospective clinical trials.

Radiologists may use CAD in one of three ways: as a first, concurrent or second reader (Figure 1). It is not yet clear how well the three methods compare to one another and this may depend on the particular CAD implementation. Therefore, the observations in this section should be regarded as preliminary.

In the “first reader” paradigm, the radiologist only reviews the CAD results and does not review the entire colon. This method has the potential advantage of reduced interpretation time and high specificity (since the choice of false positives is limited to the CAD findings) but the potential disadvantage of lower sensitivity relative to the concurrent and second reader paradigms. At present, radiologists are naturally reluctant to use the first reader paradigm because only the computer reviews the entire CTC dataset.

In the “concurrent reader” paradigm, the CAD marks are visible during the radiologist’s primary interpretation of the images. The radiologist evaluates the CAD marks as they appear in the image. The potential advantages of this method are improved sensitivity and reduced interpretation time. These advantages may not actually be realized because the CAD marks could distract the radiologist from other findings in the vicinity of a mark, leading to “satisfaction of search” errors ⁴⁹. The radiologist could also mischaracterize CAD false positives, leading to decreased specificity as well.

In the “second reader” paradigm, the radiologist reviews the images, arrives at a preliminary diagnosis, reviews the CAD findings and revises the preliminary diagnosis to arrive at a final diagnosis. Since CAD is not perfect, the radiologist should not disregard polyp candidates he or she has identified that were not found by CAD. The potential advantage of this technique is sensitivity higher than either the first or concurrent reader paradigms. The disadvantages are the longest interpretation times and potentially reduced specificity compared to either the first or concurrent reads.

While a CAD system may be marketed as being optimized for one of these three reading methods, it is quite possible that radiologists will adapt their reading style to another reading method based on personal choice and experience.

A number of research publications have recently evaluated the performance of radiologists assisted by CAD. These publications are preliminary works with small numbers of cases and readers. Some of the relevant findings include:

- a. 2-D reading with the use of CAD may be quicker than 3-D reading without CAD, with similar sensitivity ⁵⁰.

- b. CAD false positives tend to be easily dismissed by expert radiologists⁵¹. The majority of polyps missed by expert readers were detected by CAD, potentially leading to increased sensitivity if correctly characterized by the readers.
- c. 3D viewing slightly increased reader accuracy in classifying CAD polyp candidates as true or false positives⁵². Factors significantly associated with reader accuracy included polyp size and quality of the examination.
- d. CAD in the first reader mode had similar sensitivity for detecting polyps and patients with polyps compared to that of reading without the aid of CAD⁵³. The use of CAD decreased observer variability and reduced the time required to detect the first polyp by about half a minute.
- e. For non-expert readers, when CAD is used as a concurrent reader, CAD improves the sensitivity of the readers particularly for detecting polyps ≤ 9 mm, and reduces interpretation times⁵⁴. However, non-expert readers had poor sensitivity for detecting polyps even with the use of CAD.
- f. Concurrent reading with CAD is about three minutes faster than second read with CAD but the odds of finding a polyp were greater with second read when compared to concurrent read⁵⁵.
- g. In second reader mode, the use of CAD led to a statistically significant 15% increase in sensitivity for detecting polyps ≥ 6 mm, but it reduced the specificity by 14% (Figure 2)¹⁶. The review of the CAD findings added about 3 minutes to the average reading time.
- h. In second reader mode, the use of CAD significantly improved sensitivity for polyp detection by non-expert readers with increases of sensitivity of 15 to 20%⁵⁶. The use of CAD increased reading time by an average of 2.1 minutes.
- i. In second reader mode, the use of CAD by seven less-experienced readers led to a significant improvement in sensitivity from 81.0 to 90.8%⁵⁷. The number of false positive results per patient increased from 0.70 to 0.96. The use of CAD led to an increase in reading time of 3.6 minutes.
- j. In second reader mode, the use of CAD by four readers with some experience reading CTC led to detection of a few more positive patients than CTC without CAD but the improvement in per patient sensitivity was not statistically significant, both for patients with polyps 6 mm or larger or for patients with polyps 10 mm or larger⁵⁸. Specificity was nearly unchanged with CAD compared to without CAD.
- k. Increasing numbers of CAD false positive marks may not adversely affect specificity although the effect on sensitivity is unknown⁵⁹. An increased number of CAD marks did lengthen reading times in the second reader mode, adding about half a minute to the time for review of the CAD output when there were more than 15 false positive CAD marks per data set.

Challenges Ahead

While CT colonography computer-aided detection research is producing exciting results, there are many challenges ahead⁶⁰. The major advances are expected to be in the areas of increased sensitivity for smaller polyps, decreased false positive rates, electronic stool subtraction for the uncleansed colon and matching of detections on the supine and prone exams^{61–64}. The availability of larger databases of proven cases will contribute to these developments.

The major clinical challenge will be to evaluate the impact of CAD in an actual clinical interpretive setting. Studies will need to show that CAD improves clinical sensitivity without

placing an undue burden through reduced specificity or increased interpretation time. Appropriate training in how to use CAD may be a key to its success. The economics also need to be addressed, as CAD software may be expensive and the use of CAD is as yet not reimbursed. In an economic analysis, CAD may improve the colorectal cancer prevention rate and may be cost-effective for CT colonography screening ⁶⁵.

Innovative Displays for CTC

Since its inception, CT colonography has been closely associated with innovative display methodologies^{66–68}. For example, in 1994 Vining introduced virtual colonoscopy using surface reconstructions to model the interior of the colon⁶⁹. While many radiologists primarily use 2-D image display to interpret CTC, some research indicates that 3-D virtual colonoscopy displays may lead to improved sensitivity for detecting polyps although this has been somewhat controversial⁷⁰.

While 3-D virtual colonoscopy displays seem natural due to their similar appearances compared to optical colonoscopy displays, endoluminal visualization methods have some limitations. For example, polyps can be hidden behind haustral folds during endoluminal inspection⁷¹. Novel displays such as Mercator map and stereographic projections have been proposed to address the problem of unseen regions⁶⁷. Modification of the 3-D viewing angle may also improve sensitivity and reduce the number of unseen regions^{67, 72}.

One type of innovative display is called virtual dissection, virtual pathology or “filet” view ^{73–75}. These displays use computer software to virtually cut open the colon so that it can be inspected as if it were a pathological specimen. The virtual dissection technique allows the physician to see the colon laid out flat without the need to navigate its various bends and blind spots. However, the virtual dissection display is susceptible to distortion. Modifications of this technique have been developed to reduce the distortion⁷⁶. In addition, CAD has been integrated into some virtual dissection displays ^{77, 78}. In one study, virtual dissection with CAD used in the first reader mode had sensitivity exceeding 94% for detecting polyps 1 cm or larger; the effect on specificity however was unclear.

Another promising display technology is the virtual unfolded cube display ⁷⁹. In this display, a radiologist sees a 360° view of the colon and can inspect both forward, side and rear views of the colon simultaneously. The virtual unfolded cube display may improve detection of polyps hidden behind haustral folds.

A novel display has been proposed that uses the location of the three tenia coli for circumferential co-registration of supine and prone CTC scans. This display brings the CTC scans into rotational alignment enabling improved matching of findings on the supine and prone 3-D endoluminal images⁸⁰.

Conclusions

Preliminary results in CT colonography CAD are encouraging. There is evidence that high sensitivity and a low number of false positive detections per examination are achievable. The application of CAD to clinical practice is likely to help less experienced radiologists by improving their sensitivity for detecting polyps but may not reduce reading times. Novel displays may improve diagnostic accuracy and can be combined with CAD. With advances in computer technology and larger image databases, CAD performance is likely to improve rapidly and will hopefully benefit patients in the near future.

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References

1. Fletcher JG, Johnson CD, Welch TJ, et al. Optimization of CT colonography technique: prospective trial in 180 patients. *Radiology* 2000;216(3):704–711. [PubMed: 10966698]
2. Pickhardt PJ, Choi JR, Hwang I, et al. Computed tomographic virtual colonoscopy to screen for colorectal neoplasia in asymptomatic adults. *N Engl J Med* Dec 4;2003 349(23):2191–2200. [PubMed: 14657426]
3. Johnson CD, Chen MH, Toledano AY, et al. Accuracy of CT colonography for detection of large adenomas and cancers. *New England Journal of Medicine* 2008;359(12):1207–1217. [PubMed: 18799557]
4. Doshi T, Rusinak D, Halvorsen RA, Rockey DC, Suzuki K, Dachman AH. CT colonography: false-negative interpretations. *Radiology* Jul;2007 244(1):165–173. [PubMed: 17581901]
5. Summers RM. Chapter 23: How Perceptual Factors Affect the Use and Accuracy of CAD for Interpretation of CT Images. In: Samei, E.; Krupinski, E., editors. *The handbook of medical image perception and techniques*. Cambridge; 2009. p. 313–321.
6. Shaw CM, Flanagan FL, Fenlon HM, McNicholas MM. Consensus review of discordant findings maximizes cancer detection rate in double-reader screening mammography: Irish National Breast Screening Program experience. *Radiology* Feb;2009 250(2):354–362. [PubMed: 19188311]
7. Johnson CD, MacCarty RL, Welch TJ, et al. Comparison of the relative sensitivity of CT colonography and double-contrast barium enema for screen detection of colorectal polyps. *Clin Gastroenterol Hepatol* Apr;2004 2(4):314–321. [PubMed: 15067626]
8. Summers RM, Beaulieu CF, Pusanik LM, et al. Automated polyp detector for CT colonography: feasibility study. *Radiology* 2000;216(1):284–290. [PubMed: 10887263]
9. Yoshida H, Nappi J. Three-dimensional computer-aided diagnosis scheme for detection of colonic polyps. *IEEE Transactions on Medical Imaging* Dec;2001 20(12):1261–1274. [PubMed: 11811826]
10. Paik DS, Beaulieu CF, Rubin GD, et al. Surface normal overlap: A computer-aided detection algorithm, with application to colonic polyps and lung nodules in helical CT. *IEEE Transactions on Medical Imaging* Jun;2004 23(6):661–675. [PubMed: 15191141]
11. Sundaram P, Zomorodian A, Beaulieu C, Napel S. Colon polyp detection using smoothed shape operators: preliminary results. *Med Image Anal* Apr;2008 12(2):99–119. [PubMed: 17910934]
12. Wang Z, Liang Z, Li L, et al. Reduction of false positives by internal features for polyp detection in CT-based virtual colonoscopy. *Med Phys* Dec;2005 32(12):3602–3616. [PubMed: 16475759]
13. Summers RM.; Pusanik, LM.; Malley, JD.; Reed, JE.; Johnson, CD. Method of labeling colonic polyps at CT colonography using computer-assisted detection. Paper presented at: Computer Assisted Radiology and Surgery (CARS); June 28–July 1, 2000; San Francisco, CA.
14. Summers RM, Yao J, Pickhardt PJ, et al. Computed tomographic virtual colonoscopy computer-aided polyp detection in a screening population. *Gastroenterology* Dec;2005 129(6):1832–1844. [PubMed: 16344052]
15. Summers RM, Handwerker LR, Pickhardt PJ, et al. Performance of a previously validated CT colonography computer-aided detection system in a new patient population. *AJR Am J Roentgenol* Jul;2008 191(1):168–174. [PubMed: 18562741]
16. Petrick N, Haider M, Summers RM, et al. CT Colonography and Computer-aided Detection as a Second Reader: Observer Performance Study. *Radiology* 2008;246(1):148–156. [PubMed: 18096536]
17. Summers RM, Yao J, Johnson CD. CT colonography with computer-aided detection: automated recognition of ileocecal valve to reduce number of false-positive detections. *Radiology* Nov;2004 233(1):266–272. [PubMed: 15454623]

18. O'Connor SD, Summers RM, Yao J, Pickhardt PJ, Choi JR. CT colonography with computer-aided polyp detection: volume and attenuation thresholds to reduce false-positive findings owing to the ileocecal valve. *Radiology* Nov;2006 241(2):426–432. [PubMed: 17005773]
19. Iordanescu G, Summers RM. Reduction of false positives on the rectal tube in computer-aided detection for CT colonography. *Med Phys* Nov;2004 31(10):2855–2862. [PubMed: 15543795]
20. Suzuki K, Yoshida H, Nappi J, Dachman AH. Massive-training artificial neural network (MTANN) for reduction of false positives in computer-aided detection of polyps: Suppression of rectal tubes. *Med Phys* Oct;2006 33(10):3814–3824. [PubMed: 17089846]
21. Deshpande KK, Summers RM, Van Uitert RL, et al. Quality assessment for CT colonography: validation of automated measurement of colonic distention and residual fluid. *AJR Am J Roentgenol* Dec;2007 189(6):1457–1463. [PubMed: 18029885]
22. Van Uitert RL, Summers RM, White JM, Deshpande KK, Choi JR, Pickhardt PJ. Temporal and multiinstitutional quality assessment of CT colonography. *AJR Am J Roentgenol* Nov;2008 191(5):1503–1508. [PubMed: 18941092]
23. Shinnars TJ, Pickhardt PJ, Taylor AJ, Jones DA, Olsen CH. Patient-controlled room air insufflation versus automated carbon dioxide delivery for CT colonography. *AJR Am J Roentgenol* Jun;2006 186(6):1491–1496. [PubMed: 16714635]
24. Burling D, Taylor SA, Halligan S, et al. Automated insufflation of carbon dioxide for MDCT colonography: distension and patient experience compared with manual insufflation. *AJR Am J Roentgenol* Jan;2006 186(1):96–103. [PubMed: 16357385]
25. Lee MW, Kim SH, Park HS, et al. An anthropomorphic phantom study of computer-aided detection performance for polyp detection on CT colonography: a comparison of commercially and academically available systems. *AJR Am J Roentgenol* Aug;2009 193(2):445–454. [PubMed: 19620442]
26. Summers RM, Frentz SM, Liu J, et al. Conspicuity of colorectal polyps at CT colonography: visual assessment, CAD performance, and the important role of polyp height. *Acad Radiol* Jan;2009 16(1):4–14. [PubMed: 19064206]
27. Park SH, Ha HK, Kim AY, et al. Flat polyps of the colon: detection with 16-MDCT colonography--preliminary results. *AJR Am J Roentgenol* Jun;2006 186(6):1611–1617. [PubMed: 16714650]
28. Summers RM, Liu J, Yao J, Brown L, Choi JR, Pickhardt PJ. Automated Measurement of Colorectal Polyp Height at CT Colonography: Hyperplastic Polyps are Flatter than Adenomatous Polyps. *AJR Am J Roentgenol*. 2009 in press.
29. Pickhardt PJ, Choi JR, Hwang I, Schindler WR. Nonadenomatous polyps at CT colonography: prevalence, size distribution, and detection rates. *Radiology* Oct;2004 232(3):784–790. [PubMed: 15247435]
30. East JE, Saunders BP, Jass JR. Sporadic and syndromic hyperplastic polyps and serrated adenomas of the colon: classification, molecular genetics, natural history, and clinical management. *Gastroenterol Clin North Am* 2008 Mar;37(1):25–46. v. [PubMed: 18313538]
31. Nappi J, Yoshida H. Adaptive correction of the pseudo-enhancement of CT attenuation for fecal-tagging CT colonography. *Med Image Anal* Aug;2008 12(4):413–426. [PubMed: 18313349]
32. Liu J, Yao J, Summers RM. Scale-based scatter correction for computer-aided polyp detection in CT colonography. *Med Phys* Dec;2008 35(12):5664–5671. [PubMed: 19175123]
33. Tsagaan B, Nappi J, Yoshida H. Nonlinear regression-based method for pseudoenhancement correction in CT colonography. *Med Phys* Aug;2009 36(8):3596–3606. [PubMed: 19746794]
34. O'Connor SD, Summers RM, Choi JR, Pickhardt PJ. Oral contrast adherence to polyps on CT colonography. *J Comput Assist Tomogr* Jan–Feb;2006 30(1):51–57. [PubMed: 16365572]
35. Liu, J.; Chang, Y.; Summers, RM. Automated Detection of Adherent Contrast Phenomenon on Colonic Polyps on CT Colonography. Paper presented at: RSNA; 2009; Chicago.
36. Franaszek M, Summers RM, Pickhardt PJ, Choi JR. Hybrid segmentation of colon filled with air and opacified fluid for CT colonography. *IEEE Trans Med Imaging* Mar;2006 25(3):358–368. [PubMed: 16524091]
37. Wang S, Li L, Cohen H, Mankes S, Chen JJ, Liang Z. An EM approach to MAP solution of segmenting tissue mixture percentages with application to CT-based virtual colonoscopy. *Med Phys* Dec;2008 35(12):5787–5798. [PubMed: 19175136]

38. Pickhardt PJ. By-patient performance characteristics of CT colonography: importance of polyp size threshold data. *Radiology* Oct;2003 229(1):291–293. author reply 293; discussion 293. [PubMed: 14519885]
39. Summers, RM.; Yoshida, H. Future Directions: Computer-Aided Diagnosis. In: Dachman, AH., editor. *Atlas of Virtual Colonoscopy*. New York: Springer; 2003. p. 55–62.
40. Yoshida H, Nappi J, MacEneaney P, Rubin DT, Dachman AH. Computer-aided diagnosis scheme for detection of polyps at CT colonography. *Radiographics* Jul–Aug;2002 22(4):963–979. [PubMed: 12110726]
41. Kiss G, Van Cleynenbreugel J, Suetens P, Marchal G. Computer aided diagnosis for CT colonography via slope density functions. *Medical Image Computing and Computer-Assisted Intervention - Miccai 2003*, Pt 1 2003;2878:746–753.
42. Bogoni L, Cathier P, Dundar M, et al. Computer-aided detection (CAD) for CT colonography: a tool to address a growing need. *Br J Radiol* 2005;78(Spec No 1):S57–62. [PubMed: 15917447]
43. Hara AK, Johnson CD, MacCarty RL, Welch TJ. Incidental extracolonic findings at CT colonography. *Radiology* 2000;215(2):353–357. [PubMed: 10796907]
44. Gluecker TM, Johnson CD, Wilson LA, et al. Extracolonic findings at CT colonography: evaluation of prevalence and cost in a screening population. *Gastroenterology* Apr;2003 124(4):911–916. [PubMed: 12671887]
45. Pickhardt PJ, Taylor AJ. Extracolonic findings identified in asymptomatic adults at screening CT colonography. *AJR Am J Roentgenol* Mar;2006 186(3):718–728. [PubMed: 16498099]
46. Xiong T, McEvoy K, Morton DG, Halligan S, Lilford RJ. Resources and costs associated with incidental extracolonic findings from CT colonography: a study in a symptomatic population. *Br J Radiol* Dec;2006 79(948):948–961. [PubMed: 16822798]
47. Halligan S, Taylor SA, Dehmeshki J, et al. Computer-assisted detection for CT colonography: external validation. *Clin Radiol* Sep;2006 61(9):758–763. discussion 764–755. [PubMed: 16905382]
48. van Ravesteijn VF, van Wijk C, Truyen R, Stoker J. Computer Aided Detection of Polyps in CT Colonography Using Logistic Regression. *IEEE transactions on medical imaging*. 2009 Aug 7; incomplete al.
49. Berbaum KS, Franken EA Jr, Dorfman DD, et al. Satisfaction of search in diagnostic radiology. *Invest Radiol* Feb;1990 25(2):133–140. [PubMed: 2312249]
50. Taylor SA, Halligan S, Slater A, et al. Polyp detection with CT colonography: primary 3D endoluminal analysis versus primary 2D transverse analysis with computer-assisted reader software. *Radiology* Jun;2006 239(3):759–767. [PubMed: 16543593]
51. Taylor SA, Halligan S, Burling D, et al. Computer-assisted reader software versus expert reviewers for polyp detection on CT colonography. *AJR Am J Roentgenol* Mar;2006 186(3):696–702. [PubMed: 16498097]
52. Shi R, Schraedley-Desmond P, Napel S, et al. CT colonography: influence of 3D viewing and polyp candidate features on interpretation with computer-aided detection. *Radiology* Jun;2006 239(3):768–776. [PubMed: 16714460]
53. Mani A, Napel S, Paik DS, et al. Computed tomography colonography - Feasibility of computer-aided polyp detection in a “First reader” paradigm. *Journal of Computer Assisted Tomography* May–Jun;2004 28(3):318–326. [PubMed: 15100534]
54. Halligan S, Altman DG, Mallett S, et al. Computed tomographic colonography: assessment of radiologist performance with and without computer-aided detection. *Gastroenterology* Dec;2006 131(6):1690–1699. [PubMed: 17087934]
55. Taylor SA, Charman SC, Lefere P, et al. CT Colonography (CTC): Investigation of the Optimum Reader Paradigm Using Computer Aided Detection (CAD) Software. *Radiology*. in press.
56. Mang T, Peloschek P, Plank C, et al. Effect of computer-aided detection as a second reader in multidetector-row CT colonography. *Eur Radiol* Oct;2007 17(10):2598–2607. [PubMed: 17351780]
57. Baker ME, Bogoni L, Obuchowski NA, et al. Computer-aided detection of colorectal polyps: can it improve sensitivity of less-experienced readers? Preliminary findings. *Radiology* Oct;2007 245(1):140–149. [PubMed: 17885187]

58. de Vries AH, Jensch S, Liedenbaum MH, et al. Does a computer-aided detection algorithm in a second read paradigm enhance the performance of experienced computed tomography colonography readers in a population of increased risk? *Eur Radiol* Apr;2009 19(4):941–950. [PubMed: 18982331]
59. Taylor SA, Greenhalgh R, Ilangovan R, et al. CT colonography and computer-aided detection: effect of false-positive results on reader specificity and reading efficiency in a low-prevalence screening population. *Radiology* Apr;2008 247(1):133–140. [PubMed: 18292478]
60. Summers RM. Challenges for computer-aided diagnosis for CT colonography. *Abdom Imaging* 2002;27:268–274. [PubMed: 12173357]
61. Cai W, Zalis ME, Nappi J, Harris GJ, Yoshida H. Structure-analysis method for electronic cleansing in cathartic and noncathartic CT colonography. *Medical physics* 2008 Jul DTBS- Remote Drive MEDLINE 2008;35(7):3259–3277.
62. Nappi J, Yoshida H. Virtual tagging for laxative-free CT colonography: pilot evaluation. *Medical physics* May;2009 36(5):1830–1838. [PubMed: 19544802]
63. Wang, S.; Van Uitert, RL.; Summers, RM. Automated matching of supine and prone colonic polyps based on PCA and SVMs. Paper presented at: Progress in Biomedical Optics and Imaging - Proceedings of SPIE; 2008.
64. Nappi J, Okamura A, Frimmel H, Dachman A, Yoshida H. Region-based supine-prone correspondence for the reduction of false-positive CAD polyp candidates in CT colonography. *Acad Radiol* Jun;2005 12(6):695–707. [PubMed: 15935968]
65. Regge D, Hassan C, Pickhardt PJ, et al. Impact of computer-aided detection on the cost-effectiveness of CT colonography. *Radiology* Feb;2009 250(2):488–497. [PubMed: 19188317]
66. Beaulieu CF, Jeffrey RB, Karadi G, Paik DS, Napel S. Visualization modes for CT colonography: Blinded comparison of axial CT, virtual endoscopy, and panoramic-view volume rendering. *Radiology* 1998;209P:296–297.
67. Paik DS, Beaulieu CF, Jeffrey RB Jr, Karadi CA, Napel S. Visualization modes for CT colonography using cylindrical and planar map projections. *J Comput Assist Tomogr* 2000;24(2):179–188. [PubMed: 10752876]
68. Beaulieu CF, Jeffrey RB Jr, Karadi C, Paik DS, Napel S. Display modes for CT colonography. Part II. Blinded comparison of axial CT and virtual endoscopic and panoramic endoscopic volume-rendered studies. *Radiology* 1999;212(1):203–212. [PubMed: 10405743]
69. Vining DJ, Teigen EL, Stelts D, Vanderwerken B, Kopecky KK, Rex D. Virtual colonoscopy: A 60-second colon examination. *Radiology* 1995;197:281.
70. Pickhardt PJ, Lee AD, Taylor AJ, et al. Primary 2D versus primary 3D polyp detection at screening CT colonography. *AJR Am J Roentgenol* Dec;2007 189(6):1451–1456. [PubMed: 18029884]
71. Pickhardt PJ, Nugent PA, Mysliwiec PA, Choi JR, Schindler WR. Location of adenomas missed by optical colonoscopy. *Ann Intern Med* Oct 7;2004 141(5):352–359. [PubMed: 15353426]
72. East JE, Saunders BP, Boone D, Burling D, Halligan S, Taylor SA. Uni- and bidirectional wide angle CT colonography: effect on missed areas, surface visualization, viewing time and polyp conspicuity. *Eur Radiol* Sep;2008 18(9):1910–1917. [PubMed: 18414869]
73. Hoppe H, Quattropani C, Spreng A, Mattich J, Netzer P, Dinkel HP. Virtual colon dissection with CT colonography compared with axial interpretation and conventional colonoscopy: preliminary results. *AJR Am J Roentgenol* May;2004 182(5):1151–1158. [PubMed: 15100110]
74. Haker S, Angenent S, Tannenbaum A, Kikinis R. Nondistorting flattening maps and the 3-D visualization of colon CT images. *IEEE Trans Med Imaging* 2000;19(7):665–670. [PubMed: 11055781]
75. Wang G, McFarland EG, Brown BP, Vannier MW. GI tract unraveling with curved cross sections. *IEEE Trans Med Imaging* 1998;17(2):318–322. [PubMed: 9688165]
76. Kim SH, Lee JM, Eun HW, et al. Two- versus three-dimensional colon evaluation with recently developed virtual dissection software for CT colonography. *Radiology* Sep;2007 244(3):852–864. [PubMed: 17709833]
77. Johnson KT, Fletcher JG, Johnson CD. Computer-aided detection (CAD) using 360 degree virtual dissection: can CAD in a first reviewer paradigm be a reliable substitute for primary 2D or 3D search? *AJR Am J Roentgenol* Oct;2007 189(4):W172–176. [PubMed: 17885028]

78. Hock D, Ouhadi R, Materne R, et al. Virtual dissection CT colonography: evaluation of learning curves and reading times with and without computer-aided detection. *Radiology* Sep;2008 248(3): 860–868. [PubMed: 18710980]
79. Vos FM, van Gelder RE, Serlie IW, et al. Three-dimensional display modes for CT colonography: conventional 3D virtual colonoscopy versus unfolded cube projection. *Radiology* Sep;2003 228(3): 878–885. [PubMed: 12954902]
80. Huang A, Roy DA, Summers RM, et al. Teniae coli-based circumferential localization system for CT colonography: feasibility study. *Radiology* May;2007 243(2):551–560. [PubMed: 17456877]

Figure 1.

Simplified schematic of three CAD reading paradigms. Horizontal bars (clear, gray, solid) represent CTC images. Clear bar indicates image has no CAD marks and is not reviewed by reader. Gray bar indicates image has CAD marks and is reviewed by reader. Black bar indicates image has no CAD marks and is reviewed by reader. In first reader mode, reader only reviews images with CAD marks. In concurrent reader mode, CAD marks are present during the reader's first pass through all the images. In second reader mode, all images are reviewed first without CAD marks, then reader reviews only images with CAD marks to arrive at final diagnosis.

Figure 2.

Rectal 7 mm adenomatous polyp (short white arrow) initially missed by four readers but found by three of the readers after the use of CAD in the second reader mode. CAD prompts (pink indicator in A, rectangle in B) and rectal tube (long white arrows) are indicated. The polyp may have been missed initially because it was partially hidden behind the rectal tube. Reprinted from Ref. ¹⁶.