Informatics in Radiology

Dual-Energy Electronic Cleansing for Fecal-Tagging CT Colonography¹

TEACHING POINTS

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Wenli Cai, PhD • Se Hyung Kim, MD • June-Goo Lee, PhD • Hiroyuki Yoshida, PhD

Electronic cleansing (EC) is an emerging technique for the removal of tagged fecal materials at fecal-tagging computed tomographic (CT) colonography. However, existing EC methods may generate various types of artifacts that severely impair the quality of the cleansed CT colonographic images. Dual-energy fecal-tagging CT colonography is regarded as a next-generation imaging modality. EC that makes use of dual-energy fecal-tagging CT colonographic images promises to be effective in reducing cleansing artifacts by means of applying the material decomposition capability of dual-energy CT. The dual-energy index (DEI), which is calculated from the relative change in the attenuation values of a material at two different photon energies, is a reliable and effective indicator for differentiating tagged fecal materials from various types of tissues on fecal-tagging CT colonographic images. A DEI-based dual-energy EC scheme uses the DEI to help differentiate the colonic lumen—including the luminal air, tagged fecal materials, and air-tagging mixture—from the colonic soft-tissue structures, and then segments the entire colonic lumen for cleansing of the tagged fecal materials. As a result, dual-energy EC can help identify partial-volume effects in the air-tagging mixture and inhomogeneous tagging in residual fecal materials, the major causes of EC artifacts. This technique has the potential to significantly improve the quality of EC and promises to provide images of a cleansed colon that are free of the artifacts commonly observed with conventional single-energy EC methods.

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Abbreviations: DEI = dual-energy index, EC = electronic cleansing, 3D = three-dimensional, 2D = two-dimensional, VCT = virtual colon tagging

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¹From the Department of Radiology, Massachusetts General Hospital and Harvard Medical School, 25 New Chardon St, 400C, Boston, MA 02114 (W.C., J.G.L., H.Y.); and Department of Radiology, Seoul National University Hospital College of Medicine, Seoul, Korea (S.H.K.). Recipient of a Magna Cum Laude award for an education exhibit at the 2011 RSNA Annual Meeting. Received March 20, 2012; revision requested September 10 and received November 20; accepted December 10. Supported in part by Research Scholar Grant RSG-11-076-01-CCE from the American Cancer Society. W.C. and H.Y. have disclosed financial relationships (see p 000); all other authors have no relevant relationships to disclose. **Address correspondence to W.C.** (e-mail: Cai.Wenli@mgh.harvard.edu).

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Figure 1. Recovery of a submerged polyp with EC. (**a, b**) Virtual colonoscopic images obtained before (**a**) and after (**b**) EC. (**c, d**) Corresponding transverse two-dimensional (2D) CT images reveal a polyp (arrow) that had been submerged in tagged fecal materials.

Introduction

Computed tomographic (CT) colonography, also known as virtual colonoscopy, is a minimally invasive screening procedure for colon cancer that can provide an alternative to optical colonoscopy (1,2). Fecal tagging is a means of “marking” fecal residue (stool and fluid) in the colon with oral administration of a positive contrast agent (barium or iodine), thereby allowing differentiation of this residue from colonic soft-tissue structures at CT

colonography (3–7). Large-scale and multicenter clinical trials have demonstrated that CT colonography has a sensitivity comparable to that of optical colonoscopy in the detection of clinically significant polyps in a screening population (8–10).

Electronic cleansing (EC), or digital bowel cleansing, is a process for identifying tagged fecal materials and “subtracting” them from CT colonographic images (11,12). The goal of EC is to “virtually cleanse” the colon by removing tagged fecal materials that can obscure the colonic mucosal surface, especially small lesions that are submerged in or adjacent to the tagged fecal materials (Fig 1).

Table 1
Classification of Common Cleansing Artifacts and Pitfalls in Existing EC Schemes

Type	Artifact	Cause	Common Pitfalls
Type 1: image pseudoenhancement	Soft-tissue structure degradation	Inappropriate cleansing of folds and polyps submerged in tagged fecal materials	Broken or shrunken folds, deformed/shrunken polyps
Type 2: partial-volume effect	Pseudo soft-tissue structures (type 2a)	Failure to remove all or part of an entire air-tagging boundary	Pseudo folds or polyps, pseudo colonic wall
	False fistula (type 2b)	Erroneous removal of all or part of a thin soft-tissue structure (colonic fold or wall) sandwiched between the luminal air and a tagged region	False fistula on colonic wall or on folds
	False patch (type 2c)	Insufficient cleansing or overcleansing at junctions of air-tagging boundaries and the colonic wall	Pseudo depressed or flat lesions
Type 3: tagging inhomogeneity	Incomplete cleansing	Failure to remove heterogeneously tagged fecal materials (eg, air bubbles, foodstuffs) in tagged fecal materials	Stalactite- or stalagmite-like objects in the colonic lumen

The early work on EC dates back to the late 1990s (13–15). The term *electronic cleansing* was first introduced by Wax et al (13). After more than a decade of investigation, EC has reached a level of sophistication that allows visualization of the entire colonic surface (16). A set of EC methods has been developed, including voxel classification (17,18), gradient-based edge detection (12,19), material transition (20), Hessian analysis (21), mosaic decomposition (22), and hybrid methods (23–25). However, existing EC methods tend to generate artifacts and pitfalls on cleansed CT colonographic images. Commonly seen cleansing artifacts are classified into three types on the basis of their associated imaging causes: type 1 (image pseudoenhancement), type 2 (partial-volume effect), and type 3 (tagging inhomogeneity) (Table 1) (26,27). These cleansing artifacts and pitfalls severely impair the diagnostic utility of cleansed CT colonographic images, and artifact-free EC remains a challenge.

The theory of dual-energy CT was introduced by Macovski et al (28) and by Alvarez and Macovski (29) more than three decades ago. With recent technical advances such as dual-source CT (30) and fast kilovoltage-peak switching (31), dual-energy CT has become widely available in clinical practice. Dual-energy CT provides an

effective way of estimating material composition by means of analysis of two attenuation values acquired simultaneously at two different photon energies (eg, 80 and 140 kVp) (32,33). This material decomposition capability of dual-energy CT works especially well in materials such as iodine, which have a K-edge energy close to the energy range for diagnostic imaging (34,35).

Fecal-tagging CT colonography performed on a dual-energy CT scanner promises to reduce cleansing artifacts seen with existing EC methods by allowing identification of partial-volume effects at the air-tagging boundary and inhomogeneous tagging of residual fecal materials, the major causes of EC artifacts. Dual-energy EC has the potential to significantly improve the quality of cleansing tagged fecal materials on CT colonographic images (36–38).

In this article, we describe the development of a novel dual-energy EC scheme that minimizes cleansing artifacts with use of the material decomposition capability of dual-energy CT colonography. With this dual-energy EC scheme, images of a cleansed colon can be generated that are free from the EC artifacts commonly observed with use of conventional single-energy EC methods.

Teaching Point

Figure 2. Graph illustrates the x-ray attenuation values for soft tissue, bone, iodine, and water, which were calculated with the National Institute of Standards and Technology (NIST) XCOM program (version 3.1). Iodine demonstrates a large difference in x-ray attenuation between two photon energies (80 and 140 kVp), whereas bone demonstrates a medium difference and water and soft tissue (overlapping curves at bottom of graph) demonstrate a small difference.

Dual-Energy EC

Our dual-energy EC scheme makes use of the dual-energy index (DEI), calculated from dual-energy CT colonographic images, to help distinguish luminal air, tagged materials, or an air-tagging mixture caused by the partial-volume effect from colonic soft-tissue structures. We refer to the technique as virtual colon tagging (VCT) with use of DEI. In this study, we developed a DEI-based dual-energy EC scheme by combining the material decomposition capability of dual-energy CT with other advanced image processing techniques, including denoising, morphologic analysis, and image segmentation.

Dual-Energy Index

By definition, the attenuation (in Hounsfield units [HU]) of a material is calculated with use of the x-ray attenuation coefficient of water as the reference point. The attenuation value of water is 0 HU, which remains unchanged at different energy levels. In general, the x-ray attenuation coefficients of a material depend on three factors: (a) photon energy, (b) material density, and (c) atomic number (39).

Figure 2 shows the change in x-ray attenuation value for water, soft tissue, bone, and iodine as a function of photon energy. Generally, materials with a high atomic number (Z) show large differences in x-ray attenuation at different energy levels. For example, iodine ($Z = 53$) shows a large difference in x-ray attenuation between 80 and 140 kVp, whereas bone ($Z = 13.8$) shows a medium difference, and water ($Z = 7.42$) and soft tissue ($Z = 7.22$) show a small difference.

Table 2
Effective Atomic Numbers and DEI Values of Several Materials Commonly Seen on Dual-Energy CT Colonographic Images

Material	Effective Z	DEI Value
Adipose tissue	5.92	-0.0242
Soft tissue	7.22	-0.0039
Water, liquid	7.42	0.0000
Muscle, body tissue	7.46	0.0022
Carbon dioxide	7.55	0.0025
Air	7.64	0.0063
Bone, femur	14.0	0.2313
Iodine	53.0	0.5686

Note.—The elemental compositions of materials were obtained from International Commission on Radiation Units and Measurements Report No. 44 (1989) (see reference 41). Z = atomic number.

This difference in x-ray attenuation at two different photon energies can be characterized by the DEI (40):

$$DEI_i = (HU_i^{80} - HU_i^{140}) / (HU_i^{80} + HU_i^{140} + 2000), (1)$$

where HU_i^{80} and HU_i^{140} are the attenuation values of material i at photon energies of 80 and 140 kVp, respectively. The DEI value of water is 0, which serves as a reference point for other materials.

Table 2 lists the effective atomic numbers and theoretic DEI values for several materials commonly seen on dual-energy CT colonographic images. These values were calculated with the NIST XCOM program (41), with the input of manufacturer-supplied effective photon energies (51.3 keV at 80 kVp and 91.0 keV at 140 kVp), for

a.

b.

c.

Figure 3. Calculation of DEI values. (a, b) Transverse dual-energy fecal-tagging CT colonographic images obtained at 80 kVp (a) and 140 kVp (b). (c) Corresponding DEI image calculated from a and b for all of the voxels with an attenuation greater than or equal to -990 HU on the low-energy image (cf a).

a SOMATON Definition Flash scanner (Siemens Healthcare, Erlangen, Germany). The changing ratio of attenuation values of a material at two different photon energies depends on its effective atomic number compared with that of water. More precisely, if the effective atomic number of a material is higher than that of water (eg, bone, iodine), its attenuation value increases as the energy level decreases, and thus it has a positive DEI value. In contrast, if the effective atomic number of a material is lower than that of water (eg, fat), its attenuation value decreases as the energy level decreases, and thus it has a negative DEI value.

The DEI is a reliable and effective indicator for differentiating materials on the basis of the relative change in attenuation values at two different photon energies. For example, although bone and iodinated contrast agent have similar high attenuation values on conventional single-energy CT images, the DEI value of iodine is significantly higher than that of bone, which provides a means of distinguishing between bone and iodinated contrast

agent on dual-energy CT images (33). It should be noted that air and carbon dioxide (often used for insufflation at CT colonography) have very low attenuation values (approximately -1000 HU) because of their low densities (approximately 0.0013 g/cm³ of air versus 1.0 g/cm³ of water). However, their DEI values are positive and higher than that of water because their effective atomic numbers are also higher than that of water (Table 2).

Figure 3 shows two dual-energy fecal-tagging CT colonographic images and the calculated DEI image. As expected, the tagged regions have higher DEI values than do bone, soft tissue, and abdominal fat. However, we observed that the DEI value of luminal air was substantially higher than the theoretic value shown in Table 2 (ie, 0.0063). Figure 4 shows the DEI values measured in regions of interest around an air-tagging boundary. The resulting DEI values are substantially higher than the theoretic value.

a.
Figure 4. DEI values measured in the vicinity of an air-tagging boundary. **(a, b)** Transverse dual-energy CT colonographic images obtained at 80 kVp **(a)** and 140 kVp **(b)**, on which three regions of interest (1, 2, and 3) were placed manually. **(c)** Chart shows the mean and standard deviations for each region of interest and their corresponding DEI values.

ROI	80 kVp (HU)	140 kVp (HU)	DEI
1	-744±67	-891±28	0.403
2	-921±29	-960±19	0.328
3	-945±20	-976±16	0.392

c.

Figure 5 demonstrates the high DEI values of air in the colonic lumen at dual-energy fecal-tagging CT colonography. The luminal air was first segmented with a threshold-based region-growing method for the extraction of regions with attenuation values of -700 HU or lower. Erosion (shrinking) was performed in 10 steps for removal of the partial-volume effect at the boundaries, and the red mask of the luminal air was extracted (Fig 5a, 5b). Figure 5c shows the mean attenuation value of luminal air on 80- and 140-kVp images at each erosion step. The DEI value of the colonic luminal air was substantially higher than the theoretic value of 0.0063.

The theoretic DEI value of a material is not related to the density of the material; rather, it depends on the photon energy and the effective atomic number of the material. However, the DEI values that we measured were based on the attenuation values on the reconstructed images, which depend not only on the photon energy and the effective atomic number of the material, but also on its density. In general, high-density materials

generate more severe beam-hardening artifacts on reconstructed images than do low-density materials such as bone and iodine-tagged fecal materials.

The cause of this large variation in the attenuation values of colonic luminal air is twofold: inappropriate correction for beam hardening and cross-scattering between the two tubes of a dual-source CT scanner. The correction for beam hardening tends to compensate for the depressed attenuation values in the affected regions, such as high-density materials (iodine or bone). However, it may elevate the attenuation values of low-density materials in the vicinity of high-density materials, such as luminal air surrounded by tagged fecal materials and soft-tissue structures. This phenomenon has been referred to as "environmental density artifacts" (42) or pseudoenhancement (43). On the other hand, the contribution of cross-scattering, which originates from the high-energy tube and is received at the low-energy detector, may increase the proportion of high-energy photons in the low-energy detector and thus cause pseudo beam hardening in the low-energy projection data.

a.

b.

Figure 5. DEI values of colonic luminal air at dual-energy fecal-tagging CT colonography. Region growing was first applied to the colonic luminal air with an upper threshold of -700 HU, followed by erosion performed in 10 steps to remove the partial-volume effect at the boundaries. (a, b) Transverse dual-energy fecal-tagging CT colonographic images with segmented luminal air (“red mask”) obtained at 80 kVp (a) and 140 kVp (b). (c) Graph illustrates the mean attenuation values of the segmented luminal air during erosion. After erosion was complete, the mean attenuation values of the luminal air were -946 ± 33 HU and -980 ± 21 HU for the 80-kVp and 140-kVp images, respectively. The DEI value of the colonic luminal air was 0.459.

c.

As a result, the low-energy images may be erroneously overcompensated by the beam-hardening correction algorithm in CT reconstruction.

Therefore, the colonic luminal air may be “illuminated” by the inappropriate correction for beam hardening caused by higher-density materials and the cross-scattering caused by the dual-tube configuration of dual-source CT scanners. This pseudoenhancement effect is more severe on low-energy (80-kVp) images than on high-energy (140-kVp) images. As a result, the DEI value of luminal air as measured on dual-energy CT images is substantially higher than its theoretic value and that of soft tissue.

The fact that the DEI values of colonic luminal air on dual-energy CT colonographic images are substantially higher than those of either fat or soft tissue provides an effective means for differentiating air-tagging mixtures caused by the partial-volume effect from soft-tissue structures, thereby reducing the occurrence of type 2 cleansing artifacts.

Virtual Colon Tagging

Because of the partial-volume or volume-averaging effect, an air-tagging boundary is a mixture of luminal air and tagged fecal material and has a wide spectrum of attenuation values on CT colonographic images (typically between -800 and 600 HU). Thus, the attenuation value of an air-tagging boundary overlaps significantly with that of soft-tissue structures. When a thin soft-tissue structure is adjacent to tagged fecal material, its attenuation-value profile becomes very similar to that of an air-tagging boundary (Fig 6) (21). This

Figure 6. Use of the DEI for resolving the ambiguity between soft tissue and the air-tagging boundary. (a–c) Transverse dual-energy fecal-tagging CT colonographic images of a phantom obtained at 80 kVp (a) and 140 kVp (b) and single-energy image obtained at 120 kVp (c) show a soft-tissue fold (arrow) adjacent to a tagged region. (d) On a subtracted image of c obtained after the application of region growing based on a lower threshold of 200 HU, the soft-tissue fold (arrow) shows attenuation values similar to those of an air-tagging boundary. This similarity is caused by the partial-volume effect and is the major source of type 2 EC artifacts. (e) On a DEI image of the colon mask calculated from a and b, the fold (arrow) is clearly distinguished from the air-tagging boundary by its low DEI value. (f) Segmented image of e obtained with region growing shows clear segmentation of the soft-tissue fold (arrow) from the air-tagging boundary.

Figure 7. Two-dimensional histogram illustrates attenuation value at 140 kVp (x-axis) versus DEI value (y-axis). The attenuation value of soft tissue is between those of air and tagged fecal material, making it difficult to differentiate between soft tissue and the air-tagging boundary. However, the DEI value of soft tissue is lower than those of air and tagged fecal material. Thus, the DEI provides an effective means of resolving the ambiguity between soft tissue and the air-tagging boundary.

ambiguity between soft tissue and the air-tagging boundary is the major cause of type 2 EC artifacts. Current solutions to this type of artifact at conventional single-energy CT colonography are heuristic and incomplete.

Our observation that the DEI values of the colonic luminal air were substantially higher than its theoretic value and the DEI values of colonic soft-tissue structures suggests a possible technique for resolving the ambiguity between soft tissue and the air-tagging boundary. **This technique, referred to as virtual colon tagging or VCT, is used to mark the entire colonic lumen on dual-energy CT colonographic images, including luminal air and tagged fecal materials, as well as the air-tagging mixture throughout the colon. VCT provides a means to differentiate soft tissue from the air-tagging mixture caused by the partial-volume effect for reducing the cleansing artifacts.**

The attenuation value of soft tissue is between those of air and tagged fecal material (Fig 7), making it difficult to differentiate between soft tissue and the air-tagging boundary on conventional single-energy CT colonographic images. However, the DEI value of soft tissue is lower than that of air or tagged fecal material (Fig 7). Thus, on the basis of DEI values, soft tissue can

be differentiated from the mixture of air and tagged fecal material, as well as from the air-tagging boundary (Fig 6e). Use of a simple threshold-based region-growing method may help differentiate between soft tissues and the air-tagging boundary (Fig 6f).

The colonic luminal air is noisy, especially on low-energy images, causing a large variation in its DEI value (Fig 7). Therefore, denoising is an essential step in VCT with use of the DEI. To overcome the blurring effect of the conventional Gaussian denoising method, we developed a dual-energy image-space denoising method that makes use of an anisotropic diffusion filter (44), in which smoothing is formulated mathematically as a diffusive process:

$$\frac{\partial}{\partial t} u(x,t) = \text{div}[D(x,t)\nabla u(x,t)], \quad (2)$$

where $\text{div}[\]$ is the divergence operator, ∇ is the gradient operator, $u(x,t)$ is the image intensity, and $D(x,t)$ is the diffusion tensor at spatial coordinate x and iteration step t .

Figure 8. Effect of denoising in the calculation of DEI images. (**a**, **b**) Transverse dual-energy CT colonographic images obtained at 80 kVp (**a**) and 140 kVp (**b**). (**c**–**e**) DEI images of **a** and **b** calculated without denoising (ie, with the original images) (**c**), with Gaussian-filtering (**d**), and with anisotropic diffusion-filtering (**e**) show that denoising is essential for obtaining uniform DEI values at VCT.

Figure 8 illustrates the effect of denoising on the computation of a constant DEI field for VCT. Without denoising, the DEI value of the luminal air varies widely, resulting in a noisy DEI field (Fig 8c). A conventional Gaussian filter can reduce noise but may introduce blurring at structure boundaries (Fig 8d). Use of an anisotropic diffusion filter yields a better denoising result (Fig 8e), with constant DEI values for luminal air and sharper structure boundaries than when a Gaussian filter or the original images are used.

The effect of denoising is more significant on low-energy images than on high-energy images. Therefore, denoising can significantly reduce the noise on dual-energy CT colonographic images and provides a constant DEI field for VCT.

Figure 9. (a) Fused dual-energy fecal-tagging CT colonographic images show leakage to bony structures caused by the application of region growing (lower threshold of 200 HU). (b) On a DEI image calculated from the regions of a with voxels with an attenuation of 200 HU or higher, along with the surrounding areas, the tagged fecal material demonstrates substantially higher DEI values than do the bony structures. Differentiation of tagged regions from bony structures on DEI images prevents leakage of tagged regions to bony structures at initial colon segmentation.

DEI-based Dual-Energy EC

We have developed an EC scheme for dual-energy fecal-tagging CT colonography that is based on our previously developed structure-analysis EC method (21). **This dual-energy EC scheme makes use of the DEI values instead of attenuation values to differentiate soft-tissue structures from luminal air, tagged fecal materials, and air-tagging mixtures. With this method, a Hessian filter is used to enhance the foldlike and polyp-like structures submerged in the virtually tagged colon.** Our dual-energy EC scheme consists of the following five steps: (a) initial segmentation of the colon; (b) VCT with use of DEI values; (c) computation of the Hessian response field in the virtually tagged colon to characterize and enhance foldlike and polyplike structures; (d) segmentation of virtually tagged regions in the colon with use of the level set method, except for the enhanced foldlike and polyplike structures; and (e) replacement of the segmented tagged regions with air, followed by reconstruction of those portions of the colonic wall that are submerged in tagged regions.

In fecal-tagging CT colonography, initial colon segmentation is performed by applying a group of alternate region-growing methods with use of two different thresholds for air and tagged regions (eg, an upper threshold of -700 HU for

the colonic lumen air and a lower threshold of 200 HU for the tagged region) (45). On conventional single-energy CT colonographic images, leakage to bony structures tends to occur when region growing is applied to tagged regions due to the overlap between the attenuation values of tagged fecal materials and those of bony structures (Fig 9a). This type of leakage can be prevented with use of DEI values, since iodine-tagged regions can be clearly differentiated from bony structures owing to the substantially higher DEI values of tagged regions at dual-energy CT colonography (Fig 9b). Therefore, the use of DEI values may improve initial segmentation of the colon.

Figure 10 illustrates the four major steps of our dual-energy EC scheme. After initial segmentation of the colon (Fig 10a), DEI values are calculated for the segmented colon region. VCT is then performed to mark the entire colonic lumen, including air, tagged fecal materials, and air-tagging mixtures (Fig 10b). On VCT images, air-tagging boundaries can be clearly differentiated from soft-tissue structures on the basis of their substantially higher DEI values. When morphologic analysis with use of a Hessian matrix is applied (21), the polyplike and foldlike structures

Figure 10. Major steps of the DEI-based dual-energy EC scheme. **(a)** Transverse fused dual-energy CT colonographic image of the initially segmented colonic region shows a polyp (arrowhead) submerged in tagged fecal material. **(b)** VCT image shows both luminal air and tagged fecal materials with high DEI values. Arrowhead = submerged polyp. **(c)** Hessian response image of **b** shows enhancement of foldlike and polyp-like structures. The polyp (arrowhead) is well enhanced. **(d)** Resulting image of **a** shows segmentation of the virtually tagged regions in **b** (green), including the luminal air, tagged fecal materials, and air-tagging boundaries. Arrowhead = polyp.

on the VCT images are enhanced and thus preserved in the Hessian response field, whereas other structures are “de-enhanced” and thus subtracted (Fig 10c).

To segment the tagged regions precisely and subtract (cleanse) them from the colonic lumen, we applied a dynamic-thresholding level set method (46) based on the VCT images, the gradient field, and the Hessian response field. The level set front, a thick three-dimensional (3D) shell region encompassing the segmentation surface during the evolution of level set, was initialized by the regions with high DEI values on VCT images, and the level set front was evolved with use of a partial differential equation (47). Because the soft-tissue structures have lower DEI values, high Hessian response values, and high gradient values at their boundaries with tagged regions on DEI images, the level set front was designed to be sensitive to submerged soft-tissue structures but insensitive to

the virtually tagged colonic lumen. Thus, the entire virtually tagged colonic lumen was segmented, including air, tagged fecal materials, and air-tagging mixtures (Fig 10d). Finally, the segmented regions were replaced with air (-1000 HU), followed by image smoothing filtering to reduce the discontinuity between the artificial transition layer and the original soft-tissue layer.

Figure 11 shows the cleansing results for the case illustrated in Figure 10. The polyp, which was submerged in the tagged fecal material between two folds, is clearly visualized on both transverse 2D images and 3D virtual colonoscopic images obtained after the application of dual-energy EC (Fig 11c, 11d).

Experiments and Results

Our institutional review board approved this retrospective, Health Insurance Portability and Accountability Act (HIPAA)-compliant patient study. Informed consent was waived, but patient confidentiality was protected.

Figure 11. Submerged polyp before and after the application of dual-energy EC. (**a, b**) On transverse 2D (**a**) and 3D virtual colonoscopic (**b**) images obtained before EC, the polyp (arrow) is submerged in fecal material and cannot be visualized. (**c, d**) Corresponding images obtained after EC clearly depict the polyp (arrow).

We retrospectively selected 25 adult outpatients (all >18 years of age) with symptoms suggestive of colorectal cancer and a clinical need for examination of the entire colon, all of whom had undergone dual-energy CT colonography between March 2010 and March 2011. Four subjects who had undergone cathartic bowel cleansing (without fecal tagging) prior to dual-energy CT colonography were excluded from the study. The final study population consisted of 21 symptomatic outpatients.

All 21 subjects underwent a 24-hour bowel preparation consisting of a low-fiber, low-residue diet, along with oral administration of 50 mL of nonionic iodinated contrast agent (300 mg/mL concentration of iohexol [Omnipaque 300; GE Healthcare, Milwaukee, Wis]). Dual-energy CT (SOMATON Definition Flash, Siemens Healthcare) was performed with the subjects in both supine and prone positions with tube voltages of

80 and 140 kVp and with the automatic exposure control module. For both supine and prone scans, we used the soft-tissue reconstruction kernel (B30f) and a 0.625-mm section reconstruction interval. In addition, all subjects underwent video-assisted optical colonoscopy after dual-energy CT colonography. The results of optical colonoscopy served as the reference standard for the presence of polyps. In total, there were 34 pathologically confirmed polyps 6 mm or larger, among which seven submerged polyps were found at supine scanning and nine at prone scanning.

All dual-energy fecal-tagging CT colonographic images were processed with our dual-energy EC scheme. Preliminary evaluation showed that the EC artifacts were reduced significantly. We observed no more than one minor EC artifact per case involving dual-energy EC, compared with

Figure 12. Submerged 12-mm adenoma in a 47-year-old man. **(a, b)** Transverse dual-energy CT colonographic images obtained at 80 kVp **(a)** and 140 kVp **(b)** show the submerged polyp (arrow). **(c)** On a VCT image, the colonic luminal air, tagged fecal materials, and air-tagging boundaries are clearly delineated by their high DEI values, whereas soft tissues, including the submerged polyp (arrow), have low DEI values. **(d)** Transverse CT colonographic image obtained after the application of dual-energy EC shows good preservation of the submerged polyp (arrow). **(e)** Three-dimensional volume-rendered image is free of EC artifacts.

five or six significant EC artifacts in cases involving single-energy EC. In addition, all submerged polyps were clearly visualized, with no EC artifacts. The majority of artifacts at dual-energy EC came from the inconsistent CT profile at the air-tagging boundary caused by the beam-hardening effect, especially on low-energy images.

Figure 12 shows a 12-mm adenoma in the cecum, a finding that was confirmed at optical colonoscopy. The VCT image in Figure 12c clearly

depicts the polyp submerged in the tagged fecal material and demonstrates the effectiveness of VCT in the differentiation of soft tissue from air-tagging mixtures at air-tagging boundaries. After the application of our dual-energy EC scheme, tagged fecal materials and air-tagging boundaries were removed, with no resulting artifacts. A 3D volume-rendered image was free of all major EC artifacts (Fig 12e).

Figure 13. Submerged 10-mm polyp in a 55-year-old man. (a, b) Transverse dual-energy CT colonographic images obtained at 80 kVp (a) and 140 kVp (b) depict the submerged polyp (arrow). (c) On a cleansed image of a and b obtained after dual-energy EC, the polyp (arrow) has been preserved. Note the uncleansed tagged regions within the small bowel. (d) Virtual colonoscopic image obtained before the application of dual-energy EC shows a thin tagging layer, small amounts of stool, and uneven air-tagging boundaries. (e) On a virtual colonoscopic image obtained after dual-energy EC, the tagged regions including air-tagging boundaries seen in d have been removed without any EC artifacts.

Figure 13 shows a submerged 10-mm polyp. The polyp was still clearly visualized after the application of dual-energy EC (Fig 13c). However, the uneven air-tagging boundaries, as well as the

thin tagging layer and a small amount of stool on the colonic wall, were accurately and precisely removed, with no EC artifacts (Fig 13e).

We compared our dual-energy EC scheme with two conventional single-energy EC packages (Fig 14). One was a commercial EC package,

Figure 14. Dual-energy EC versus two conventional single-energy EC packages. (**a, b**) Virtual colonoscopic images obtained after the application of a gradient-based commercial EC package show severe EC artifacts, including type 1 (broken folds and a shrunken polyp in **a**, shrunken folds in **b**), type 2b (false fistula in **a**), and type 2c (false patch at the air-tagging boundaries in **b**) artifacts. (**c, d**) On images obtained after structure-analysis cleansing, the polyp is well preserved and there are no EC artifacts in **c**, whereas in **d**, parts of the air-tagging boundary were not cleansed, causing a type 2a EC artifact (arrow). (**e, f**) Images obtained after dual-energy EC show a well-cleansed colon that is free of any EC artifacts. The polyp is well preserved in **e**.

Figure 15. Results of cleansing at an air-tagging boundary. **(a, b)** On 3D **(a)** and 2D **(b)** images obtained after the application of a gradient-based commercial EC package, the air-tagging boundary remains uncleansed because of the low magnitude of the gradient caused by the low tagging level in the tagged region (arrow in **b**). **(c, d)** Corresponding images obtained after structure-analysis cleansing show partial cleansing of the air-tagging boundary. However, the junctions between the air-tagging boundary and the colonic wall have not been cleansed (arrow in **d**), causing the typical type 2c EC artifact of a false patch. In addition, an air bubble was not cleansed, causing the artifact of a false polyp **(c)**. **(e, f)** Corresponding images obtained after dual-energy EC show accurate and precise cleansing of the entire air-tagging boundary. No visible artifact was observed on either 2D or 3D images.

and the other was the structure-analysis cleansing scheme that we had developed previously (21). Both conventional EC packages were applied to fused dual-energy CT colonographic images. Virtual colonoscopic images obtained after the application of the commercial EC package showed severe EC artifacts (Fig 14a, 14b). Images obtained after structure-analysis cleansing showed significant reduction of type 1 EC artifacts; however, a type 2a EC artifact was noted (Fig 14c, 14d). Images obtained after dual-energy EC were free of EC artifacts (Fig 14e, 14f).

These three EC packages were compared in detail in terms of their performance at an air-

tagging boundary (Fig 15). The commercial EC package, which is based on the gradient-based method, could not detect the air-tagging boundary because of the low magnitude of gradients caused by the lower tagging level in the tagged region (Fig 15a, 15b). The structure-analysis cleansing scheme removed only part of the air-tagging boundary and caused typical type 2c EC artifacts (Fig 15c, 15d). The entire air-tagging boundary was accurately and precisely removed with dual-energy EC, with no EC artifacts (Fig 15e, 15f).

Figure 16. Relationship between radiation dose and image noise at dual-energy CT of a phantom. (**a, b**) Transverse dual-energy CT colonographic images of the phantom obtained at 80 kVp (**a**) and 140 kVp (**b**). (**c**) Transverse single-energy CT colonographic image obtained at 120 kVp on the same dual-energy CT scanner (switching off one tube) with the same radiation dose (9.15 mGy). Other imaging parameters were the same as those used for **a** and **b**.

a.

b.

c.

Limitations of Dual-Energy CT Colonography

Computational Cost

One of the key challenges in 3D medical image processing, such as our dual-energy EC scheme, is that it requires high computational power and high data throughput. In addition to the complexity of the image processing, a large amount of data—including both low- and high-energy CT colonographic images, as well as intermediate images—need to be processed.

The computational cost of this dual-energy EC method is relatively high. It takes approximately 30 minutes to electronically cleanse a dual-energy CT colonographic study on a standard personal com-

puter. We are developing a high-performance computing platform (48) for conventional as well as dual-energy EC with optimization and parallelization of the EC code. Preliminary evaluation of the computing platform on an 8-core computer (Intel Xeon; Intel, Santa Clara, Calif) with a 3-GHz processor and 16 GByte of RAM showed that it can achieve an approximately 10-fold reduction in execution time for EC.

Radiation Dose

Dual-energy CT and dual-energy EC are promising technical advances in CT colonography. The major limitation of dual-energy CT colonography is that dual-energy CT scanning may increase the radiation dose without improving image quality, or reduce image quality at the same radiation dose. Thus, radiation dose is one of the major

Table 3
Mean and Standard Deviation of CT Attenuation Values at Bony Structures, Tagged Regions, and Abdominal Fat before and after the Application of an Anisotropic Diffusion Denoising Filter

Image Type	Bony Structures		Tagged Regions		Abdominal Fat	
	Mean	STD	Mean	STD	Mean	STD
Before Application of Filter						
140 kVp	784.60	67.82	580.11	63.74	-100.60	34.47
80 kVp	1334.61	130.47	1158.23	159.89	-119.95	46.30
Fused image (w = 0.7)*	949.65	75.03	753.60	83.52	-106.36	29.44
120 kVp	868.92	60.49	664.72	75.90	-101.07	28.61
After Application of Filter						
140 kVp	785.54	53.52	580.36	50.10	-100.57	14.54
80 kVp	1336.73	112.47	1157.65	143.79	-119.90	23.70
Fused image (w = 0.7)*	950.44	67.34	753.10	74.96	-106.90	15.26

Note.—All values are in Hounsfield units. STD = standard deviation.

*Default weighting factor for the fusing of dual-energy CT images.

concerns in the use of dual-energy CT colonography in clinical practice.

Figure 16 compares the quality of images obtained in a phantom study with dual-energy CT (tube voltages, 80 and 140 kVp) and single-energy CT (tube voltage, 120 kVp [switching off one tube]) on a dual-energy CT scanner (SOMATON Definition Flash, Siemens Healthcare). The total radiation dose, represented by the CT radiation dose index, was 9.15 mGy for both low- and high-energy scanning. By adjusting the tube current, single-energy CT was performed at the same radiation dose (Fig 16c). We measured the mean and standard deviation of attenuation values at the bony structures, tagged regions, and abdominal fat on both dual-energy and single-energy CT images and observed that the dual-energy images had higher noise levels (ie, lower image quality) than did the single-energy (120-kVp) images (Table 3).

Therefore, reduction of the radiation dose is a significant task in high-quality dual-energy CT. CT manufacturers have offered solutions based on hardware and projection data, such as optimizing the x-ray beam with use of tin filtration (49), applying automatic dose exposure control

(50), and using iterative reconstruction methods (51). Unfortunately, these methods are inaccessible to most clinical researchers. We propose an alternative solution that makes use of image-space denoising filters.

Traditional denoising filters remove image noise with smoothing techniques such as Gaussian smoothing and median smoothing, which tend to cause loss of image detail or image blurring. Advanced smoothing filters, including anisotropic diffusion (52), total variation minimization (53), and bilateral smoothing (54), are highly effective in removing image noise while preserving image detail. Figure 17 illustrates denoising of dual-energy CT colonographic images with a method based on an anisotropic diffusion filter (44). The measured mean and standard deviation of attenuation values on the filtered images are shown in the lower part of Table 3. A comparison of the two parts of Table 3 shows that a proper denoising filter can reduce image noise while preserving image details, thereby offering a means of reducing the radiation dose.

Figure 17. Noise reduction. (a–d) Transverse dual-energy CT colonographic images obtained at 80 kVp (a, b) and 140 kVp (c, d). The images in b and d represent detailed views of the area in the box in a and c, respectively. (e, f) Denoised images of b and d, respectively. An anisotropic diffusion filter reduced the noise while preserving image details. (g, h) Images show the difference in noise, defined as subtraction of the denoised image from the original image: (g = b – e, h = d – f).

Teaching Point

RadioGraphics

Conclusion

The material decomposition capability of dual-energy CT has the potential to significantly improve the quality of EC. The latest advances in dual-energy EC have demonstrated its effectiveness in substantially reducing the major cleansing artifacts and pitfalls on cleansed CT colonographic images compared with conventional single-energy EC methods. We have combined a set of advanced image processing techniques for dual-energy CT colonography to develop a dual-energy EC scheme. Preliminary evaluation has shown that this dual-energy EC scheme can effectively help differentiate soft tissues from air, tagged materials, and air-tagging mixtures, thereby providing artifact-free visualization of the colonic lumen at fecal-tagging CT colonography. Dual-energy CT colonography has limitations in terms of computational cost and the radiation dose, but we have also suggested possible solutions.

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Informatics in Radiology

Dual-Energy Electronic Cleansing for Fecal-Tagging CT Colonography

Wenli Cai, PhD • Se Hyung Kim, MD • June-Goo Lee, PhD • Hiroyuki Yoshida, PhD

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Fecal-tagging CT colonography performed on a dual-energy CT scanner promises to reduce cleansing artifacts seen with existing EC methods by allowing identification of partial-volume effects at the air-tagging boundary and inhomogeneous tagging of residual fecal materials, the major causes of EC artifacts.

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The fact that the DEI values of colonic luminal air on dual-energy CT colonographic images are substantially higher than those of either fat or soft tissue provides an effective means for differentiating air-tagging mixtures caused by the partial-volume effect from soft-tissue structures, thereby reducing the occurrence of type 2 cleansing artifacts.

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This technique, referred to as virtual colon tagging or VCT, is used to mark the entire colonic lumen on dual-energy CT colonographic images, including luminal air and tagged fecal materials, as well as the air-tagging mixture throughout the colon. VCT provides a means to differentiate soft tissue from the air-tagging mixture caused by the partial-volume effect for reducing the cleansing artifacts.

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This dual-energy EC scheme makes use of the DEI values instead of attenuation values to differentiate soft-tissue structures from luminal air, tagged fecal materials, and air-tagging mixtures. With this method, a Hessian filter is used to enhance the foldlike and polyplike structures submerged in the virtually tagged colon.

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The material decomposition capability of dual-energy CT has the potential to significantly improve the quality of EC. The latest advances in dual-energy EC have demonstrated its effectiveness in substantially reducing the major cleansing artifacts and pitfalls on cleansed CT colonographic images compared with conventional single-energy EC methods.