THE NORWAY ELBOW REPLACEMENT

DESIGN, TECHNIQUE AND RESULTS AFTER NINE YEARS

FINN RISUNG

From Betanien Hospital, Skien, Norway

The Norway elbow prosthesis is a non-constrained cemented total replacement. It depends on intact collateral ligaments for stability, and allows a full range of movement. The system includes several sizes of components, all freely interchangeable, and semi-constraint can be provided by a locking ring if damaged collateral ligaments make dislocation possible.

The prosthesis has been used in more than 350 elbows in Norway and the detailed results for 118 elbows studied prospectively since 1987 are reported. It is inserted through a posterolateral triceps-splitting incision with minimal muscle disruption and bone resection, preserving the collateral ligaments. The results as regards pain relief and range of movement were comparable with those of other elbow prostheses, but there were fewer serious complications. At a mean follow-up of 4.3 years, the failure rate was 3.4%.

Received 21 February 1996; Accepted after revisions 19 November 1996

Many designs of prosthesis have been used to replace arthritic elbows. The early implants had constrained hinges and early loosening became apparent, often with much bone resorption. For some time, total elbow replacement was discredited.

In an attempt to avoid some of the problems of constrained prostheses, the ‘Norway elbow’ was designed by Finn Risung in Skien, and Jan A. Pahle and Jens Teigland in Oslo, Norway. The aim was to restore normal anatomy and function with minimal bone resection, preserving the normal ligamentous support. This unconstrained design has been shown to reproduce the normal kinematics of the elbow, while allowing greater laxity than the normal elbow. Mechanical testing by a programme of 1 million cycles under load in an elbow simulator gave satisfactory results.

The long, straight-stemmed humeral component carries a polyethylene bobbin which is free to rotate on an axle bolt (Fig. 1). A flange along each side distally has holes which allow the suturing or wiring of loose bone fragments. The ulnar component has a claw-like proximal end, which fits loosely around the bobbin. This allows free distraction and also varus-valgus and rotatory toggle with possible flexion and extension beyond the normal range of motion (Fig. 2). There are two separate gliding surfaces, one between the axle-bolt and the bobbin and the other between the bobbin and the ulnar claw.

The ulnar claw is 5 mm deeper than a half circle; this effectively prevents posterior or sideways dislocation which can be common with some shallower designs like the Ewald, Wadsworth and Kudo prostheses. As an extra precaution against dislocation there is the unique option of using a ‘locking ring’, which does not contact the bobbin under normal muscle tensions, but will prevent dislocation during distraction. This is used only when the collateral ligaments are insufficient to provide stability (Fig. 3), and can easily be applied or removed at any stage.

Many designs of prosthesis have been used to replace arthritic elbows. The early implants had constrained hinges and early loosening became apparent, often with much bone resorption. For some time, total elbow replacement was discredited.

In an attempt to avoid some of the problems of constrained prostheses, the ‘Norway elbow’ was designed by Finn Risung in Skien, and Jan A. Pahle and Jens Teigland in Oslo, Norway. The aim was to restore normal anatomy and function with minimal bone resection, preserving the normal ligamentous support. This unconstrained design has been shown to reproduce the normal kinematics of the elbow, while allowing greater laxity than the normal elbow. Mechanical testing by a programme of 1 million cycles under load in an elbow simulator gave satisfactory results.

The long, straight-stemmed humeral component carries a polyethylene bobbin which is free to rotate on an axle bolt (Fig. 1). A flange along each side distally has holes which allow the suturing or wiring of loose bone fragments. The ulnar component has a claw-like proximal end, which fits loosely around the bobbin. This allows free distraction and also varus-valgus and rotatory toggle with possible flexion and extension beyond the normal range of motion (Fig. 2). There are two separate gliding surfaces, one between the axle-bolt and the bobbin and the other between the bobbin and the ulnar claw.

The ulnar claw is 5 mm deeper than a half circle; this effectively prevents posterior or sideways dislocation which can be common with some shallower designs like the Ewald, Wadsworth and Kudo prostheses. As an extra precaution against dislocation there is the unique option of using a ‘locking ring’, which does not contact the bobbin under normal muscle tensions, but will prevent dislocation during distraction. This is used only when the collateral ligaments are insufficient to provide stability (Fig. 3), and can easily be applied or removed at any stage.

We have used it in only three elbows and are uncertain about the long-term effects. Special tools have been developed to minimise bone resection, and to ensure a close fit of the prosthesis (Fig. 4).

The humeral component is available in four patterns: small, large, and large with 5 or 10 mm extension of the articulating parts, used to compensate for excessive laxity in the collateral ligaments. The ulnar components are large, small and mini size, but all articulating parts are identical, and therefore interchangeable (Fig. 5).

Metal components are machined from titanium alloy (Ti-6Al-4V) and the bobbins are of medical grade ultrahigh-molecular-weight polyethylene (UHMWPE). Polyethylene components are not usually considered to be autoclavable because of possible deformation.
Photograph showing the various components of the prosthesis. A left humeral component is shown on the left. The holes in the side flanges accept sutures and the carrying angle is built into the humeral component. The ulnar component has a claw which is 5 mm deeper than a half circle. The articular surface corresponds to the 'dumb-bell' shape of the bobbin, but with a 5° larger angle, which prevents the waist of the bobbin coming into contact with the ulnar claw.

The prosthesis allows 45° of hyperextension and almost 180° flexion, ensuring that the range of motion is limited only by ligaments, tendons and the bulk of the soft tissues.

A model of the left elbow showing the prosthesis with a constraining ring applied. Note the wide spacing between the bobbin and the ring. This is the position in which the ring may readily be applied or removed.
bobbins are manufactured by machining heat-extruded rods of polyethylene. Their symmetrical compact form does not warp or deform during autoclaving at low temperature (121°C), provided that cooling is slow (overnight in the autoclave) to minimise changes in crystallinity.\textsuperscript{17,18} Other methods of sterilising UHMWPE include gamma irradiation, but this has recently been shown to cause oxidative degradation,\textsuperscript{19} allowing abnormal wear and release of microscopic particles.\textsuperscript{20,21} Gas sterilisation with ethylene oxide may become more common.

The first Norway elbow prosthesis was implanted in 1982 and it has since been in regular use. Over 350 prostheses have been implanted in two hospitals up to June 1996, with a mean follow-up of over five years. Since 1992 three other Norwegian hospitals have started using this prosthesis. The 118 prostheses implanted at Skien have been followed prospectively since 1987.

METHODS

Operative technique. A dorsal midline skin incision is made from 7 to 10 cm proximal to 5 to 7 cm distal to the olecranon (Fig. 6). The triceps fascia is split in the direction of the muscle fibres to the lateral corner of the olecranon. The septum between the long and the lateral heads of the triceps is identified deep to the central part of the triceps tendon. The lateral and deep heads are peeled off this septum in continuity with the lateral fascia (Fig. 7). This is safe because the long and lateral heads of the triceps each

Fig. 4
A set of the special instruments showing the rasps for the humerus and ulna with the corresponding prosthetic components. The slotted hammer is used with the rasps and the humeral and ulnar introducer-extractors, which are shown to the right, with the driver for the axle screw.

Fig. 5
A complete set of components for the left elbow. The humeral components are, from above, the small and large sizes, then large prostheses with the articular part extended by 5 mm and 10 mm. The ulnar prostheses are mini, small and large, with the optional locking ring or circlip.

Fig. 6
A dorsolateral incision leaves the triceps tendon substantially intact.
have their own blood supply and innervation. The incision then runs along the lateral side of the ulna, through anconeus to the radial head.

A thorough synovectomy is performed and the radial head is resected. Care is taken to avoid injury to the ulnar nerve which is not transposed unless it is under undue tension or pressure.

The central part of the trochlea is resected in the axis of the humeral shaft, and the medullary cavity opened enough to introduce a small humeral rasp, which is carefully driven home. If the bone is of normal size, and reaming is easy, the large rasp is also used (Fig. 8). The necessary width of trochlear resection is marked on the bone as is the position of the side flanges of the prosthesis in correct rotation. Resection is completed with an oscillating saw, and adjustments are made until the humeral component is snugly seated in the bone, with the bobbin in the correct position relative to the remnants of the trochlea and the natural centre of rotation, with minimal resection of bone. Very tight fitting is avoided; this may lead to stress fractures of the epicondylar ridges.

The ulna is resected by two saw-cuts, removing little more than the articular surface. One cut is parallel to the axis of the ulna and perpendicular to the plane of the semilunar ridge. The other cut is at right angles to this, near the tip of the coronoid process (Fig. 9). The medullary cavity of the ulna is defined and reamed in the angle between these saw-cuts.

Bones of normal size in rheumatoid adults usually accept large components. The small sizes are used only when the large rasps cannot be introduced as in juvenile chronic arthritis or in some muscular patients with thick bony cortices.

During the final reduction of the prosthetic joint the coronoid horn must pass over the bobbin which requires 8 mm stretching of the collateral ligaments. It is essential to test the tension in these ligaments and the ease of reduction of the joint before cementing. Trial reduction of the joint is attempted, but complete reduction must be avoided, since disengagement of the uncemented prosthesis may be very difficult. If the ligaments are too tight to allow reduction, the seating of the components is adjusted. If the collateral ligaments seem too slack, an extended humeral component (5 or 10 mm) is used to ensure adequate ligament tension; ruptured collateral ligaments or fractured epicondyles must be repaired. A locking ring is rarely needed to give temporary stability while the ligament heals, or permanent support.

After cementing and cleaning out all debris, the joint is reduced, the triceps reapproximated and the wound closed in layers over suction drainage.

**Documentation and follow-up.** All 118 elbows were examined before operation, after 3, 6 and 12 months and then annually. Angles were measured with a goniometer, and rounded to the nearest 5°. Valgus angles were omitted as being unreliable when there was a flexion contracture of over 45°. Elbow stability, tricipital weakening, synovitis and ulnar-nerve involvement were estimated clinically and arbitrarily graded from 0 to 3. Pain and function were recorded, using a scoring table modified from Ewald\(^2^3\) (Table I). Freedom from pain is usual after any type of elbow replacement; pain is therefore a poor parameter for the comparison of results.

<table>
<thead>
<tr>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
</tr>
<tr>
<td>None or ignored</td>
</tr>
<tr>
<td>When used much, certain movements</td>
</tr>
<tr>
<td>With all movements</td>
</tr>
<tr>
<td>At all times, at rest</td>
</tr>
<tr>
<td>Disabling, disturbing sleep</td>
</tr>
<tr>
<td>Function</td>
</tr>
<tr>
<td>Full normal use</td>
</tr>
<tr>
<td>Full use, but tiresome, weak</td>
</tr>
<tr>
<td>Fit for most uses, not lifting &gt;5 kg</td>
</tr>
<tr>
<td>Unable to dress self</td>
</tr>
<tr>
<td>Unable to manage toilet alone</td>
</tr>
<tr>
<td>Unable to feed self</td>
</tr>
</tbody>
</table>
Radiographs were taken before and after operation, whenever there were problems, and at the three-year follow-up (Fig. 10).

**PATIENTS**

A total of 118 prostheses was inserted in 85 patients (33 bilateral) from February 1987 to June 1996 at Betanien Hospital in Skien, Norway. This hospital serves a population of 360,000, but some patients were referred from other districts.

Twenty patients died from causes unrelated to their elbow replacements (23 prostheses). Four prostheses failed and one was lost to review after complications from the insertion of a long-stemmed shoulder prosthesis elsewhere.

The mean age of the patients was 62.1 years (40.7 to 80.4) at the time of surgery. The mean age at the onset of rheumatoid disease was 41.2 years (3.2 to 65.0), with a mean duration of the disease before elbow problems of 10.1 years (0 to 47). The mean duration of the elbow affection before arthroplasty was 10.8 years (0.3 to 33.0). There was no meaningful difference between the means and medians for these periods.

The mean review was at 4.3 years (0.2 to 9.4). Eighty-three implants had follow-up for over three years with 48 elbows for over five years. Eighty-nine of the prostheses were used in female patients and 29 in male.

Synovectomy had been performed earlier in 54 elbows. Of these 19 had little or no relief from this procedure. The mean time between synovectomy and prosthetic replacement was 6.5 years.

**Diagnosis.** All but one patient had chronic polyarticular progressive rheumatoid arthritis. The one non-rheumatic patient had severe osteoarthritis after a malunited humeral fracture treated by resection of the whole elbow 31 years before arthroplasty. Three of the rheumatoid patients had old distal humeral fractures involving both epicondylar areas. These four patients all had severe pain and malfunction and were the only cases of prosthetic dislocation with ensuing complications, including the first prosthetic failure. These cases were unusual, but are included because of the need to report all complications. Most elbows showed rheumatoid destruction of Larsen-Dale-Eek grades 4 or 5 with several patients exceeding grade 5.

Eighteen patients had major ipsilateral shoulder problems, 9 had serious involvement of the hand and 37 of both shoulder and hand on the same side. Only 54 had elbow involvement alone.

At the time of operation 40 patients were on continuous steroid therapy, but this did not seem to have had any effect on the results or the frequency of complications.

**RESULTS**

The results are given for the 83 elbows with a three-year follow-up. Complications are reported for all 118 elbows, with the prostheses shown in Table II.

**Pain.** The mean score for pain was 59 points preoperatively, and 1 point at three years with a trend for further improvement as time passed.

**Function.** The mean score for function was 21 points preoperatively and 89 at three years with, again, a further increase in function with longer observation.
Table II. Sizes and numbers of components in 118 consecutive replacements

<table>
<thead>
<tr>
<th>Humerus</th>
<th>Number</th>
<th>Ulna</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>9</td>
<td>Mini</td>
<td>2</td>
</tr>
<tr>
<td>Large</td>
<td>104</td>
<td>Small</td>
<td>10</td>
</tr>
<tr>
<td>+5 mm</td>
<td>4</td>
<td>Large</td>
<td>106</td>
</tr>
<tr>
<td>+10 mm</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Custom</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Movement. The mean range of flexion-extension increased gradually from 94° preoperatively to 115° at the three-year follow-up. This shows a gain of 21°, which was mainly in flexion (14°) with only 7° reduction in flexion contracture. The range of supination/pronation increased from 122° to 145° at three years, equally divided between supination and pronation. In 46 patients, however, there were also wrist problems which interfered with free rotation of the forearm. Souter has suggested primary resection of the ulnar head at the wrist during elbow arthroplasty, but we did not do this routinely, although 35 of our patients had had previous synovectomies of the ipsilateral wrist with resection of the ulnar head, and 19 had dorsal wrist synovectomy at a later date.

There was considerable varus/valgus instability in 54% of the 118 elbows preoperatively. At three years, only one had significant and eight had slight instability. We found no apparent difference in the results for the dominant or non-dominant elbow.

The four patients mentioned above with old epicondylar fractures were the only ones with insufficient collateral ligaments. Three of these suffered early dislocation of the prosthesis, but the fourth had had a locking ring at the primary operation, and dislocation was avoided.

Radiological results. Two patients had asymptomatic radiological loosening of a humeral component after follow-up for four and seven years, respectively. These prostheses were replaced, and the cases recorded as failures. One other patient shows definite radiolucency around the proximal stem and no subsidence of the prosthesis, suggesting that the cause is stress shielding.

Complications

Failure. There were four failures in the 118 elbows. One prosthesis showed asymptomatic radiological loosening after seven years with sideways tilting threatening to perforate the medial cortex of the humerus: it was replaced. One patient had an epicondylar fracture when swimming at four years. The fracture healed but one year later radiographs showed humeral loosening. Revision with bone grafting and cementing of a new humeral component was satisfactory; the ulnar component was intact and stable. One prosthesis was removed early for deep infection after dislocation and several revisions. The fourth elbow developed deep infection with streptococci from an olecranon bursa at eight years, and required removal of all foreign bodies (Table III).

Peroperative. There was one epicondylar fracture caused by hasty repositioning of the prosthesis during a transient cardiac arrest. In one severely destroyed elbow the ulnar nerve was damaged; it was lying inside the joint cavity surrounded by masses of inflamed synovium. In two elbows small ulnar rasps of stainless steel fractured. The tip of one is still distal to the titanium-alloy stem at eight years with no symptoms or radiological signs of osteolysis. The other tip was removed before cementing, and the rasp has now been redesigned.

Three patients on long-term steroids had superficial skin lesions during operation, but these healed uneventfully after being taped in position.

Early. As reported above three prostheses in patients with old comminuted distal humeral fractures dislocated early. One became infected and the prosthesis was removed. Another became stable after osteosynthesis and the third after the addition of a locking ring. Eleven patients had reversible problems with the ulnar nerve, two requiring decompression and anterior transposition. Four patients in the first part of our series had partial ruptures of the triceps tendon, which led us to modify the triceps splitting incision.

One patient had a loose axle screw without symptoms. Three superficial infections healed with antibiotics and three patients had discharges from the olecranon bursa postoperatively which healed spontaneously. One of these had recurrent infection after three years but was successfully revised, another had recurrences after 2, 3, 6 and 8 years and then developed osteomyelitis requiring removal of all foreign material.

Three elbows showed extra-articular cement extrusions, one of which required removal of the cement lump.

Late. One patient with a deep haematogenous joint infection after three years also had a loose axle screw. The joint was revised and cleaned out, the bobbin and axle screw replaced and antibiotic therapy continued for one year. The elbow was symptom-free for two years until the patient died from heart failure.

Table III. Major complications in 118 elbow replacements

<table>
<thead>
<tr>
<th>Complication</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure (removal)</td>
<td></td>
</tr>
<tr>
<td>Loosening of components</td>
<td>2</td>
</tr>
<tr>
<td>Deep infections</td>
<td>2</td>
</tr>
<tr>
<td>Revision</td>
<td></td>
</tr>
<tr>
<td>Osteosynthesis of epicondyles</td>
<td>2</td>
</tr>
<tr>
<td>Application of locking ring</td>
<td>1</td>
</tr>
<tr>
<td>Synovectomy for infection and replacement of bobbin and screw</td>
<td>1</td>
</tr>
<tr>
<td>Other reoperations</td>
<td></td>
</tr>
<tr>
<td>Removal of suture in drain</td>
<td>1</td>
</tr>
<tr>
<td>Removal of extruded cement</td>
<td>1</td>
</tr>
<tr>
<td>Late revision of olecranon bursa</td>
<td>2</td>
</tr>
<tr>
<td>Decompression of the ulnar nerve</td>
<td>2</td>
</tr>
</tbody>
</table>
epicondyles at two months probably because the fitting of the humeral component was too tight. The fracture healed spontaneously, but with a large flexion contracture. One had symptomless loosening of an axle screw on radiographs at four years. This was unchanged two years later. There was one case of radiological loosening after seven years; revision was performed but the patient died seven months later of disseminated lung cancer.

Another patient had sudden pain while swimming at 4.5 years after the operation. A large lateral epicondylar fragment had broken loose in relation to a radiolucent zone along the radial side flange of the humeral component. At first the prosthesis did not seem loose, and the pain disappeared gradually as the fracture healed with callus formation. One year later radiographs showed obvious loosening of the humeral component, and this was revised.

Survival analysis. A Kaplan-Meier survival curve is shown in Figure 11. Two of the four failures were due to aseptic loosening, the other two to deep infection, unrelated to the specific design of implant.

DISCUSSION

All our patients with the Norway elbow prosthesis were included, although the exclusion of the four elbows with old distal humeral fractures would have removed all the cases of prosthetic dislocation, one early deep infection with failure and two other prosthetic revisions.

Our posterior longitudinal incision through the olecranon bursa has produced no problems other than occasional effusion into the bursa and two discharging fistulae, which healed. There was no skin necrosis or delayed wound healing, even after prior synovectomy through other incisions. This contrasts with other reports, and may be due to careful atraumatic handling and suturing. Early postoperative passive mobilisation using a motorised apparatus has given no problems, although its effect on final mobility has been difficult to assess.

The surgical technique is simple, since the posterior exposure gives good access to the joint for a thorough synovectomy and easy insertion of the prosthesis. In our earlier cases we cut part of the triceps tendon, but feared postoperative insufficiency and in later cases we placed the triceps split much more laterally. As detailed above we are now able to avoid cutting any fibres of the triceps tendon. This has allowed us to avoid any restrictions on postoperative flexion. This posterior triceps-sparing approach is similar to that described by Bryan and Morrey, but our incision is on the lateral side of the tendon and the ulna rather than medially.

In rheumatoid arthritis, with long-standing destruction and contracture of the elbow, an attempt to achieve normal anatomy is controversial, since this may stretch the nerves and vessels as well as the ligamentous structures and lead to postoperative flexion contracture and pain.

Cadaver studies of the Norway elbow indicate that the varus/valgus stability of the joint would be improved if the radial head could be preserved, but this is difficult through our posterior approach, and such instability has not been a problem.

The minimal bone resection required in the trochlea leaves enough support for a bone graft from the iliac crest should the removal of a prosthesis be needed, but too tight a fit may lead to stress fracture of the epicondyles.

Many of the complications which we have described could follow any type of prosthetic replacement, but a few are specific to the Norway design.

The two loose axle screws were obviously due to failure to tighten them at operation. Both were in the first ten cases and extra tightening has prevented any more loosenings. New commercially-available prostheses will now be delivered with the screw already tightened, but the use of a screw design will still allow exchange of the bobbin and axle if excessive wear should develop.

The three prosthetic dislocations occurred after attempted repair of the collateral ligaments despite the deep ulnar claw. The primary use of the locking ring would have prevented them.

Future development. The Norway elbow prosthesis offers a wide choice of non-constrained or semiconstrained combinations, all within one system of a few different components. The only changes since 1982 have been to extend the choice of component size, the addition of an optional locking ring and the placing of holes in the side flanges of the humeral component.
The wear properties of titanium alloys against UHMWPE in vivo have been questioned.\textsuperscript{29-31} We have seen no abnormal wear of metal or polyethylene, symptomatic metallosis or significant inflammation in five cases at revision and three at post-mortem after several years of use. Possible polyethylene wear is still a concern.

The mechanical wear properties of titanium alloy against UHMWPE are now improved by coating the surface of the titanium components with nitride to harden it and reduce the friction and wear of polyethylene.\textsuperscript{32-36} This also increases the corrosion resistance and may improve the bio-compatibility of the implants.\textsuperscript{37} Such coatings are now approved by the FDA.\textsuperscript{38}

Recent disapproval of titanium alloys as bearing surfaces could have been met by changing to chrome-cobalt alloy but this would have increased costs. Prosthetic components of titanium alloy can be produced most economically and easily in moderate numbers by high-pressure water-jet cutting followed by machining and finishing with computerised tools. Chrome-cobalt alloys have a glass-like hardness which precludes machining; they are produced by casting in a mould and then finished by polishing. This is expensive for small numbers.

The quality assurance of joint replacements has been discussed by Faro and Huiskes.\textsuperscript{3} The Norwegian elbow prosthesis is one of the last ‘pioneer’ prostheses, being designed by a group of surgeons for seriously affected rheumatoid patients at a time when the early arthroplasties of the elbow were often failing.\textsuperscript{6}

The first 35 prostheses inserted in Oslo from 1982 to 1986 gave promising results and few complications. During the same period 34 Souter prostheses were used in Oslo, with a large number of failures, particularly loosening (Teigland, personal communication). Similar results have been reported from Sweden.\textsuperscript{30} Since then over 350 prostheses have been implanted in Oslo and Skien, with a longest follow-up of 14 years and a mean review of about five years.

The evaluation of the operative results in patients with severe and progressive polyarticular rheumatoid arthritis is extremely difficult. Pain and function in these patients show considerable diurnal, periodic and barometric variations. Malfunction in the elbow is highly influenced by, and often indistinguishable from, the condition of the shoulder and hand on the same arm, and the state of the other arm, and side dominance is important. Other problems are the varying effects of medication and general therapy and differences in individual tolerance of pain.

Most elbow scores add numbers for pain, function and motion into one sum. This is inadequate and we prefer to record these values separately. Radiographs in exact standardised projections have not been possible, which has precluded direct measurement of radiolucent zones and migration of components.

The reporting of results by the operating surgeon must raise questions about objectivity and possible bias. For this reason the results have been kept as simple and objective as possible. Patients’ reports on pain and function may have been influenced by the wish to please their surgeon, but these criteria are of less importance than the hard data on serious complications and failures.

I wish to express my gratitude to my former teachers, the late Halfdan Schjelderup, the late Henrich Nissen-Lie and to Jan A. Pahle. I am grateful for the co-operation of Jens Teigland and Jan A. Pahle during the development of the prosthesis and the operative technique, and indebted to Knut Johnsen of Brodrene Johnsen AS for technical advice and the design of the tools. I also wish to thank my colleague Øystein Aasen for stimulating discussions and his assistance and also the staff at Betanien Hospital in Skien, Norway.

Most of all, I thank my patients, who have freely given their informed consent to be part of the clinical trials, and have inspired my work on this project. The author has received and will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article.

REFERENCES