Periprosthetic bone remodelling measurements in vivo

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Introduction
It is commonly recognized that bone reacts to the implantation of a femoral stem in total hip arthroplasty (THA). This reaction is typically seen as a periprosthetic bone density reduction (Engh et al. 1987). As a consequence, numerous attempts were conducted to simulate and to predict adaptive bone remodelling in computer models which combine bone remodelling theories with finite element analysis (Cowin 1993, Carter et al. 1987, Hart et al. 1984, Huiskes et al. 1987, 1992, Huiskes 1995). These models, however, like earlier computer models (Kummer 1971) and theoretical descriptions (Roux 1881, Wolff 1892, Pauwels 1980, Frost 1964) are difficult to validate. One of the few validation studies was based on animal experiments (Weinans et al. 1993, van Rietbergen et al. 1993. The first validation project with human data was obviously published by Kerner et al. (1999). They considered a previous retrieval study (Engh et al. 1992) where ten femora were analysed for periprosthetic bone stock using dual X-ray absorptiometry (DEXA). They claimed that patterns of predicted bone loss corresponded very well with the DEXA measurements on the retrievals. This kind of post-mortem analysis, however, implies a major restriction: bone density information is provided exclusively at the time of death and the assumption has to be made that the contralateral control bone represents the immediate post-operative condition. The time-dependent process of bone-remodelling itself during the post-surgery period is not measured and therefore not validated as merely the end-point simulation result can be compared with the morphological reality. There are already prospective bone mineral density studies after THA (e.g. Sabo et al. 1998). However, again the DEXA method was used having a rather low resolution, giving no complete circumferential information and, first of all, DEXA measures only twodimensionally. Undoubtedly, one necessitates prospective volumetric bone density follow-up measurements in patients after THA, as these data are not available, yet, although they represent the only information which allows fully validation of time-dependent bone-remodelling computer simulations. The collection of these data is the objective of the paper presented here.

Methods
In a prospective study design seven post-menopausal female patients suffering from primary osteoarthritis underwent unilateral total hip arthroplasty between December 1997 and February 1998. Preoperative clinical, radiological and laboratory findings gave no evidence for systemic bone diseases and traumatic or tumorous bone lesions. Neither anti-osteoporotic medication preoperatively nor during the follow-up period was allowed. The mean age at the time of operation was 64 years and 4 months (range 55 years and 7 months to 71 years and 7 months years). In five cases the right hip was affected, and in two, the left. None of the patients had undergone a previous operation at the hips. All operations were performed exclusively by the first author. A transgluteal approach was chosen to implant a forged press-fit cemented titanium alloy stem (Marburg system; Sulzer Orthopedics Ltd., Baar, Switzerland) in a standardized procedure. There were no intra- and postoperative complications seen. Full weight bearing was permitted immediately after surgery.

Spiral computerized tomography (CT) scanning of the patient’s femora (Somatom Plus-4, Siemens, Erlangen, Germany) was done postoperatively, 3, 6, 12 and 24 months after surgery. A scan through the femoral condyles gave control over the anteversion angle. The scanner setting was 140 kV, 206 mA, 17 s with a recalculated slice thickness of 2 mm. The raw CT values were converted into Hounsfield units (HU) by relating the bone values to nearby water (HU=0) and air values (HU=-1000) (Hounsfield 1973, Rho et al. 1995). Based on a cranio-caudal table feed direction, the first slice, where the tip of the greater trochanter is intersected is always matched in the follow-ups and in the contralateral comparisons. Hence, maximum error refers approximately to the slice thickness of 2 mm. During the prospective study, there were also a drop out rate. The postoperative and 3 months follow up CT scan of patient No. 2 and the postoperative CT scan of patient No. 6 are incomplete. Patient No. 3 missed the 3 and 6 months controls. This patient underwent also a THA at the contralateral side between the 12 and 24 months controls.
In order to obtain also long-term information a retrospective CT-study was added. Besides the retrospective approach the study design was quite similar. 11 female patients with unilateral THA of the same implant were identically scanned in a mean follow up time of 12 years after surgery (range 11 years and 3 months to 13 years and 8 months). In this retrospective part of the study, the contralateral side without endoprosthesis served as a control. The mean age at the time of operation was 56 years and 1 month (range 40 years and 5 months to 63 years and 11 months). In 5 cases the right hip was affected, and in 6, the left. Tables 1 gives a summary of the patient data (prospective study) including also height and weight and the selected stem size. Statistical analysis was limited to intra-individual evaluations because of the small case number. The two way Wilcoxon-test (signed-rank-test) was applied. The level of statistical significance was set at 5%. Mean CT density values of the whole slice, of the anterior, posterior, medial and lateral halves, of the anteromedial, anterolateral, posteromedial and posterolateral quarters of all slices were separately calculated. The study was approved by the ethics commission of the Philipps-University of Marburg. Informed consent is documented.

Table 1 Data of patients included in the prospective study

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age at Operation</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Side</th>
<th>Anteversion angleº</th>
<th>Hip stem size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66 y</td>
<td>160</td>
<td>77</td>
<td>Right</td>
<td>R:13; L:6</td>
<td>Large</td>
</tr>
<tr>
<td>2</td>
<td>55 y</td>
<td>176</td>
<td>80</td>
<td>Right</td>
<td>R:6; L:10</td>
<td>Large</td>
</tr>
<tr>
<td>3</td>
<td>68 y</td>
<td>165</td>
<td>75</td>
<td>Right</td>
<td>R:19; L:6</td>
<td>Medium</td>
</tr>
<tr>
<td>4</td>
<td>59 y</td>
<td>172</td>
<td>82</td>
<td>Left</td>
<td>R:26; L:39</td>
<td>Medium</td>
</tr>
<tr>
<td>5</td>
<td>58 y</td>
<td>174</td>
<td>80</td>
<td>Left</td>
<td>R:15; L:32</td>
<td>Large</td>
</tr>
<tr>
<td>6</td>
<td>71 y</td>
<td>155</td>
<td>52</td>
<td>Right</td>
<td>R:17; L:11</td>
<td>Medium</td>
</tr>
<tr>
<td>7</td>
<td>70 y</td>
<td>154</td>
<td>76</td>
<td>Right</td>
<td>R:34; L:23</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Results & Discussion

A data set of about 100 000 bone voxels of each femur was collected. In order to use the density values to validate computer simulation results the complete data of one or several cases are necessary. A few typical examples of the results are presented here: Figure 1 shows the result of the CT density change within 2 years at the horizontal slices (voxels of the medial and lateral half are averaged) of the implanted femur (patient No. 1).

![Fig. 1](image-url)

Fig. 1: Note the clear density decrease at the lateral half of the femur (right diagram). The density decrease at the medial half (left diagram) is lower. The slice number refers to slice number one at the tip of the greater trochanter.
The predominant change is seen during the first year representing an average loss between 50 and 150 HU (approx. 10 %) at the lateral side. As regards the medial side, density reductions are observed at the proximal femur only, while the bone around the distal part of the stem became more dense during the first postoperative year. The values differ, however, within the horizontal slices. The 10-12 years results of the retrospective part of the study demonstrate similar results to the prospective 2 year follow-up CT density values.

So called Wolff’s law has been the basis for adaptive bone remodelling theories and attempts to describe this "law" in a mathematical or even quantitative sense have been undertaken (e.g. Pauwels 1980, Frost 1964, Cowin and Hegedus 1976, Carter et al. 1987, Huiskes et al. 1987). These adaptive bone remodelling theories assume a relationship between a local mechanical stimulus and a bone remodelling rate. They were particularly applied for the prediction of periprosthetic bone densities with iterative finite element calculations (e.g. Huiskes and van Rietbergen 1995). Although the combination of bone remodelling theories with finite element analysis is highly developed and might predict even the clinical success of an endoprosthesis, there still subsist a lack of validation.

The limitations of previous validation projects based on animal experiments (Weinans et al. 1993, van Rietbergen et al. 1993) and DEXA measurements at human retrieval subjects (Engh et al. 1992, Kerner et al. 1999) are obvious. The objective specifically addressed in the study presented here is therefore the collection of time dependent bone remodelling data after THA in a prospective clinical densitometry study.

The striking advantage of the CT scans is the acquisition of fully 3D density values while providing also geometric data, which can be easily postprocessed by a variety of 3D finite element meshing techniques (Lengsfeld et al. 1998, Viceconti et al. 1998).

Besides the aim of validation, the method may be useful in future clinical studies to differentiate THA-induced demineralization from other reasons as medication-induced bone remodeling. As far as we are aware, this is the first collection of fully prospective 3D validation data in vivo for periprosthetic adaptive bone remodelling theories. The data are also unique as they are suitable for direct patient-specific 3D finite element meshing and individual weight related loading. Whoever combines bone remodelling theories with finite element analyses will now be able to validate his simulations with the clinical reality.

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References


