Aspects of current management

COMPUTER-ASSISTED ORTHOPAEDIC SURGERY: DO WE NEED CAOS?

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In orthopaedic surgery there is a well-recognised relationship between accuracy and outcome. Accurate reduction of fractures improves the chance of union and the cosmetic and the functional results. Precise correction of childhood deformities is necessary to ensure growth in a mechanically appropriate direction. A well-aligned hip or knee replacement is less likely to dislocate and will last longer.^{1,2}

Surgeons respond to the need for accuracy by taking care and continually modifying their techniques to improve their performance. They have been helped enormously by the increased and increasing safety of anaesthesia.³ In most operations there is no longer any premium on operating time. Patients having joint replacements do not suffer if the surgeon takes an extra 30 minutes to produce improved overall alignment. A better technical outcome now usually takes precedence over a quick operation.

In striving to improve accuracy we have called on a large array of tools and aids. Intraoperative radiology is used routinely in fracture surgery. Endoscopy has allowed a much more focused approach than is possible with open procedures. Nerve stimulators identify nerves which may be at risk. In joint replacement freehand techniques have been augmented by the introduction of mechanical alignment jigs and cutting blocks. Each of these technical refinements has initially met with some resistance, but has become established as the resulting improvement in outcome has become clear.

We are now being presented with another technical aid, which promises to do much for accuracy in a wide range of surgical endeavour. In some respects it is little different from other tools and aids which we have accepted in the past. It is going through the similar stages of introduction, assessment and acceptance as did fluoroscopy or arthro-

scopy. It promises to have an impact of similar magnitude. Yet computer-assisted orthopaedic surgery (CAOS) is different in some important respects.

Overview of CAOS systems

The principle of CAOS is simple. A digital image is produced which serves as a map for each particular procedure. That image is made available to surgeons to guide them through the operation. Surgical instruments can be incorporated into the map so that their position, attitude and progress can be controlled and monitored to an accuracy of fractions of a millimetre or degree. The surgery is turned into something akin to an instrumented landing of an aircraft, or driving a car using a ground-positioning satellite system.

The process of producing the digital maps subdivides the systems into three categories. The first, 'preoperatively-imaged', requires anatomical information which is collected before operation in the form of a CT scan or MRI. This has to be done at a participating centre so that the data can be stored and transferred in the appropriate format (compact disc, zip drive or DVD) to be loaded onto the system computer. The patient is therefore exposed to the inconvenience and cost of the CT or MRI. The second category is 'peroperatively-imaged' in which anatomical imaging occurs in the operating suite at the time of surgery. This uses a specially modified fluoroscopy unit which requires the manoeuvring of a relatively bulky and expensive machine during surgery, with all the implications for time loss and potential for infection. The data are transferred directly to the computer through a hard-wired connection. These two groups comprise the 'image-based systems'. They usually need considerable preoperative planning as well as the acquisition of the images. The third group is 'image-free'. An anatomical model is embedded in the software and is upgraded by the process of registration.

All systems demand 'registration' (Fig. 1), a pre-determined sequence in which the surgeon identifies key anatomical landmarks for the computer. The 'Stryker computer navigation' for total knee replacement uses 14 landmarks which take about five minutes to identify. The accuracy of the registration process is fundamentally important. Although averaging algorithms are used, a poorly per-

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Fig. 1a

Fig. 1b

Fig. 1c

Fig. 1d

Photographs showing the registration process. Figure 1a – Finding the centre of rotation of the femoral head. Two fixed beacons are shown. The surgeon is putting the hip through a range of movement. Figure 1b – Identifying the anatomical landmarks of the lower end of the femur. The mobile beacon or pointer is in the surgeon's hand and two fixed beacons are shown in the lower femur and upper tibia. Figure 1c – Identifying the principal landmarks of the upper tibia. Figure 1d – Identifying the principal landmarks of the ankle.

formed registration will result in downgrading of the accuracy of the alignment.

Once the registration is complete it is possible to proceed with the operation (Fig. 2). The essential components are the setting up of the cutting blocks (Figs 2a and 2c) and checking that the cut is correct (Figs 2b and 2d). Errors which are made can be corrected and cuts re-checked. The alignment which is produced is shown on the computer screen, in real time (Fig. 3).

While they are quicker, simpler and cheaper, the 'image-free' systems do not have some of the anatomical detail that the image-based systems possess. Our experience with an image-free machine suggests that all is well in the routine situation, but that some deficiencies start to appear when major deformities are encountered. It seems likely that the two types of system will establish their places in different

surgical situations. It is also probable that the ultimate CAOS system will have the facility to perform either type of procedure, the choice being determined by exactly how much anatomical information is required in any specific situation.

Hardware. The hardware is similar in most systems (Fig. 4). The computer receives information from an infrared camera array. The cameras track the signals which come from beacons. These can be active, when they generate the infrared signal, or passive if they simply reflect the infrared radiation which comes from a source. The beacons can be fixed to the patient and therefore indicate fixed anatomy, or they can be mobile. Mobile beacons can act as pointers or can be attached to specific instruments which the computer can recognise. The progress of an instrument can therefore be followed in its relationships to the anatomy. The compu-

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Photographs showing the making and checking of the bone cuts. Figure 2a – Pinning the femoral cutting blocks. The lower femoral beacon is shown as is the mobile beacon which is mounted directly on the cutting block. The screen display is shown in Figure 3b. Figure 2b – Checking the femoral cut. The mobile beacon is attached to a small plate which is placed onto the cut that has been made. The cutting block is still in place. Figure 2c – Setting up the tibial cutting block. The screen display is shown in Figure 3a. Figure 2d – The tibial cut is being checked.

Fig. 3a

Fig. 3b

The screen displays of an image-free system. Figure 3a – The display seen when the tibial cut is being made. The varus/valgus angle, depth of cut and posterior slope are shown simultaneously and in 'real time'. Figure 3b – The display seen when the femoral cut is being made.

Fig. 4

Diagram of the hardware arrangements of most computer-navigation systems. The relative position of the fixed beacons and tools are detected by the infrared camera which sends this information to the computer. The result is shown on the computer screen.

ter screen acts first as an interactive data-gathering instrument and later provides the visual images necessary for the surgery.

Software. The software constructs the structural model, provides interactive images and allows storage of data which describe the surgery. A major difference between CAOS products is the degree to which the user is captive to the software. Currently, each brand of hardware requires its own software. None of the machines has an 'open architecture'. For generically different operations such as total knee replacement, total hip replacement, pedicular screw fixation etc, completely different software programs are required. In some systems one procedure can demand different software packages for different implants. These are 'closed' systems. Thus, with these systems the software for knee replacement with prosthesis A cannot be used for prosthesis B. A different software package is required. Changes in prosthetic design may well require the buying of new upgrades of the software.

These 'closed' systems produce visual displays of the prosthesis, which are attractive but may not be necessary. Some are clearly over-engineered and allow the performance of functions such as prosthetic sizing in a more complex, but no more accurate, manner. The financial and logistic implications of the need for software to be kept up to date with every variation in prosthetic design are significant. Revising an old implant with a new part may be beyond the capacity of such systems.

'Open' systems still need their own software but this is not prosthesis-specific, although it is operation-specific. With these products surgeons can move between implants at will, provided that they are aware of the requirements of each. These systems tend to have less impressive graphics but are simpler and more versatile in use.

Current state of CAOS

In the formative years progress in this field has been charted by the International Society for Computer Assisted Surgery which started life as two separate organisations, one Euro-

pean and one North American. The amalgamation occurred in February 2000. The Society has annual meetings and publishes its proceedings. In 2002 there were 108 presentations on various aspects of the field.⁴ Rapid changes are being made and experience is being gathered across a range of orthopaedic procedures. At the time of writing substantial experience has been gained in spinal surgery and knee replacement. Hip replacement systems are being introduced and evaluated. Developments include computer-assisted anterior cruciate ligament surgery, unicompartmental knee replacement and trauma. CAOS is being evaluated as an adjunct to minimally invasive surgery of both the knee and the hip. While it originated in Europe it is being enthusiastically adopted by the Australians and has started in the USA.

Even those products which are being used effectively in clinical practice need further refinement, either because they are cumbersome or because they do not use the process to its full capacity. They are not fool-proof, need careful introduction and their use can give rise to errors. Their accuracy is determined in part by the quality of the information which is entered so that the quality of the image, the accuracy of localisation of landmarks and the stability of beacons all play an important part. They all depend on assumptions which are built into the algorithms which they use. Some of these assumptions are not fully tested. Thus, even systems which have an excellent track record overall can occasionally lead a surgeon into error, especially when the patient has grossly abnormal anatomy.

Competition to produce CAOS involving software companies and implant manufacturers, is keen. The result is that some of the products are being launched prematurely and are not ready for widespread clinical use.

Postulated advantages

Computer-assisted orthopaedic surgery has the potential to provide a very much higher degree of accuracy and control than is possible without such a system. Any surgeon who has used one of these systems cannot fail to be impressed by the experience. The surgeon is given control, feedback, the ability to correct errors and excellent documentation. The systems have some capacity to deal with anatomical variants but the limits in this respect have not yet been defined. The first few operations are inevitably excellent learning experiences even for the most experienced surgeon. In knee replacement the system used by the authors provides information on eight separate parameters of bone cut as well as data on soft-tissue tensions. The computer can present data to an accuracy of 0.1 mm and 0.1°. This does not imply, however, that the final outcome can be controlled to the same extent. The mechanics of making the bone cuts, aligning cutting blocks, fixing pins and using pneumatic saws impose variations which are much greater. The limitations of these systems are not electronic; they are intellectual and mechanical, and this becomes evident as soon as the surgeon starts using them.

Cost/benefit of CAOS

Currently, the benefit of CAOS is conjectural. If surgery is performed better the patient should benefit in having less morbidity, with a better functional outcome and greater longevity for implants. This, if realised, will produce material benefits to surgeons, patients and the community at large. There should be fewer revision procedures with all the attendant savings. There will be more satisfied patients.

Cost is significant. The computer-assisted operations involve additional steps which take both time and manpower. Operations take longer. Some products require additional imaging to which the patient has to submit. All systems need to have infrared beacons anchored to bone and these produce minor but significant morbidity and risk. The machine is the same size as an image intensifier, taking up space in the operating suite and needs attending. The principal item, however, is the financial cost. The machines are very expensive. The software contracts associated with each system can be exorbitant, especially if a 'closed' type is chosen. One machine would not itself satisfy the needs of any hospital with a considerable orthopaedic throughput.

The path ahead

The challenge for all advocates of CAOS is to prove that the technology works well, provides a valuable service to the community and is cost-effective. This inevitably means that the assumptions on which they are based have to be validated and refined. We need methods of measurement which are of sufficient sensitivity to measure the improvement in accuracy that is claimed. Clinical studies need to be undertaken to demonstrate that the theory is reflected in better patient outcomes. Finally, we need to know that the investment which is proposed is well spent, in the face of competing claims for health finance.

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