Published in final edited form as:

Acad Radiol. 2008 February ; 15(2): 176–185. doi:10.1016/j.acra.2007.08.009.

Radiographic Texture Analysis in the Characterization of Trabecular Patterns in Periprosthetic Osteolysis

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Abstract

Rationale and Objectives—Periprosthetic osteolysis is a disease attributed to the body's reaction to fine polyethylene wear debris shed from total hip replacements. The purpose of this preliminary study was to investigate the ability of radiographic texture analysis (RTA) to characterize the trabecular texture patterns on pelvic images for osteolysis and normal total hip arthroplasty (THA) cases.

Materials and Methods—Fourier-based and fractal-based texture features were calculated for a database of digitized radiographs from 202 THA cases, 70 of which developed osteolysis. The features were calculated from ROIs selected at two time points: less than one month after surgery, and at the first clinical indication of osteolysis (or randomly selected follow-up time for normal cases.) Receiver operating characteristic (ROC) analysis was used to compare feature performance at baseline and follow-up for osteolysis and normal cases.

Results—Separation between the RTA features for osteolysis and normal cases was negligible at baseline and increased substantially for the follow-up images. The directional Fourier-based feature provided the best separation with an A_z value from ROC analysis of 0.75 for the follow-up images, in the task of distinguishing between normal and osteolytic cases.

Conclusion—The results from this preliminary analysis indicate that qualitative changes in trabecular patterns from immediately after surgery to the eventual detection of osteolysis correspond to quantitative changes in RTA features. It therefore appears that RTA provides information that could potentially be useful to aid in the detection of this disease.

Keywords

Texture analysis; orthopaedics; radiography

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Introduction

Periprosthetic osteolysis is a common long-term complication in total hip replacement surgeries. It is a man-made disease attributed to the body's reaction to fine polyethylene wear debris shed by the artificial hip articulation (1-6). The process begins when macrophages ingest submicron polyethylene debris particles, leading to the stimulation of osteoclasts and resorption of adjacent bone (2). The disease strongly contributes to weakening of the surrounding bone and disappearance of its trabecular pattern. This continual destruction of bone and consequent bone weakening can eventually lead to severe fractures and bone destruction, often necessitating complex revision surgeries.

The biologic process causing osteolysis is initially asymptomatic, with major bone destruction often occurring in the early stages, prior to any loosening of the components of the replacement (4). As a result, the disease is typically diagnosed when a region of localized trabecular bone loss is visible radiographically (3). However, osteolytic lesions tend to evolve in a slow process and radiographic evidence is not usually visually apparent on earlier postoperative radiographs (Fig 1). Moreover, trabecular texture patterns are difficult for even experts to quantify radiographically. The disease, therefore, commonly goes unnoticed until severe bone loss and loosening of the hip replacement or fracture has occurred, making surgical reconstruction difficult and clinical outcomes poor.

The authors propose to investigate the application of radiographic texture analysis (RTA) as a possible aid in the detection of periprosthetic osteolysis. Texture analysis has been previously investigated by several researchers using a range of imaging modalities (7-21). RTA has previously been studied in the authors' lab as a method to quantify trabecular bone patterns for the assessment of osteoporosis (22-28). Caligiuri et al. characterized the trabecular structure of lateral lumbar spine radiographs using Fourier-based features (22), and fractal dimension based on the box-counting technique (23). They found that RTA yielded improved performance over BMD in the task of distinguishing between patients with and without fractures at other sites in the body. Chinander et al. applied RTA to femoral neck specimens using Fourier-based features and fractal-based features to characterize bone strength (24,25). Their results showed that RTA may be a practical method to assess bone strength over a range of typical clinical exposure conditions. Jiang et al. characterized the structure of femoral neck specimens using the fractal dimension based on the Minkowski method and found an improvement in predicting bone mechanical properties when combining this feature with BMD over BMD alone (26). Wilkie et al. showed the portability of RTA for assessing osteoporosis across imaging modalities, i.e. computed radiography and bone densitometer (27).

RTA may also be well-suited to the assessment of osteolysis, since the disease tends to cause changes in the trabecular patterns of bone surrounding the hip implant. Moreover, follow-up pelvic radiographs of THA patients are typically acquired as part of routine clinic visits. In order to assess the potential of RTA as a possible aid in the detection of osteolysis, it is first necessary to investigate whether RTA differences exist between clinically detected osteolysis cases and normal THA cases. In this preliminary study, RTA features calculated from baseline images taken shortly after surgery are compared to those calculated from later follow-up images. These feature values are assessed in order to determine whether changes in the trabecular patterns between baseline and follow-up images caused by osteolysis result in quantitative changes in RTA features.

Materials and Methods

Database

The database consisted of two hundred and two total hip replacement cases, from the Anderson Orthopaedic Research Institute (AORI) in Alexandria, VA. The cases were obtained under an IRB approved protocol. Each case included a series of digitized 14" × 17" screen-film images of the anterior-posterior pelvis. The images were acquired with either a single emulsion Fuji film and HR regular cassette, or a single emulsion Kodak film with a Kodak MA cassette. They were digitized using a Vidar Diagnostic Pro digitizer, at a resolution of 300 dots per inch (dpi) at twelve bits/pixel. The patient clinical files were also available for all 202 cases. Cases were considered to be positive for osteolysis if the disease was indicated at some point in the clinical chart. When there was no indication of the disease in the chart, the case was considered to be negative for osteolysis. Summary data for the osteolysis and normal THA patient populations are listed in Table 1.

ROI Selection

For all cases, two images were used for RTA: the baseline image and a follow-up image. For the osteolysis cases, the follow-up image corresponded to the radiograph on which the actual clinical detection of the disease (from the patient files) was first noted. A single 128 pixel by 128 pixel region of interest (ROI) was selected within the clinically indicated osteolytic region in this follow-up image. The distribution of follow-up times for the osteolysis cases was determined from the clinical detection times. For the normal cases, follow-up times were randomly assigned based on available images, in order to create a follow-up distribution that closely matched that of the osteolysis cases. A single 128 pixel by 128 pixel ROI was placed within a region typically associated with osteolysis on each of these normal follow-up images. For all cases, baseline ROIs were selected by visually matching the region to the follow-up ROI. The chosen ROIs were then used for the computerized texture feature calculation.

Feature Calculation

Features based on the Fourier transform and the fractal dimension were used for this analysis (22,24-27). To characterize the frequency content of the trabecular texture, the first moment of the power spectrum (FMP) was calculated according to equation 1, as done previously in our osteoporosis studies (24,25,27):

$$\text{FMP} = \frac{\sum_m \sum_n \sqrt{m^2 + n^2} |F_{m,n}|^2}{\sum_m \sum_n |F_{m,n}|^2}. \quad (1)$$

Here, $F_{m,n}$ represents the two-dimensional Fourier transform of the ROI at horizontal and vertical positions m and n , respectively. To take the structural texture orientation into account, the power spectrum was also divided into 24 angular sectors at 15 degree intervals. The FMP was calculated for each sector as shown in equation 2:

$$\text{EMP}_\theta (\theta_i \leq \theta < \theta_{i+1}) = \frac{\sum_m \sum_n \sqrt{m^2 + n^2} |F_{m,n}|^2}{\sum_m \sum_n |F_{m,n}|^2} \quad \text{for } \theta_i \leq \arctan\left(\frac{n}{m}\right) < \theta_{i+1}, \quad (2)$$

where θ_i was incremented in 15° intervals. The minimum of the angular FMP values (Min. FMP(θ)) was taken as the minimum of these twenty-four angular FMP values.

To calculate the fractal dimension of the ROIs, the Minkowski method was employed (26). The global Minkowski dimension ($MINK_g$) is based on “volume” differences between two processed versions of an ROI using morphological operators. This “volume” difference, $V_g(r)$ was calculated by (26):

$$V_g(r) = \sum_{i=1}^N \sum_{j=1}^N \{(f \oplus rg) - (f \otimes rg)\}, \quad (3)$$

where N is the ROI size, and $(f \oplus rg)$ and $(f \otimes rg)$ are the respective dilated and eroded versions of the ROI f , obtained with a 3×3 pixel square structuring element g , at a scale r . The slope of the logarithmic plot of $V_g(r)/r^3$ versus $1/r$ was then used to calculate the fractal dimension:

$$MINK_g = \lim_{r \rightarrow 0} \frac{\log [V_g(r) / r^3]}{\log [1/r]}. \quad (4)$$

Data Analysis

Receiver operating characteristic (ROC) analysis (29) was used to evaluate the performance of the texture features in distinguishing between osteolysis and normal cases at each time point. Two ROC curves were calculated for each feature: one from analysis of the baseline images, and one from analysis of the follow-up images. For both conditions, the input to the ROC analysis was the calculated texture values. The ROCKIT package (30) was used to compare A_z values from ROC curves for the two time points for each of the four texture features. The ROCKIT package measures the correlation between the two ROC curves, and calculates a p -value for the likelihood that the measured differences in A_z values are due to chance alone. This value can therefore be useful in determining whether the observed differences in ROC curves are statistically significant.

Results

A comparison of baseline and follow-up images for an osteolysis case and a normal case is shown in Fig 2. For the osteolysis case, the change in texture between the baseline image (Fig 2a) and the image at time of clinical detection of the disease (Fig 2b) is visually apparent. In Fig 2b, there is a demarcated zone in which osteolysis is present, and this region lacks a visible texture pattern. The texture feature values are displayed below each image. The Fourier-based features measure the spatial frequency content of the texture within the ROI. Larger values for FMP and Min. FMP(θ) indicate a higher average frequency content in the ROI. The fractal-based feature, $MINK_g$, measures the overall roughness of image texture in an ROI (26).

For the osteolysis case, in Fig 2, the three features are lower for the follow-up image (Fig 2b) than the baseline image (Fig 2a), which is consistent with the radiolucent appearance of this zone in the later image. For the normal case, the texture pattern in the follow-up image (Fig 2d) is evident, and appears to be even stronger than the pattern in the baseline image (Fig 2c). This is also indicated by the change in texture feature values, which shift in the direction of stronger texture, perhaps due to the patient's increased activity and contact stress (see discussion section). It is interesting to note that the actual feature values for the follow-up images in these two cases are similar, indicating that temporal RTA to elucidate changes over time may be beneficial in detection of the disease (see discussion section).

Non-directional RTA Features

Feature plots from the two non-directional texture features are shown in Fig 3. In this figure, the relationship between global Minkowski dimension ($MINK_g$) and the first moment of the power spectrum (FMP) is shown for osteolysis and normal cases. Fig 3a demonstrates the initial separation between osteolysis and normal cases, from the baseline images. It is evident that this separation is small as expected, because the disease has not yet begun to develop. This is further indicated by the A_z values from the ROC analysis as shown in Table 2. In Fig 3b, it is apparent that there is an increase in feature separation between osteolysis and normal cases for the follow-up images, and this is reflected by the increase in A_z values. The A_z values increase to 0.69 for FMP and 0.67 for $MINK_g$ and these differences from baseline are both statistically significant at the α 0.05 level (Table 2).

The average feature values were examined for the osteolysis cases and the normal cases for the two image sets (baseline and follow-up). These values are given in Table 3. Although there is clearly overlap among the features at both time points, the general trend of increasing separation at the follow-up time period can be seen from the average values in the table. For the FMP feature, the average values for osteolysis cases and normal cases are 0.71 cycles/mm and 0.70 cycles/mm, respectively, for the baseline images. A Student's *t*-test performed on these two groups of data produces a *p*-value of 0.75, again indicating that there is no clear distinction between the groups at this point. However, the averages change to 0.66 cycles/mm and 0.77 cycles/mm for the two respective groups at the follow-up times, with a statistically significant *p*-value of < 0.001 for this difference. For $MINK_g$, the average values at baseline are 2.349 for osteolysis cases and 2.361 for normal cases. The *p*-value from a Student's *t*-test for these values is 0.11. The averages shift to 2.327 and 2.360, respectively, for the osteolysis and normal cases at the follow-up time points. The *p*-value attains statistical significance at the $\alpha=0.05$ level for the follow-up images, with a value of < 0.001 .

Directional RTA feature

The distribution of the directional feature, the angular minimum of the first moment of the power spectrum (Min. FMP(θ)), is shown in Fig 4. In this figure, Min. FMP(θ) is plotted versus FMP for comparison purposes. These features are clearly correlated, but the distribution of Min. FMP(θ) is evident in the figure. The separation between osteolysis and normal cases for Min. FMP(θ) is small with an A_z value of only 0.54 for the baseline images (Fig 4a). However, the shift in values for the follow-up images leads to a larger separation for this feature as seen in Fig 4b. The A_z value for this feature calculated on images at the time of diagnosis is 0.75. The difference in A_z values between the follow-up and baseline images is statistically significant at the $\alpha=0.05$ level for the Min. FMP(θ). ROC curves for the directional feature values from baseline and follow-up images are shown in Fig 5. This figure also demonstrates the improved performance of Min. FMP(θ) at the follow-up times as compared to baseline.

The average values demonstrate that feature separation for the follow-up images compared to the baseline images greatly increases for Min. FMP(θ). Average values for this feature are 0.41 for the osteolysis cases and 0.42 for the normal cases at baseline as listed in Table 3. A Student's *t*-test shows no distinction between these groups with a *p*-value of 0.70. For the follow-up images, however, the average values are 0.35 and 0.48 for the osteolysis and normal cases, respectively (Table 3). The difference in these averages is highly significant, with a *p*-value of < 0.001 .

Discussion

The results of this study indicate that differences in radiographic texture analysis (RTA) exist between osteolysis cases and normal cases for THA patients at the time corresponding to

clinical detection of osteolysis. These differences do not exist in baseline post-operative images, when the disease has not had time to begin to develop. This indicates that qualitative changes in trabecular patterns from immediately after surgery to the eventual detection of periprosthetic osteolysis correspond to quantitative changes in RTA features. The RTA features also appear to have the ability to distinguish between osteolysis and normal cases for the follow-up detection time. The features examined in the study attained A_z values from ROC analysis of 0.67 to 0.75 for this task. For the three features investigated, there was an increase in separation from the baseline post-operative images to the follow-up images, and these differences were statistically significant at the $\alpha = 0.05$ level. The results of the study suggest that RTA may have the potential to be a useful aid in the detection of osteolysis.

It is evident from the results of this study that the feature with the greatest ability to separate osteolysis and normal cases at the time of diagnosis is the directional feature, Min. FMP(θ). The performance of this feature was significantly greater than either of the other features for this task as measured by the ROCKIT software package (30). This result was not unexpected for two reasons. First of all, trabecular texture patterns tend to have a directional orientation, and this is more strongly captured by directional features such as Min. FMP(θ). Secondly, there is some variability in patient positioning since the baseline and follow-up images analyzed in this study were taken several years apart. Although care is taken to visually match the ROIs for a given case, because of slight differences in positioning, this can be difficult. Min. FMP(θ) appears to be better able to account for slight angular differences in ROI orientation, and thus it yields improved performance as compared to the non-directional features.

Although the main purpose of this research was to determine the ability of RTA to distinguish between osteolysis and normal cases, regardless of feature values, the change in feature values over the time periods is also worth noting. The behavior of the feature values for the normal group tended to be opposite of that for the osteolysis group (Table 4). In fact, the two Fourier-based features decreased substantially between baseline and follow-up images for the osteolysis group, while they increased substantially between these images for the normal group (Table 4). This suggests that in reconstructed cases without osteolysis, normalization of hip stresses and utilization results in improved bone quality/texture, while in the osteolytic cases, a decrease in bone quality/texture is observed. The most likely explanation for improved texture measures in the normal cohort is that patients with arthritic hips have decreased contact stress and utilization secondary to osteophyte formation and pain related immobility. Successful surgeries allow the patients to gradually resume regular activities and increase contact stress to normal levels, leading to a buildup of the trabecular texture pattern on radiographs, and consequently increased values of FMP and Min. FMP(θ). For patients who develop osteolysis, this effect would be overridden by the deterioration of the trabecular pattern caused by the disease. However, it is not clear why values of $MINK_g$ would not also increase over time for normal cases, but separation between osteolysis and normal cases for this feature occurs because of the decrease in values for osteolysis cases.

The images used in this study were acquired as part of routine patient clinical follow-up. This means that there were no set guidelines for imaging technique, outside of the normal guidelines used by technologists. The advantage of using these clinical images is that the results may more directly apply to the clinical situation, and suggest that RTA may be easily implemented. Moreover, the images were not acquired specifically to be used for texture analysis, but for visual analysis of implant stability and wear. It is encouraging that RTA differences between osteolysis and normal cases were observed under these conditions. However, using clinical images also means that exposure techniques are not known and may vary among technologists and with time. This variation may affect RTA performance, and may obscure the differences caused by trabecular texture buildup and deterioration.

Because of the potential competing effects of trabecular texture buildup caused by increased activity, and deterioration due to osteolysis, it may be important to monitor RTA features at multiple time points. Moreover, since the images examined in this study only corresponded to baseline and clinical detection times, they were unable to provide information related to early detection of the disease. The authors believe that in order for RTA to achieve its full potential as an aid in the detection of periprosthetic osteolysis, it will be necessary to develop methods to assess the changes in RTA over the time leading up to clinical detection of the disease (i.e. prior to the follow-up images used for osteolysis cases in this study). This temporal radiographic texture analysis (tRTA) could indicate whether it is possible to detect the development of the disease before it is visible radiographically. Any earlier detection of osteolysis could potentially reduce patient complications and improve the overall performance of long-term hip replacements. As a result, tRTA features are currently being developed and the authors plan to evaluate them on a patient database in the future.

In conclusion, this preliminary study indicates that qualitative changes in the trabecular patterns of osteolysis and normal THA cases correspond to quantitative texture changes measured by RTA. This suggests that RTA has the ability to characterize trabecular patterns in periprosthetic osteolysis, and may provide useful information to potentially aid in the detection of this disease.

Acknowledgments

The authors would like to thank Lorenzo Pesce, Ph.D., for his assistance with statistical analysis, and for helping with the ROCKIT package (30). This research was supported in part by USPHS grant AR42739. M. L. Giger is a shareholder in R2 Technology, Inc. (Sunnyvale, CA). It is the University of Chicago Conflict of Interest Policy that investigators disclose publicly actual or potential significant financial interests that would reasonably appear to be directly and significantly affected by the research activities.

This research was supported in part by USPHS grant AR42739.

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Figure 1. Radiographic example of osteolysis. The baseline image (a) and the four year follow-up image (b) show no signs of the disease. The fourteen year follow-up image (c) contains a large region of osteolysis indicated by the arrows.

Figure 2. Sample image comparison and ROI selection for an osteolysis case at (a) baseline and (b) follow-up, and a normal case at (c) baseline and (d) follow-up. The corresponding three texture feature values are indicated below each image.

(a)

(b)

Figure 3.
Relationship between First Moment of the Power Spectrum (FMP) and Global Minkowski Dimension ($MINK_g$) for ROIs from (a) baseline and (b) follow-up images.

(a)

(b)

Figure 4. Relationship between First Moment of the Power Spectrum (FMP) and angular minimum of the FMP (i.e., Min. FMP(θ)) ROIs from (a) baseline and (b) follow-up images.

Figure 5. Receiver Operating Characteristic (ROC) curves for the angular minimum of the FMP (i.e., Min. FMP(θ)). The A_z value for the ROC curve from the follow-up ROIs (dashed line) is 0.75 while the A_z value for the curve from the baseline ROIs (solid line) is 0.54. The difference in A_z is statistically significant with a *p-value* of < 0.001.

Table 1

Database summary for the osteolysis (N=70 cases) and normal (N=132 cases) total hip arthroplasty (THA) populations.

	Patient Age at Surgery (Years)		Follow-up Time (Years)	
	Osteolysis	Normal	Osteolysis	Normal
Mean	49.3	57.7	10.3	10.3
Range	[23, 78]	[26, 83]	[2, 17]	[2, 17]

Table 2

Results from ROC analysis of the three features for baseline and follow-up images in the task of distinguishing between normal and osteolysis cases. The 95% confidence intervals for the difference in A_z values between follow-up and baseline are also listed, along with the *p-values* for this difference.

	Baseline A_z	Follow-up A_z	ΔA_z	<i>p-value</i>
FMP	0.52	0.69	[0.08, 0.27]	< 0.001
Min. FMP(θ)	0.54	0.75	[0.13, 0.30]	< 0.001
MINK _g	0.59	0.67	[0, 0.17]	0.05

Table 3

Average feature values for the three features from (a) baseline and (b) follow-up images. Student's *t*-tests were performed to determine the significance of the feature differences between osteolysis and normal cases. Corresponding *p*-values are also shown.

Baseline	Osteolysis Average [95% C.I.]	Normal Average [95% C.I.]	<i>p</i> -value
FMP (cycles/mm)	0.71 [0.66, 0.75]	0.70 [0.67, 0.72]	0.75
Min. FMP(θ) (cycles/mm)	0.41 [0.38, 0.45]	0.42 [0.40, 0.45]	0.70
MINK _g	2.349 [2.335, 2.363]	2.361 [2.354, 2.369]	0.11
(a)			
Follow-up	Osteolysis Average [95% C.I.]	Normal Average [95% C.I.]	<i>p</i> -value
FMP (cycles/mm)	0.66 [0.63, 0.69]	0.77 [0.74, 0.80]	< 0.001
Min. FMP(θ) (cycles/mm)	0.35 [0.32, 0.38]	0.48 [0.45, 0.51]	< 0.001
MINK _g	2.327 [2.316, 2.339]	2.360 [2.351, 2.368]	< 0.001
(b)			

Table 4

Average values and 95% confidence intervals for the three features from baseline images and follow-up images for (a) osteolysis and (b) normal cases. Paired Student's *t*-tests were performed to determine the significance of the feature differences between baseline and follow-up images and the resulting *p-values* are shown in the table.

Osteolysis	Baseline Average [95% C.I.]	Follow-up Average [95% C.I.]	<i>p-value</i>
FMP (cycles/mm)	0.71 [0.66, 0.75]	0.66 [0.63, 0.69]	0.08
Min. FMP(θ) (cycles/mm)	0.41 [0.38, 0.45]	0.35 [0.32, 0.38]	0.003
MINK _g	2.349 [2.335, 2.363]	2.327 [2.316, 2.339]	0.002
(a)			
Normal	Baseline Average [95% C.I.]	Follow-up Average [95% C.I.]	<i>p-value</i>
FMP (cycles/mm)	0.70 [0.67, 0.72]	0.77 [0.74, 0.80]	< 0.001
Min. FMP(θ) (cycles/mm)	0.42 [0.40, 0.45]	0.48 [0.45, 0.51]	< 0.001
MINK _g	2.361 [2.354, 2.369]	2.360 [2.351, 2.368]	0.61
(b)			