Navigation of Computer-Assisted Designed Hip Arthroplasty

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Introduction

Acetabular and stem component mal-position during hip arthroplasty increase the risk of dislocation, reduce range of motion and may cause long-term wear. Computer assisted preoperative planning for total hip arthroplasty is used in our institution since 1990 on the basis of computer-assisted designed custom femoral stem [1]. Due to the recent developments in computer intra-operative assistance, the logical evolution was to obtain three dimensional data for intra-operative cup positioning during total hip arthroplasty (THA). After the initial work of DiGioia [2], numbers of computer-assisted orthopaedic systems have been described based on CT-based navigation or on imageless navigation. CT-based navigation need an intra-operative matching witch increases blood loss and time for surgery [3]. Among the imageless systems, one is based on Bone Morphing® technology initially described by Stindel [4] for computer assisted knee arthroplasty and adapted for THA. The principle is based on plastic intra-operative modeling of a statistical model. Thus anterior pelvic plane is registered intra-operatively by percutaneous palpation and cup impactor navigated in order to reach Lewinnek goals for cup abduction and anteversion angles. These types of imageless system do not require any extra radiation exposure for patients, or any loss of time for intra-operative matching with pre-operative planning. However, the benefits of an imageless system based on Bone Morphing® technology over freehand techniques for cup positioning should be proven.

The purpose of this study was to present the concept and evaluate the performance of dedicated software for cup positioning combined to the computer-assisted preoperative planning routinely used in our institution for total hip arthroplasty in a prospective and randomized controlled study.

Methods

The Concept of Computer-Assisted Designed Hip Arthroplasty

The concept of individual computer-assisted design (CAD) has been the consequence of the natural evolution of the authors in the field of total hip arthroplasty (THA), facing the unacceptable failure rate of conventional cemented stems as reported in the literature for young and active patients [5]

Basic studies showed that successful cementless fixation include proximal adaptation and avoidance of micro-movements in order to obtain an optimal load transmission to the bone [6]. This adaptation to the proximal femur is only possible when the stem can match the patient femoral anatomy. Several anatomical studies have shown the wide range of proximal femoral anatomy [7, 8]. The logic answer for the necessary adaptation to the proximal intra-medullary femoral anatomy combined to the obligatory corrections in the prosthetic neck for solving extra-medullary deformities was CAD of individual stem geometry. The design of a three-dimensional custom neck allows corrections in length, lever arm and anteversion. The clinical consequence of such design is the restoration of length, abductor function and proper lower limb rotation [1]. The appropriate anteversion of the neck may also contribute to reduce dislocation rate [9]. The intra-medullary stem design is a combination of CT-based reconstruction of the proximal femur anatomy and priority areas of contact to obtain stability in rotation. The distal diameter of the stem is reduced to avoid any cortical impingement distally, possible source of thigh pain with maximal canal fillings stems. It is thus of high importance to preserve all the cancellous bone around the whole stem from proximal to distal by the use of a smooth compactor of identical shape than the final prosthesis (Fig. 45.1).

3-D Pre-Operative Planning

Preoperative Data

X- Ray Data

The radiographic analysis is based on several X-ray views. A full view of the two limbs using scannography is needed to assess the global pelvis and limb anatomical status, and to evaluate the extent of disturbance of the pelvic balance by assessing bilaterally the position of the hip rotation centers (in the vertical axis). A frontal pelvic view is used to determine the extent of lever arm between the rotation centers and the corresponding femoral axis. Pre-operative planning included pelvic version analysis on M-L standing X-ray of the pelvis. Angle between

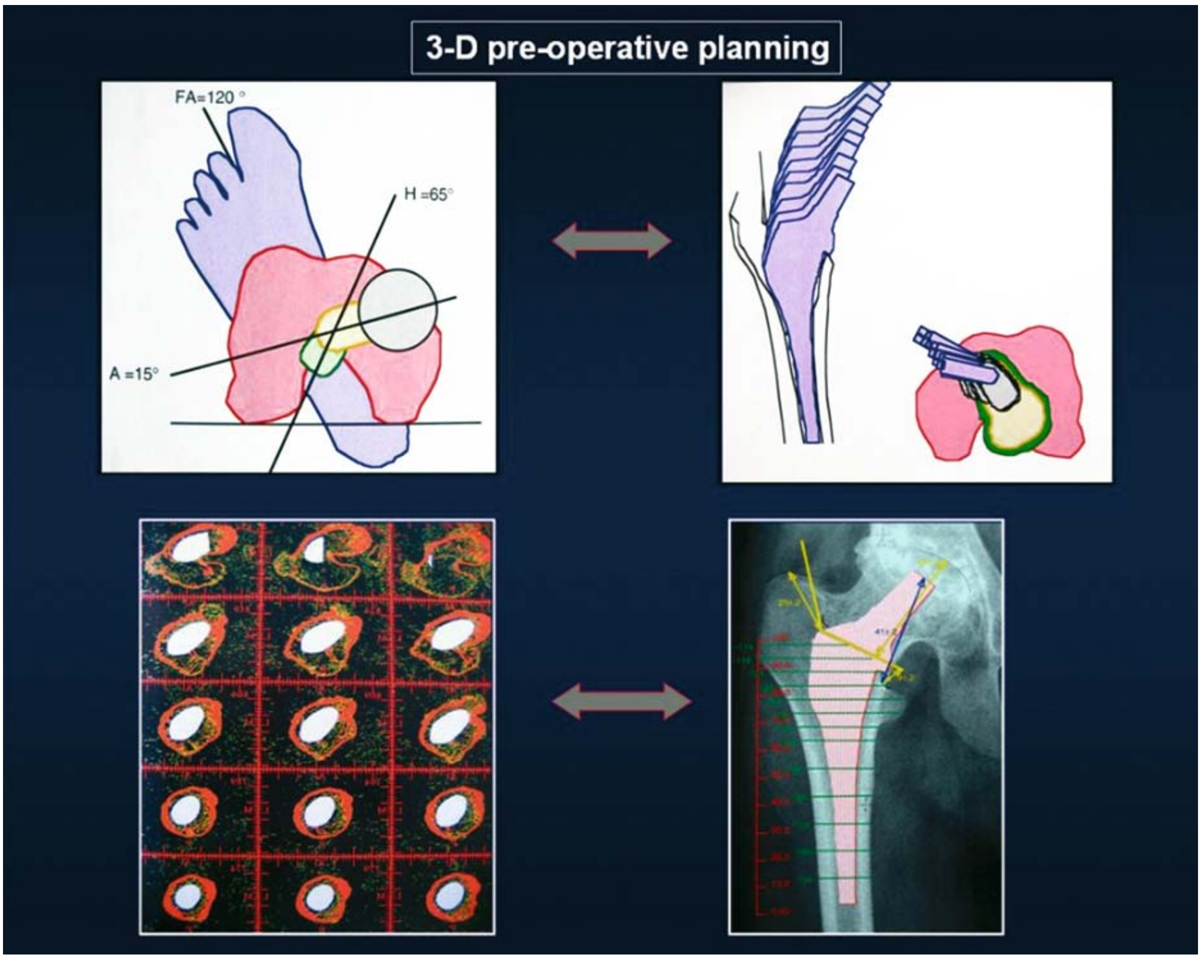


Fig. 45.1. Computer-assisted pre-operative planning of computer-assisted designed hip arthroplasty

vertical plane and anterior pelvic plane was calculated pre-operatively for each patient.

CT Data

Data obtained from computerized tomography scanner are necessary both for the design of the intra-medullary femoral stem and for the planning of the extra-medullary part of the joint reconstruction. The intra-medullary femoral anatomy is assessed by CT-views taken every 5 mm from the top of the iliac crest down to the bottom of the lesser trochanter, then every 10 mm until the femoral isthmus. The extra-medullary planning requires CT views taken at the base of the femoral neck, at the knee level across the femoral condyles and at the foot level, by the second metatarsus axis.

Preoperative Planning

Acetabular Cup

The size is determined using the CT view passing through the center of the true acetabulum (witch allows furthermore assessment of bone stock).

Corresponding Position of the Femur

The future position of the femur (as determined for instance by the location of the greater trochanter) is determined on the frontal view based on the position of the acetabular socket, on the desired lengthening as determined from the scannogram, and on the neck lever arm. This position will determine the level of the femoral cut and assess the correct neck lever arm on the frontal view.

Neck Anteversion

The anteversion angle of the prosthesis neck must be set such as that normal gait anatomy can be restored. The normal gait anatomy requires three conditions:

1. foot axis showing 10°–20° of external rotation,
2. posterior bicondylar axis perpendicular to the gait direction,
3. anteversion of the femoral neck between 15° and 20° with respect to the bicondylar axis.

By superimposing the three CT views above the lesser trochanter and at the knee and foot levels, it is possible to calculate the correction angle to add (or substract) to the helitorsion angle such that a final prosthetic anteversion angle of 15°–20°, referencing the knee condylar axis, is achieved.

The Concept of Imageless Navigation Based on Bone Morphing for Total Hip Arthroplasty

We performed an adaptation of the Hiplogics Universal Protocol (PRAXIM Medivision™) for cup positioning control. This system is CT-free, based on Bone-Morphing Technology [4]. In an image-free-based concept, the goal is to obtain easily per-operatively a reliable 3D model. This 3D model is specific to each patient's anatomy. The 3D shapes of the bones are built from data collected with a 3D optical pointer in relative coordinate systems attached to the bones using clouds of points and deformable models. For hip arthroplasty, the first step was to obtain the patient pelvic 3D model by percutaneous palpation of anterior-superior iliac spines, pubic symphysis and intra-operative palpation of the acetabulum. The second step was to reference the acetabular reamer and the cup impaction device in the relative coordinate system. Then navigation of the acetabular reaming and the cup impaction will be performed (▫ Fig. 45.2).

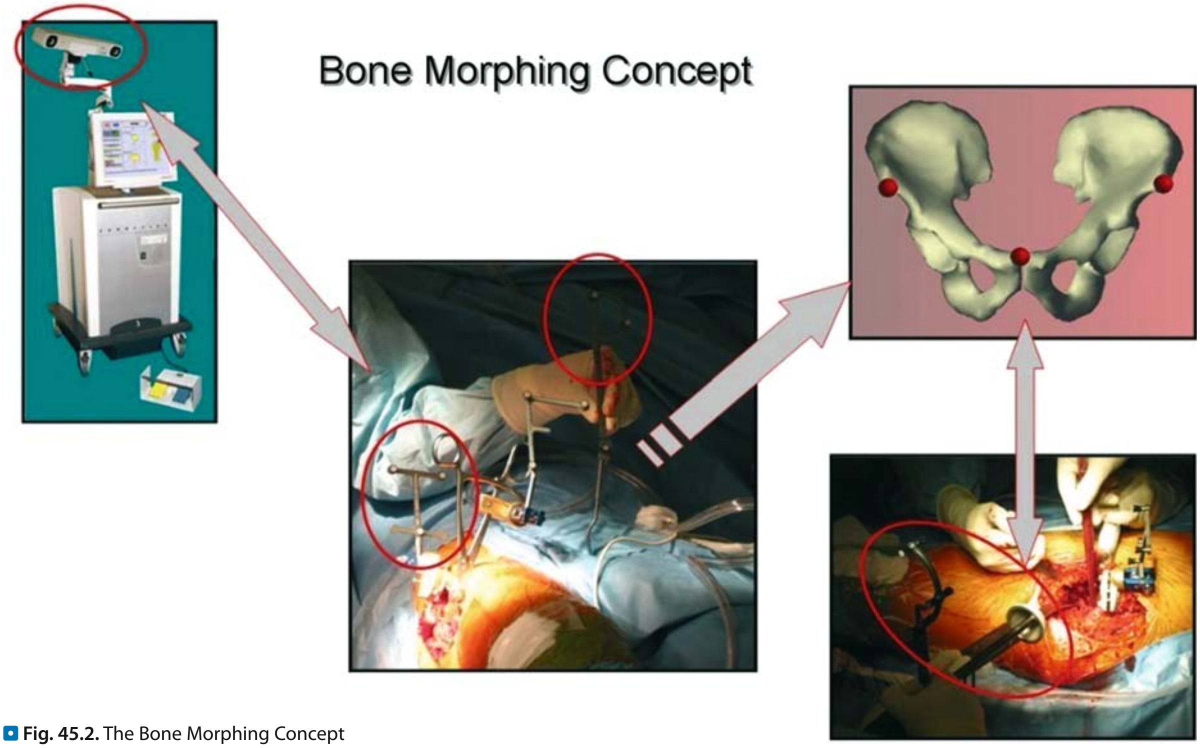
Cup Positioning Validation: a Prospective Comparative Randomized Controlled Study

Study Design

We performed a controlled, randomized matched prospective study including two groups of 30 patients with previous approval of French Ethic Committee. In the first group, cup positioning was assisted by computer-assisted orthopaedic system (CAOS group). Inclusion criteria were: age >20 years and <80 years, weight <100 kg, primary hip arthroplasty, antero-lateral approach, same surgeon (JNA), same cementless cup. Exclusion criteria were: trochanterotomy or revision. In the control group, a free-hand cup placement was performed by the same surgeon, using the same implant.

Surgical Procedure

We developed a specific hip surgical procedure for the use of an imageless cup positioning computer-based naviga-



■ **Fig. 45.2.** The Bone Morphing Concept

tion system trough an antero-lateral approach, the patient in supine position. The acetabular component was a cementless socket and the femoral stem was a custom made prosthesis. All the patients have been operated through an antero-lateral approach by the same surgeon under general or rachi-anesthesia. Patient was draped in such a way that both anterior-superior iliac spines and pubic symphysis could be palpated. An iliac rigid-body was positioned in the acetabular roof trough the conventional exposure. Lewinnek plane [10] was obtained by percutaneous palpation of anterior-superior iliac spines and pubic symphysis with a special palpation device. Pre-operative pelvic version angle was registered on the computer. Then an acetabular bone morphing was realized. After this first step of spatial pelvic reconstruction, reamer navigation was performed (■ Fig. 45.3). Finally, we performed cup impactor navigation in order to control per-operative cup anteversion and abduction angles (■ Fig. 45.4). Angular goals were 40° of abduction and 15 ° of anteversion. The standard definitions of cup orientation (anteversion and abduction angles) in operative, radiographic and anatomic referentials of Murray [11] were used.

Post-Operative Evaluation

Cup positioning was evaluated post-operatively for each patient in the two groups by an independent observer on CT-scan with a special cup evaluator soft-ware (■ Fig. 45.5). Full pelvic CT-scans were performed one month after surgery for all patients with the same protocol in the same center. We performed a 3-D reconstruction for each patient with the special post-operative evaluator software. Then Lewinnek plane [10] was registered on the 3-D model and pre-operative pelvic version integrated. Cup anteversion and abduction angles were measured in operative, radiographic and anatomic referential of Murray [11].

Results

There were 16 males and 14 females in each group, 14 right hips and 16 left. Mean age was 61 years (24–80) and mean Body Mass Index was 24 (17–37). The mean pelvic version angle measured pre-operatively on the standing M-L pelvic X-ray was –1.72° (–15°/14°). Mean acetabular

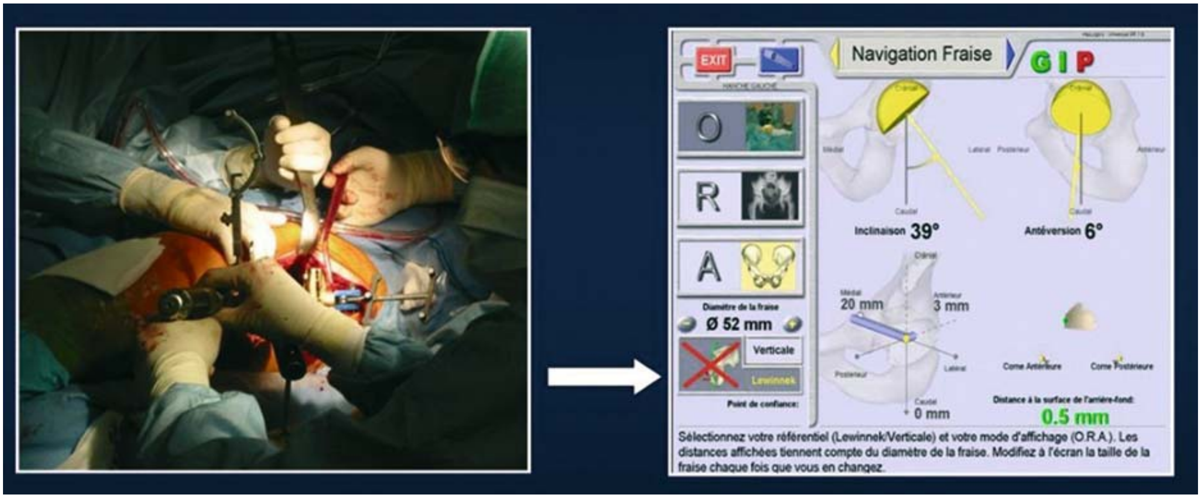


Fig. 45.3. Reamer Navigation

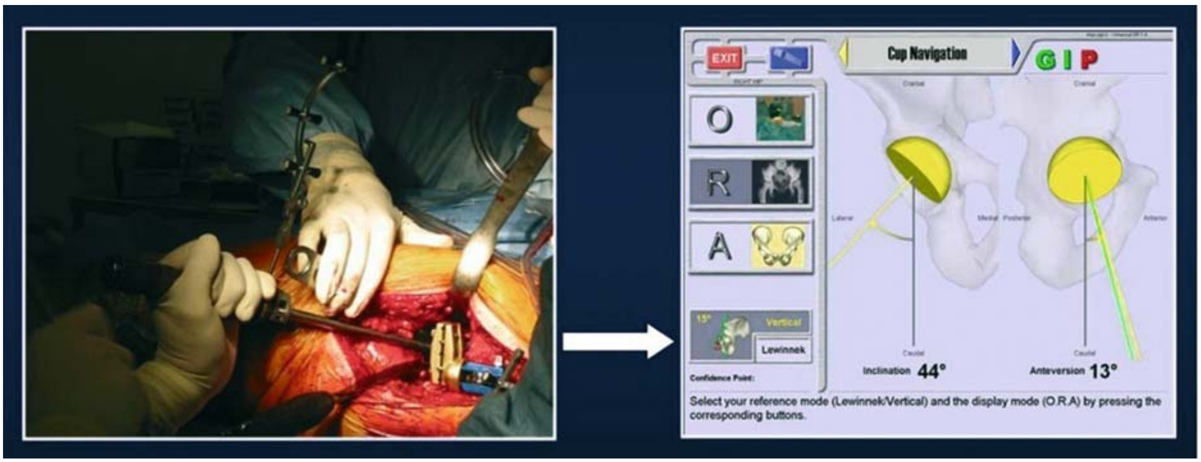


Fig. 45.4. Cup impaction navigation

cup diameter was 52 mm. We never needed additional skin incision. Mean additional time for the CAOS procedure was 12 min (8–20). Intra-operative subjective agreement by the surgeon with the computer guidance system demonstrated a high correlation in 23 cases, weak correlation in 6 cases and a poor correlation in 1 case.

The results of the post-operative angles in the two groups are detailed in Table 45.1. The differences between the intra-operative values and the post-operative values were in 95% of the cases less than 5° for the abduction angles and less than 10° for the anteversion angles. The differences were mainly found in obese patients.

Table 45.1. Results of the postoperative angles in the CAOS group and in the Control group

	Abduction (°) CAOS/Control	Anteversion (°) CAOS/Control
Operative mode	30 (25–46)/32 (21–48)	14 (0–25)/17 (0–37)
Radiologic mode	35 (25–47)/34 (23–50)	13 (0–26)/15 (0–35)
Anatomic mode	36 (27–47)/38 (22–55)	19 (0–27)/22 (0–39)

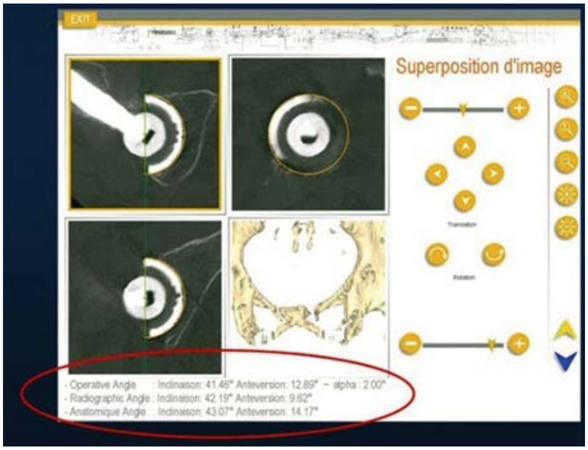


Fig. 45.5. 3D scannographic post-operative evaluation

There was no statistical difference between the CAOS group and the Control group for the abduction and inclination angles.

Discussion and Conclusion

Stem Positioning Validation

The next step of the protocol will be the validation of computer-assisted guidance of stem introduction by performing a prospective randomized controlled study. The computer-assisted measurement of intra-medullary stem placement according to the pre-operative planning should be evaluated as well as the extra-medullary parameters like neck anteversion, varus-valgus and neck lever arm. Navigation of the cup alone is not sufficient for optimizing hip range of motion after THA [12]. Thus computer-assisted per-operative control of both intra and extra-medullary stem parameters have to be achieved.

Limits of the System

Cutaneous Lewinnek Plane

During the procedure, a percutaneous bony landmark registration is performed. Considering that the anterior pelvic plane registration is modified by subcutaneous fat tissue, we call it the »Cutaneous Lewinnek plane«. Thus the poor correlation between intra-operative and post-operative measurements for obese patients observed in our study was probably due to the limits of the percutaneous registration of the Lewinnek plane [10]. This point is probably one of the most obvious limitation of the image-less anatomical navigation system [13, 14] based on Bone Morphing® in THA.

Pre-operative Individual Pelvic Motion Analysis

Analysis of the pelvic version in our study has shown important inter-individual differences witch should be considered pre-operatively to provide the best anteversion angle intra-operatively. Furthermore, a few studies [15, 16] considering motion analysis of the pelvic tilt have shown important variations according to the patient‘s position or the patient's thoracic cage motion. Considering pelvic tilt in standard standing position as we have done in the current study seems to be not reliable enough. A kinematic analysis of the pelvic tilt could allow the surgeon to define preoperatively a functional anteversion angle goal to reach during intra-operative computer-assisted cup positioning.

Future of the System

Echo-Morphing™

Alternative solutions for percutaneous palpation could be realized by intra-operative echographic morphing of the anterior pelvic plane. Reproducibility and accuracy of the percutaneous registration of the Lewinnek plane and the echographic morphing have been studied during an anatomical study (Fig. 45.6). Echo-morphing™ could

Fig. 45.6. Cadaveric study for echo-morphing evaluation

represent a good alternative to percutaneous palpation and should be tested in vivo.

Difficult Cases: Revision, Dysplastic Hip

Validation studies were necessary to confirm the usefulness of both computer-assisted designed and computer-assisted positioning in THA for conventional cases. Then we will be able to adapt the concept to revision or dysplasia. The system may be very helpful for reconstruction of the original patient anatomy in a reproducible way for theses difficult cases.

Conclusion

The results of this study are in accordance with the recent ones published on the same subject showing less variability for cup positioning when using a navigation system [17–20]. Whether the definition of correct acetabular orientation is still debated, the effects on hip stability and optimal range of motion are proven [9]. The next steps will be the potential for reducing error analysis by using echo-morphing instead of skin reference planes, and the validation of computer-assisted guidance of stem introduction either standard or custom.

The combination of an optimal cup positioning to a three-dimensional designed prosthetic neck may provide the best conditions for adequate range of motion after THA while reducing the risk of potential dislocation. Further research in the biomechanical field including the evaluation of the patient hip function before and after THA using gait analysis, stereoradiography, fluoroscopy, or accelerometry during everyday or sport activities will be also necessary in order to improve our knowledge in patient‘s quality of life and hip function after THA.

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