Improved Curvature Estimation for Computer-aided Detection of Colonic Polyps in CT Colonography

Hongbin Zhu, PhD, Yi Fan, PhD, Hongbing Lu, PhD, Zhengrong Liang, PhD

Rationale and Objectives: Current schemes for computer-aided detection (CAD) of colon polyps usually use kernel methods to perform curvature-based shape analysis. However, kernel methods may deliver spurious curvature estimations if the kernel contains two surfaces, because of the vanished gradient magnitudes. The aim of this study was to use the Knutsson mapping method to deal with the difficulty of providing better curvature estimations and to assess the impact of improved curvature estimation on the performance of CAD schemes.

Materials and Methods: The new method was compared to two widely used kernel methods in terms of the performance of two stages of CAD: initial detection and true-positive and false-positive classification. The evaluation was conducted on a database of 130 computed tomographic scans from 67 patients. In these patient scans, there were 104 clinically significant polyps and masses >5 mm.

Results: In the initial detection stage, the detection sensitivity of the three methods was comparable. In the classification stage, at a 90% sensitivity level on the basis of the input of this step, the new technique yielded 3.15 false-positive results per scan, demonstrating reductions in false-positive findings of 30.2% ($P < .01$) and 27.9% ($P < .01$) compared to the two kernel methods.

Conclusions: The new method can benefit CAD schemes with reduced false-positive rates, without sacrificing detection sensitivity.

Key Words: Colonic polyps; CT colonography; computer-aided detection; shape analysis; curvature; Knutsson mapping; kernel method.

According to recent statistics from the American Cancer Society (1), colorectal cancer is the third most common cause of both cancer deaths and new cancer cases in both men and women in the United States. Most colon cancers start from benign polyps, and the transformation from benignity to malignance often takes 5 to 10 years. Therefore, early detection and removal of colonic polyps prior to their malignant transformation can effectively decrease the incidence of colon cancer (2–4). Colon polyps are not commonly associated with any symptoms. Therefore, adequate time interval screening is recommended for people aged > 50 years by the American Cancer Society (1). As a new minimally invasive screening technique, computed tomographic colonography (CTC) or computed tomography–based virtual colonoscopy has shown several advantages over the traditional optical colonoscopy (5). To improve the performance of CTC in detecting polyps, computer-aided detection (CAD) has shown the potential to assist physicians in finding and analyzing polyps in the colon (6–11).

In most currently available CAD systems in CTC, principal curvatures, estimated through kernel methods (12,13), and principal curvature–related measures, such as mean curvatures, Gaussian curvatures, sphericity ratio, shape index, and curvedness, are widely used to characterize the shapes of colon polyps (7,8,14–21). However, when a kernel contains two surfaces (as happens for thin slab objects such as colonic folds and spherical objects such as polyps), spurious estimations of curvatures are frequently observed, indicating false high curvature (22). This is due to the discontinuity at thin structures, where the curvatures are discontinuous because of the diminished gradient magnitude. Fortunately, this discontinuity problem can be solved using Knutsson mapping (23), which maps a discontinuous orientation field into a continuous one. In this study, we adapted the Knutsson mapping technique to accurately estimate principal curvatures and explored the possible benefits of such improved curvature estimation for CAD performance in CTC. Evaluation of the new technique using both phantom experiments and patient studies demonstrated a noticeable reduction in the false-positive (FP) rate for CAD of colonic polyps compared to two current kernel methods.

Acad Radiol 2011; 18:1024–1034

From the Department of Radiology, HSC L4 Room 120, State University of New York, Stony Brook, NY 11794 (H.Z., Y.F., Z.L.); and the Department of Biomedical Engineering, Fourth Military Medical University, Xi'an, China (H.L.). Received December 11, 2010; accepted March 23, 2011. This work was partially supported by grants CA082402 and CA120917 from the National Cancer Institute (Bethesda, MD). Dr Lu is supported by the National Nature Science Foundation of China under grant 60772020. **Address correspondence to:** Z.L. e-mail: Jerome.Liang@sunysb.edu

doi:10.1016/j.acra.2011.03.012

MATERIALS AND METHODS

Methods

In this section, we outline three curvature estimation techniques: Knutsson mapping and two widely used kernel methods. The details of each technique can be found in the related references. The focus of this section is on the immunity property of Knutsson mapping to the discontinuity problem for CAD of colon polyps.

Kernel methods for estimation of principal curvatures. In differential geometry theory (24), for any point on a smooth surface, any nonsingular curve through that point on the surface will have its own tangent vector $\boldsymbol{T}$ lying in the tangent plane of the surface orthogonal to the normal vector. The curvature associated with $\boldsymbol{T}$ at that point is then defined as

$$k_T = \mathbf{k} \times \boldsymbol{N}, \tag{1}$$

where k is the curvature vector of the concerned curve at that point, and $\boldsymbol{N}$ is the unit normal at that point on the surface. Nonsingular curves that have the same tangent vector $\boldsymbol{T}$ will have the same curvature $k_{\boldsymbol{T}}$. Among all possible tangent vectors, the maximum and minimum values of $k_{\boldsymbol{T}}$ at that point are called the principal curvatures, k_1 and k_2, and the directions of the corresponding tangent vectors are called principal directions.

To compute the principal curvatures for implicit surfaces (eg, isosurfaces) embedded in a three-dimensional volume image, various kernel methods were developed (12,13). In the kernel method developed by Monga et al (12), denoted as KM_1 in the following text, equation 1 was rewritten as

$$k_T = -(\boldsymbol{T}^t \boldsymbol{\Omega}_{\mathrm{H}} \boldsymbol{T})/\|\boldsymbol{g}\|, \tag{2}$$

where $\boldsymbol{\Omega}_{\mathrm{H}}$ is the Hessian matrix of the volume image, and $\boldsymbol{g}$ is the gradient vector (the normal vector). The resulted principal curvatures and directions were expressed as functions of the first and second derivatives of the image. In the kernel method developed by Thirion and Gourdon (13), denoted as KM_2 in the following text, equation (1) was rewritten as

$$k_{1,2} = H \pm \sqrt{\Delta} \text{ with } \Delta = H^2 - K, \tag{3}$$

where $H = (k_1 + k_2)$ and $K = k_1 k_2$ are the mean and Gaussian curvatures. They can be computed using the following formulas:

$$\begin{aligned} H = \frac{1}{2\|g\|^3}\Big[& I_x^2\left(I_{yy} + I_{zz}\right) - 2I_yI_zI_{yz} + I_y^2(I_{xx} + I_{zz}) \\ & - 2I_xI_zI_{xz} + I_z^2\left(I_{xx} + I_{yy}\right) - 2I_xI_yI_{xy}, \end{aligned} \tag{4}$$

$$\begin{aligned} K = \frac{1}{\|g\|^4}\Big[& I_x^2\left(I_{yy}I_{zz} + I_{yz}^2\right) - 2I_yI_z\left(I_{xz}I_{xy} - I_{xx}I_{yz}\right) \\ & + I_y^2\left(I_{xx}I_{zz} + I_{xz}^2\right) - 2I_xI_z\left(I_{yz}I_{xy} - I_{yy}I_{xz}\right) \\ & + I_z^2\left(I_{xx}I_{yy} + I_{xy}^2\right) - 2I_xI_y\left(I_{xz}I_{yz} - I_{zz}I_{xy}\right). \end{aligned} \tag{5}$$

In equations 4 and 5, the notions associated with I with various subscripts indicate the corresponding partial derivatives of the image intensity I. Therefore, both methods, KM_1 and KM_2 (12,13), represent the principal curvatures as functions of the first and second spatial derivatives of the volume image.

Knutsson mapping. In the aforementioned kernel methods, the curvature is essentially evaluated as $I_{\boldsymbol{TT}}/\|\nabla I\|$, with $\boldsymbol{T}$ representing the associated principal direction, where $I_{\boldsymbol{TT}}$ indicates the second derivative of the image intensity along the principal direction. Therefore, severe overestimation occurs when the gradient magnitude $\|\nabla I\|$ approaches very small values or close to zero. Rieger et al (23) presented a method based on Knutsson mapping, KM_M, to solve the discontinuity problem. The basic idea is described below using the same terms and notations as above.

The curvature k in direction $\boldsymbol{T}$ can also be defined as the magnitude of the change of the surface normal $\boldsymbol{N}$:

$$k_T = \|\nabla_T \boldsymbol{N}\|. \tag{6}$$

The normal $\boldsymbol{N}$ and the two principal directions $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$ are aligned with the three eigenvectors $\boldsymbol{e}_1$, $\boldsymbol{e}_2$, and $\boldsymbol{e}_3$, with decreasing eigenvalues of the gradient structure tensor $\overline{G} = \overline{\mathbf{v}\mathbf{v}^t}$ with $\mathbf{v} = \nabla I$, where the overhead bar $\overline{(\bullet)}$ stands for smoothing in a local (Gaussian) neighborhood. Therefore, two scales are involved here: the scale σ_g for evaluating the gradient vector $\nabla I = I \times \nabla G(\sigma_g)$ with Gaussian derivatives $\nabla G(\sigma_g)$ of the Gauss kernel $G(\sigma_g)$ and the scale σ_T for the Gaussian weighted tensor smoothing $\overline{G} = \overline{\mathbf{v}\mathbf{v}^t} = (\mathbf{v}\mathbf{v}^t) \times G(\sigma_T)$. ∇_T is the operator of directional derivative along $\boldsymbol{T}$. Equation 6 essentially defines the principal curvatures by differentiating the normal with respect to the principal directions: $|k_{1,2}| = \|\nabla_{T_{1,2}}\boldsymbol{N}\|$. Therefore, the gradient magnitude does not serve as denominator, and the discontinuity problem of the gradient magnitude is then avoided in theory. However, the eigenvectors of $\overline{G}$ contain only orientation, without direction information (an orientation has two directions reverse to each other), which leaves room for ambiguity in representing directional vectors (eg, $\mathbf{e_1} = \pm\boldsymbol{N}$). The ambiguous representation leads to troublesome descriptions (ie, the so-called discontinuity issue in the orientation space) (25). Direct computation of the partial derivatives within the discontinuous orientation field will lead to spurious curvatures. To establish a continuous orientation representation, Knutsson (26) proposed that the following three properties or criteria had to be satisfied: (1) uniqueness: vectors $\pm\boldsymbol{e}$ of the original space should be mapped onto the same vector in the representation space; (2) polar separability: the norm of the mapped vector should be independent of the direction of the original vector; and (3) uniform stretch: the mapping should locally preserve the angle metric of the original space.

As discussed by Rieger and van Vliet (25), gradient structure tensor stands as a mapping itself satisfying the first two