MEASUREMENT OF HIP PROSTHESES USING IMAGE ANALYSIS

THE MAXIMA HIP TECHNIQUE

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A computer-based image analysis system has been developed as a research tool in total hip replacement. The system has been programmed to take multiple measurements from coronal plane radiographs. Poor quality radiographic images can be enhanced and standardised. The measurements which can be obtained include stem subsidence, cup migration, cup wear, and stem loosening. Reproducibility and accuracy were ± 0.01 mm and ± 0.5 mm respectively. The present application is in retrospective research, but prospective monitoring of radiographs is planned.

Computerised storage and manipulation of records are particularly useful in resource management, audit and research. Pictorial data, including radiographs, can also be stored by computer as digital images for analysis. Applications of such techniques include three-dimensional reconstruction from computed tomograms (CT), which can be used in the manufacture of 'customised implants'; the management of fractures; and even the analysis of histopathology (Bechtold 1986; Sutherland 1986; Herzenberg et al 1988).

Orthopaedic research frequently involves angular and linear measurement from plain radiographs. Even in prospective studies, the accurate standardisation of such radiographs, both in projection and exposure, is rare. Furthermore, manual techniques of measurement are time consuming, tedious, highly subjective and seldom defined objectively. Even if the collected data are reliable,

further time is needed to transfer the information into a database for statistical analysis. The application of computers to aid measurement of radiographs has been described previously (Huang 1987; McEachron et al 1989; Dhawan 1990; Davis and Mackay, in press).

In this paper, we describe an image analysis system and its use to measure multiple parameters from the radiographs of patients with a total hip replacement (THR). Measurements are made either automatically, by the computer, or interactively, by the user and the computer together. Thus the method is more rapid than, for example, measurement using a digitising tablet; it also has the advantage that all measurements are under the control of the computer software so that they are defined explicitly and made objectively. Many of the shortcomings of previous methods have been overcome by the Manchester X-ray image analysis (MAXIMA) technique: the software can be used on inexpensive personal computers.

MATERIALS AND METHODS

The image analysis system consists of a personal computer (PC), a light box, a video camera and a high resolution monochrome television (TV) monitor. The heart of the system is a frame grabber card contained within the PC. The camera is mounted on a copy stand above a back-lit radiograph. The analog camera output is fed into the frame grabber which, under software control, converts it into a digital image. This image is held in the computer memory and used to reconstruct an analog signal for

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Fig. 1

(a) An unmodified digital image. (b) Mathematical filters have been applied to two regions of the image (A,B) to enhance contrast.

Fig. 2

(a) Graphic overlays have been used to indicate the position of the reference points, many of which are generated automatically and lie at the centre of the circles shown here. The diameter of the head of the femoral prosthesis is used to scale all measurements – in some of the illustrations the head appears to be oval rather than circular. This is an artefact from photographing a curved screen. (b) The reference points are used to define individual measurements, a selection of which have been illustrated using graphic overlays. The reference points are also used to define mapping lines (1-12). Graphs and histograms may be overlaid; in this case a grey-level profile has been taken along mapping line 9. This helps the user to identify the change in pixel intensity (shade of grey) that occurs at an interface e.g., between the bone and cement.

simultaneous display on the TV monitor (Jones et al 1988).

The image analysis software, in addition to controlling image acquisition, has two important functions: to improve the quality of the image and to quantify predefined parameters. The digital copy of a poor radiograph can be manipulated to enhance its intensity, contrast or consistency of exposure by filtering the image mathematically (Ballard and Brown 1982; Loeb1 1985). In addition, areas of specific interest can be selectively enhanced (Fig. 1).

The second function, to quantify predefined parameters, is achieved using features within the image to generate points and lines of reference (Fig. 2a, Jones et al 1988, 1989). Many of these points of reference are generated automatically, whilst others are identified interactively following cues provided by the computer software. The system can overlay both temporary and permanent graphics on the displayed image to aid interaction (Fig. 2b). The dimension of the head of the

femoral prosthesis is used for calibration since it has a circular outline which is independent of radiographic projection. The reproducibility of measurements is better than 0.01 mm and their accuracy is in the region of ± 0.5 mm.

An archive of digital images is being assembled by recording them on 10 Mb cartridges. Each cartridge is capable of storing up to 50 images. The measurements are also stored on disk or written directly into databases or spreadsheets, to be analysed by standard statistical packages. Examples have been selected from a research project on the long-term success of cemented total hip replacement.

APPLICATIONS

Stem bending and fracture. Stem fracture (Fig. 3) was a problem early in the evolution of THR but is now rarely encountered. However, there are certain instances when the early detection of a fatigue fracture is important. The

computer can readily detect bending of the femoral component, which would eventually lead to fracture, by measuring the angle between the midline of the neck of the femoral component and the midline of its stem in successive follow-up radiographs (Fig. 4).

It is obvious that rotation of the leg will cause an apparent change in the radiographic angle between the axes of the neck and the shaft of the femoral component. However, for the small rotations likely to be encountered in practice, this effect should be small, because it depends on the cosine of the angle of rotation, which is a slowly

allowed us to incorporate the method of Brand, Pedersen and Yoder (1986) with our method for measuring medial cup migration (Jones et al 1989). This amalgamation of methods has permitted us to measure cup migration in both the horizontal and vertical planes (Fig. 7). The measurement of cup wear depends upon the change in the separation of the centres of the cup and the femoral head (Fig. 8).

Shenton's line. Shenton's line can be generated and automatically plotted on the image. The user indicates four points on the superior margin of the obturator

Fig. 3

varying function when the angle is close to zero. Figure 4 confirms this expectation. The variability in the angle measured from independent radiographs of a successful THR, over a period of more than 12 years, is only about 3° . In contrast, in a prosthesis which eventually fractured, stem bending of greater than 5° was detectable within two years. A consistent and progressive change in the angle was measured until the time of complete failure.

Stem subsidence. Subsidence of the femoral component is much more common than fracture of the stem, and can be quantified by making sequential measurements between proximal and distal transverse lines, perpendicular to the midline of the femoral medulla. The proximal perpendicular is defined by the lesser trochanter and the distal by the tip of the femoral component (Fig. 5). Allowance has been made for foreshortening of the stem caused by out of plane angulation (Jones et al 1988), an effect overlooked by Loudon (1986). When stem subsidence does occur it often has a non-linear time course (Fig. 6).

Cup migration and wear. Automatic and interactive identification of the appropriate reference points has

Fig. 4

The neck angle is plotted against the length of follow-up for a successful THR and one in which the stem fractured. Point A on the graph corresponds to the status of the prosthesis in Figure 3a. Bending as indicated by a reduction in the angle is evident even at this early stage. As the follow-up time increased, the stem continued to bend and fractured at point B, corresponding to Figure 3b.

Fig. 5

Stem subsidence is quantified by making sequential measurements of the separation between two perpendiculars to the midline of the femoral medulla. The midline of the femoral medulla, the mid-point of the lesser trochanter, the tip of the stem and both the perpendiculars are generated by the computer. Any increase in their separation between consecutive radiographs is a measure of subsidence. The total length of the stem is measured to adjust for any foreshortening caused by out-of-plane angulation.

Fig. 7

Cup migration is measured by recording any change in the vertical and horizontal offset of the cup. The horizontal offset is defined as the distance of the cup centre from the pubic midline. The vertical offset is defined as the distance of the cup centre above the teardrop. Any rotational change in the cup position will be identified by changes in the separation of the ends of the wire marker.

foramen, four points on the medial margin of the femur (between the femoral head and the superior aspect of the lesser trochanter) and two points in between. A fifth order polynomial plotted through these points reproduces the shape drawn by Shenton (1911).

Bone remodelling. Image analysis techniques enabled the thickness of cortical bone of the femoral shaft to be measured easily and reliably (Jones et al 1988). Analysis

Fig. 6

A comparison is made of the subsidence of a successful THR and one that was revised after 10 years because of aseptic loosening. In the one that was revised there was marked subsidence after three years. During the 14-year follow-up of the successful replacement no subsidence occurred after an initial subsidence of between 4 and 5 mm in the first three years (consistent with the findings of Loudon and Older (1989)).

of sequential films allows the effects of bone remodelling to be quantified (see Fig. 9).

DISCUSSION

Image analysis has an increasing number of applications in orthopaedics. The system we describe allows us to investigate important sequential radiological features in THR. Its advantages over conventional methods are numerous. Quite apart from the time saved in measure-

Fig. 8

Cup wear is assessed as displacement of the centre of the femoral head from a line drawn between the wire marker ends as seen in Figure 7 and shows a time-related linear progression.

Fig. 9

A comparison is made between the thickness of the medial cortex at three positions plotted against follow-up time for a successful THR (upper three curves) and one that was revised after 10 years because of aseptic loosening (lower three curves). The failed THR: there was virtually no change in the cortical thickness at mid-stem for the first eight years but then there was a rapid decrease in the year prior to revision. Distally there was an initial increase in cortical thickness suggesting an alteration in the load transfer by the prosthesis. After four years, the distal cortex began to decrease. The gradual decrease was still occurring at the time of revision. Proximally there was rapid bone loss in the first 3.5 years after surgery continuing at a slower rate for the next six years and followed by a sudden total loss of proximal bone in the year before revision. The thickness of medial cortical bone remained virtually unchanged in the surviving replacement.

ment, the quality of the data is far superior to that obtained by making line measurements on radiographs. The known dimensions of the femoral prosthesis are used to calibrate the radiograph and so overcome the problem of lack of standardisation. Enhancement techniques makes it possible for features to be observed and quantified even in poor quality radiographs.

Radiographs provide a two-dimensional (projected) representation of a three-dimensional object, and this might be expected to present difficulties when measuring routine clinical radiographs, even under so-called standardised conditions. However, our experience, as exemplified by stem bending, is that radiographs can provide reasonably reproducible retrospective measurements, over a period of many years, when measured by the MAXIMA technique.

In prospective clinical trials the use of computer image analysis would ensure that all measurements were defined explicitly. Standardisation of quantitative methods would corroborate comparability and allow results from different centres to be combined for statistical analysis and presentation. The routine digitisation of radiographs could be useful in clinical practice: cup wear, stem fatigue failure and subsidence could be identified and anticipated at an early stage; patients at risk could be monitored objectively.

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