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Correlations between fabric tensors computed on cone beam and micro computed tomography images

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ABSTRACT: Anisotropy measurements of 15 trabecular bone biopsies from the radius estimated by different fabric tensors on images acquired through cone beam computed tomography (CBCT) and micro computed tomography (micro-CT) are compared. The results show that the generalized mean intercept length (MIL) tensor performs better than the global gray-scale structure tensor (GST), especially when the von Mises-Fisher kernel is applied. Also, the generalized MIL tensor yields consistent results between the two scanners. These results suggest that this tensor is appropriate for images acquired in vivo through CBCT.

Keywords: Fabric tensors, CBCT, micro-CT, generalized MIL tensor, GST

1 INTRODUCTION

Fabric tensors aim at modelling through tensors both orientation and anisotropy of trabecular bone. Many methods have been proposed for computing fabric tensors from segmented images (cf. Moreno et al., 2013 for a complete review). However, due to large bias generated by partial volume effects, these methods are usually not applicable to images acquired in vivo, where the resolution of the images is in the range of the trabecular thickness. Recently, different methods have been proposed to deal with this problem. In general, these methods directly compute the fabric tensor on the gray-scale image, avoiding in that way the problematic segmentation step.

Different imaging modalities can be used to generate 3D images of trabecular bone in vivo, including different magnetic resonance imaging (MRI) protocols and computed tomography (CT) modalities. The main disadvantages of MRI are that it requires long acquisition times that can easily lead to motion-related artifacts and the obtained resolution with this technique is worse compared to the one obtained through CT in vivo (Griffith & Genant 2012). Regarding CT modalities, cone beam CT (CBCT) (Monje et al. 2013) and high-resolution peripheral quantitative CT (HR-pQCT) (Burghardt et al. 2011) are two promising CT techniques for in vivo imag-

ing. Although these techniques are not appropriate to all skeletal sites, their use is appealing since they can attain higher resolutions and lower doses than standard clinical CT scanners. CBCT has the extra advantages with respect to HR-pQCT that it is available in most hospitals in the western world, since it is used in clinical practice in dentistry wards, and, on top of that, the scanning time is shorter (30s vs. 3min), so it is less prone to motion artifacts than HR-pQCT.

From the clinical point of view, it seems more relevant to track changes in anisotropy than in the orientation of trabecular bone under treatment, since osteoporosis can have more effect on its anisotropy than on its orientation (Odgaard et al. 1997, Huiskes 2000). Thus, the aim of the present study is to compare anisotropy measurements from different fabric tensors computed on images acquired through cone beam computed tomography (CBCT) to the same tensors computed on images acquired through micro computed tomography (micro-CT).

Due to its flexibility, we have chosen in this study our previously proposed generalized mean intercept length (MIL) tensor (Moreno et al., 2012) with different kernels and the global gray-scale structure tensor (GST) (Tabor & Rokita, 2007).

2 MATERIAL AND METHODS

2.1 Material

The samples in this study consisted of 15 bone biopsies from the radius of human cadavers donated to medical research. The biopsies were approximately cubic with a side of 10 mm. Each cube included a portion of cortical bone on one side to facilitate orientation. The bone samples were placed in a test tube filled with water and the tube was placed in the centre of a paraffin cylinder, with a diameter of approximately 10 cm, representing soft tissue to simulate measurements in vivo. After imaging, a cube, approximately 8 mm in side, with only trabecular bone was digitally extracted from each dataset for analysis.

2.2 Image acquisition and reconstruction

The specimens were examined both through CBCT and micro-CT. The CBCT data were acquired with a 3D Accuitomo FPD 80 (J.Morita Mfg. Corp., Kyoto, Japan) with a current of 8mA and a tube voltage of 85kV. The obtained resolution was 80 microns isotropic. The micro-CT data were acquired with a μ CT 40 (SCANCO Medical AG, Bassersdorf, Switzerland) with a tube voltage of 70 kVp. The voxels have an isotropic resolution of 20 microns.

2.3 Methods

The tensors were computed through the generalized MIL tensor and the GST. The generalized MIL tensor has two advantages: first, it can directly be used for gray-scale images, and second, different kernels can be used in order to improve the results. Basically, the tensor is computed in three steps. The mirrored extended Gaussian image (EGI) (Horn 1986) is computed from a robust estimation of the gradient. Second, the EGI is convolved with a kernel in order to obtain an orientation distribution function (ODF). Finally, a second-order fabric tensor is computed from the ODF.

More formally, the generalized MIL tensor is computed as:

$$\text{MIL} = \int_{\Omega} \frac{v v^T}{C(v)^2} d\Omega,$$

where v are vectors on the unitary sphere Ω , and C is given by:

$$C = H * E,$$

that is, the angular convolution (“*”) of a kernel H with the mirrored EGI E .

In this study, the half-cosine (HC) and von Mises-Fisher (vMF) kernels have been applied to the imag-

es. The HC has been selected since it makes equivalent the generalized and the original MIL tensor. The HC is given by:

$$H(\varphi) = \begin{cases} \cos \varphi & , \text{if } \varphi \leq \pi/2 \\ 0 & , \text{otherwise,} \end{cases}$$

with φ being the polar angle in spherical coordinates.

Moreover, the vMF kernel, which is given by:

$$H(\varphi) = \frac{\kappa}{4\pi \sinh \kappa} e^{\kappa \cos \varphi},$$

has been selected since it has a parameter κ that can be used to control its smoothing action. In particular, the smoothing effect is reduced as the values of κ are increased (Moreno et al., 2012).

On the other hand, the GST computes the fabric tensor by adding up the outer product of the local gradients with themselves (Tabor & Rokita, 2007), that is:

$$\text{GST} = \int_{p \in I} \nabla I_p \nabla I_p^T dI,$$

where I is the image.

3 RESULTS

The following three values have been computed for each tensor: $E1' = E1/(E1+E2+E3)$, $E2' = E2/E1$ and $E3' = E3/E1$ where $E1$, $E2$ and $E3$ are the largest, intermediate and smallest eigenvalues of the tensor. These three values have been selected since they are directly related to the shape of the tensor.

Table 1 shows the mean and standard deviation of the differences between CBCT and micro-CT for these three values for the tested methods. As a general trend, the tested methods tend to overestimate $E1'$ and underestimate $E2'$ and $E3'$ in CBCT. As shown, the best performance is obtained by vMF with $\kappa=1$. It is also worthwhile to notice that the standard deviation increases with narrower kernels, such as vMF with $\kappa=10$ and GST. This means that using broader kernels have a positive effect in the estimation of fabric tensors, since the differences between micro-CT and CBCT are reduced.

Table 1. Mean (SD) of the differences of $E1'$, $E2'$ and $E3'$ for fabric tensors computed on CBCT and micro-CT. HC and vMF refer to the generalized MIL tensor, with the HC, and vMF kernels respectively. Parameter κ for vMF is shown in parenthesis. Positive and negative values mean over- and under estimations of CBCT with respect to micro-CT. All values have been scaled by 100.

Tensor	E1'	E2'	E3'
HC	2.25 (0.84)	-5.58 (2.98)	-6.11 (2.19)
vMF(1)	0.42 (0.15)	-1.59 (0.89)	-1.84 (0.73)
vMF(5)	4.51 (1.82)	-9.55 (4.49)	-8.48 (3.09)
vMF(10)	5.11 (2.13)	-8.96 (4.43)	-6.64 (2.70)
GST	0.90 (2.09)	2.24 (7.41)	-6.31 (4.40)

Table 2 shows the correlations between the measurements obtained on CBCT and micro-CT. Also, Figure 1 shows the corresponding correlation plots for $E1'$, $E2'$ and $E3'$ for HC, vMF (with $\kappa = 10$) and GST. It can be seen that the best correlations are yielded by vMF with different values of κ , and GST has a poor performance.

Table 2. Correlations between CBCT and micro-CT of $E1'$, $E2'$ and $E3'$ of different fabric tensors. HC and vMF refer to the generalized MIL tensor, with the HC, and vMF kernels respectively. Parameter κ for vMF is shown in parenthesis. 95% confidence intervals are shown in parentheses.

Tensor	$E1'$	$E2'$	$E3'$
HC	0.90 (0.73;0.97)	0.91 (0.76;0.97)	0.67 (0.23;0.88)
vMF(1)	0.90 (0.72;0.97)	0.90 (0.73;0.97)	0.70 (0.29;0.89)
vMF(5)	0.91 (0.75;0.97)	0.91 (0.75;0.97)	0.80 (0.48;0.93)
vMF(10)	0.92 (0.76;0.97)	0.90 (0.72;0.97)	0.84 (0.57;0.94)
GST	0.51 (0.00;0.81)	0.71 (0.33;0.90)	0.51 (0.00;0.81)

Figure 2 shows correlation plots of the three eigenvalues normalized by the sum of them for the same three methods. As shown in this figure, the tensors yielded by the three methods have different shapes. First, vMF with $\kappa = 10$ generates the most anisotropic tensors with larger differences between $E1$ and $E2$ than HC and GST. Second, HC generate the most isotropic tensors with smaller differences between values of $E1$, $E2$ and $E3$ than the other tensors. Finally, unlike GST, both HC and vMF generate tensors that are close to be orthotropic, that is, $E2 \approx E3$. This is in line with the common assumption of orthotropy for trabecular bone (Zysset et al. 1998).

Figure 3-5 show Bland-Altman plots for the generalized MIL tensor with the HC and vMF (with $\kappa=10$) kernels and the GST. As seen in these figures, GST yields wider limits of agreement, i.e., larger discrepancies between CBCT and micro-CT, than HC and vMF, in particular for $E2'$ and $E3'$.

One of the advantages of using the vMF kernel is that its parameter can be adjusted in order to improve the correlations between CBCT and micro-CT. Figure 6 shows the evolution of the correlations between CBCT and micro-CT with the parameter κ of the generalized MIL tensor with the vMF kernel.

From this figure, $E1'$ and $E2'$ attain their maxima at $\kappa = 10$, $\kappa = 5$ respectively, while $E3'$ asymptotically approaches a correlation of 0.875 when $\kappa \rightarrow \infty$. Since the three measurements determine the shape of the tensor, we suggest to choose the value of κ that maximizes the three correlations, that is, that maximizes $(E1' + E2' + E3')/3$. In our case, such a value is

Figure 1. Correlation plots for $E1'$ (top), $E2'$ (middle) and $E3'$ (bottom) between CBCT and micro-CT for HC, vMF ($\kappa=10$) and GST.

Figure 2. Correlation plots for HC (top), vMF vMF ($\kappa=10$) (middle) and GST (bottom) between CBCT and micro-CT for the three eigenvalues normalized by the sum of them.

Figure 3. Bland-Altman plots for E1' (top), E2' (middle) and E3' (bottom) between CBCT and micro-CT for HC. The vertical and horizontal axes show the measurements on micro-CT minus those computed on CBCT, and the mean between them respectively. The mean difference and the mean difference ± 1.96 SD are included as a reference in dotted lines.

$\kappa = 10$, as is also shown in Figure 6.

4 DISCUSSION

This paper compares the anisotropy of different fabric tensors estimated on images acquired through CBCT and micro-CT of 15 trabecular bone biopsies from the radius.

The results presented in the previous section show strong correlations between micro-CT and CBCT for the generalized MIL tensor with HC and vMF kernels, especially with $\kappa = 10$. In addition, good agreements between measurements in CBCT and the reference micro-CT have been shown through Bland-Altman plots for HC, vMF with $\kappa = 10$ and GST.

An interesting result is that the GST yields clearly lower correlation values than the generalized MIL tensor using either HC or vMF kernels. We have shown that the GST can be seen as a variant of the generalized MIL tensor where the impulse kernel is

Figure 4. Bland-Altman plots for $E1'$ (top), $E2'$ (middle) and $E3'$ (bottom) between CBCT and micro-CT for vMF with $\kappa=10$. The vertical and horizontal axes show the measurements on micro-CT minus those computed on CBCT, and the mean between them respectively. The mean difference and the mean difference $\pm 1.96SD$ are included as a reference in dotted lines.

applied instead of the HC (Moreno et al., 2012). In this line, the results from the previous section suggest that the use of broader smoothing kernels such as HC or vMF has a positive effect for increasing the correlation of the tensors computed on images acquired through suitable scanners for in vivo with the ones that can be computed from images acquired in vitro. Although the three tested methods yield tensors that share their eigenvectors, their eigenvalues are different, as shown in Figure 2, which is a natural consequence of using different smoothing kernels. Moreover, the high correlations reported for HC and vMF make it possible the removal of the systematic errors reported in Table 1 and the Bland-Altman plots for these two types of fabric tensors.

Another interesting observation is that vMF yielded better results than the standard HC. This means that κ can be used to tune the smoothing in such a way that the results are correlated with in vitro measurements. For the imaged specimens, a value of $\kappa = 10$ yielded the best correlation results.

Figure 5. Bland-Altman plots for $E1'$ (top), $E2'$ (middle) and $E3'$ (bottom) between CBCT and micro-CT for GST. The vertical and horizontal axes show the measurements on micro-CT minus those computed on CBCT, and the mean between them respectively. The mean difference and the mean difference $\pm 1.96SD$ are included as a reference in dotted lines.

Figure 6. Evolution of the correlations between CBCT and micro-CT with the parameter κ of the generalized MIL tensor with the vMF kernel.

The results presented in this paper suggest that advanced fabric tensors are suitable for in vivo imaging, which opens the door to their use in clinical

practice. In particular, the results show that the generalized MIL tensor is the most promising option for in vivo. As shown in this paper, this method is advantageous since it has the possibility to improve its performance by changing the smoothing kernel by a more appropriate one, as it was shown in this paper for the vMF kernel.

Ongoing research includes performing comparisons in different skeletal sites, different degrees of osteoporosis and comparing the results with images acquired through HR-pQCT.

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