Introduction

Development of knee arthroplasty

After Smith-Petersen's successful use of a Vitallium mould in resurfacing of the femoral head in 1940 (Smith-Petersen 1948), Campbell introduced the first endoprosthetic knee arthroplasty with a metallic mould which covered the femoral condyles (Campbell 1940). Subsequent development of a metallic tibial plateau resurfacing arthroplasty by McKeever and MacIntosh had some limited success, though long term results were disappointing (McKeever 1960, MacIntosh and Hunter 1972). Hinged implants with long intramedullary stems were developed to confer stability and-restore alignment (Walldius 1957, Walldius 1980). The mechanical incompatibility of a simple hinge, excessive wear debris from the metal on metal articulation, and the high incidence of loosening reported with these implants led to an unacceptable failure rate (Walldius 1961, Shiers 1965, Jones 1973, Lettin et al. 1978, Sheehan 1978, Jones et al. 1979, Hui and Fitzgerald 1980, Wilson, Fajgenbaum and Venters 1980, LeNobel and Patterson 1981, Schurman 1981).

Gunston initiated the current era of knee arthroplasty when he incorporated the low friction concept into a minimally constrained knee prosthesis (Gunston and MacKenzie 1977).

Current designs

For limited unicompartmental arthrosis of one side of the femoro-tibial joint, and a well preserved patello-femoral joint a unicompartmental design is recommended (Insall and Walker 1976, Goodfellow and O'Connor 1978, Laskin 1978, Marmor 1979, Insall and Aglietti 1980, Scott and Santore 1981, Walker et al. 1982, Marmor 1984, Marmor 1985, Goodfellow and O'Connor 1986). For cases of arthrosis in which both sides of the tibio-femoral joint are affected, or where significant patello-femoral disease is present, and for inflammatory arthritis a total condylar type of prosthesis is used (Ewald et al. 1984, Freeman, Samuelson and Bertin 1985, Hungerford and Krackow 1985, Insall et al. 1985). For the uncommon situation in which extreme amounts of knee deformity or true collateral ligament instability is present, a semiconstrained or constrained hinge may be used (Lettin et al. 1978, Matthews and Kaufer 1982). At the present time it is estimated that 40,000 hip and 15,000 knee arthroplasties are performed each year in the United Kingdom, and approximately 3 to 400,000 arthroplasties in the United States of America (Goldring et al. 1983).

Complications

Following knee arthroplasty the incidence of local complications is higher than that reported in hip arthroplasty. This has been attributed to the implantation of a large amount of foreign material into this superficial joint, the poor response of the surrounding tissue to trauma and the inbuilt instability of resurfacing prostheses.

The incidence of deep venous thrombosis and pulmonary embolism following total knee arthroplasty is much higher than was originally thought. The clinical incidence of venous thrombosis is reported to be from 1% to 10% (Stulberg et al. 1984, Francis, Marder and Evarts 1986). However, when radioactive fibrinogen scans and venography are used as the routine postoperative investigation, the incidence of venous thrombosis in unilateral knee replacement is 40–60% and in bilateral cases 50–70% (Cohen et al. 1973, Lynch 1974, McKenna et al. 1976, Stulberg et al. 1984). The clinical incidence of pulmonary embolism is reported to be from 0.5% to 6%; however, radioisotope lung scans demonstrate pulmonary embolism in 10% of patients (Cohen et al. 1973, McKenna et al. 1976, Tooms 1987).

With hinged knee implants and early total condylar designs, tibial looseing was a major cause of prosthetic failure (Insall et al. 1976). Contemporary techniques have been developed to improve the implant-cement and cement-bone interface. These include: hypotensive anesthesia, shaft irrigation, brushing, and drying, low viscosity cement, cement centrifugation, cement restriction, retrograde filling, pressurisation of the cement, late insertion of the components, and the use of precoated prostheses (Miller, Burke and Stachiewicz 1978, Dobbs 1980, Miller, Krause and Krug 1981, Harris, McCarty and O'Neill 1982, Malcolm 1988, Davies et al. 1989, Stone, Wilkinson and Stother 1989). The effect of these techniques in knee arthroplasty has not been evaluated.

In recent reports on the use of unconstrained total condylar devices with metal backing inserted with contemporary cementing techniques (Miller, Burke and Stachiewicz 1978) and accurate restoration of the mechanical limb axis (Tew and Waugh 1985) the incidence of component loosening has been reduced to less than 5% at 10-year follow-up (Lotke and Ecker 1977,

Hood, Vanni and Insall 1981, Ranawat 1981, Hungerford, Kenna and Krackow 1982, Tew and Waugh 1982, Insall, Lachiewicz and Burstein 1982, Hungerford and Kenna 1983, Dorr et al. 1984, Hvid and Nelson 1984, Hungerford and Krachow 1985, King and Scott 1985, Tew and Waugh 1985, Goodfellow and O'Connor 1986).

Constrained and semiconstrained implants result in a much higher incidence of loosening than total condylar designs (Insall et al. 1976, Haberman and Hirsh 1978, Lacey 1978, Freeman et al. 1978, Kaufer and Matthews 1979, DeBurge et al. 1979, Hui and Fitzgerald 1980, Grimer, Karpinski and Edwards 1984). This has been attributed to the increased stress transferred to the bone-cement interface in constrained mechanisms (Insall et al. 1976). Unconstrained devices have an associated incidence of joint instability of approximately 1% (Skolnick et al. 1976, Insall, Tria and Scott 1979).

Wear and deformation of polyethylene in knee implants has been recognised as a distinct clinical problem. This has been particularly associated with: metal-backed patellar components (Wright et al 1988); tibial components with polyethylene thinner than 5 mm (Ducheyne, Kagan and Lacey 1978, Hood et al. 1981); and incorrect limb alignment (Shoji, D'Ambrosia and Lipscombe 1976, Habermann and Hursh 1977). Metal tray backing for the tibial component can help limit polyethylene deformation and reduce loosening (Bartel, Santavicca and Burstein 1980). Disruption of metal-backed components is increasingly being reported especially in association with patellar components (Wright et al. 1988). The present role of the uncemented tibial component is unresolved, but provisional reports of a high incidence of tibial loosening are unfavorable (Hungerford and Kenna 1983, Hungerford, Krachow and Kenna 1989).

Patella resurfacing as part of total knee arthroplasty has been shown to result in a reduction in anterior knee pain, and improved knee function (Insall et al. 1976, Insall, Scott and Ranawat 1979, Moreland, Thomas and Freeman 1979, Simison, Noble and Hardinge 1986). However, patella replacement is not uniformly undertaken due to the high incidence of patello-femoral complications which have been reported in up to 30% of cases (Merkow, Soudry and Insall 1985, Simison, Noble and Hardinge 1986). Patello-femoral complications reported include: patello-femoral subluxation, patella fracture, patella tendon rupture, prosthetic patella disruption, prosthetic loosening, and persistent anterior knee pain (Merkow, Soudry and Insall 1985, Simison, Noble and Hardinge 1986, Ranawat 1986, Lynch, Rorabeck and Bourne 1987). Patello-femoral subluxation is the most common and has been reported in up to 26% of cases (Mochizuki and Schurman 1979). Lateral retinacular release of the patella is often performed during surgery to correct abnormal patella tracking and prevent subsequent patella subluxation. Patella tendon rupture has been reported almost exclusively following the use of constrained implants or following revision surgery. Tendon rupture is thought to be due to an alteration in the blood supply to the tendon from the underlying infrapatellar fat pad.

Other postoperative complications include supracondylar fractures of the femur following stemmed semiconstrained implants (Oni 1982, Delport et al. 1984), and peroneal nerve injury (Skolnick et al. 1976, Sheehan 1978, Insall, Tria and Scott 1979, Moreland, Thomas and Freeman 1979, Rose et al. 1982).

The incidence of wound failure following knee arthroplasty has been variously reported to be from 2% to 37% and probably averages 16% (Insall, Lachiewicz and Burstein 1982). The incidence of deep infection following knee arthroplasty has been reported to be from 0.8% to 10.3% in unconstrained prostheses (Walker and Schurman 1984, Goodfellow and O'Connor 1986). Infection and failed wound healing following knee arthroplasty will subsequently be discussed further.

Factors predisposing to infection and failed wound healing after knee arthroplasty

Preoperative factors

The preoperative factors which may account for the high incidence of wound healing problems and infection following primary knee arthroplasty, as compared to hip arthroplasty, include the presence of scars around the knee from previous menisectomy or synovectomy, and the major deformity which is commonly present. Surgical correction of a valgus, varus or fixed flexion deformity requires additional soft tissue dissection and the duration of surgery may be prolonged compared with the minimally deformed knee.

Operative factors

The diminished infection rate for hip arthroplasty which has resulted from the use of laminar flow systems, has not been found in association with knee arthroplasty (Salvati et al. 1982, Lidwell et al. 1983a). Indeed, horizontal laminar flow has resulted in a higher incidence of infection than would be expected with conventional operating theatres (Salvati et al. 1982).

This difference in the effect on hip and knee arthroplasty has been attributed to the position of the surgeon who must stand directly over the wound in knee surgery.

In knee arthroplasty it is usual to use a tourniquet after elevation or exsanguination of the knee. This effectively renders the limb ischemic for the duration of the operation, though there is still some blood flow (estimated at 1% of the original circulation) via the intramedullary vessels.

Gentamicin cement has been shown to reduce the early and late incidence of sepsis (Rottger et al. 1979) and to reduce the incidence of aseptic loosenings in hip replacement (Carlsson, Josefsson and Lindberg 1978). One complication of adding antibiotics to cement is a weakening of the cement (Klopper and Rijkmans 1983). This may be significant in hip arthroplasty where the femoral cement is loaded in shear. However, in a knee arthroplasty, all the cement lying beneath the components is loaded in compression and this is the dimension in which methyl methacrylate is strongest. Thus there is no theoretical contraindication to the use of antibiotic-loaded cement in knee arthroplasty.

The preferred incision for knee arthroplasty is a choice between a curved medial incision (Figure 1), a straight parapatellar incision centred on the medial border of the patella, or an anterior midline incision as first proposed by Insall (1984). The curved medial incision created a large curved lateral skin flap which was subject to wound breakdown and this incision is rarely used. It has been suggested that changing from a medial parapatellar incision to an anterior midline incision is associated with a reduction in the incidence of wound breakdown and infection (Lettin et al. 1984). No substantiating evidence for this statement was presented, nor could any be found in the literature.

The choice of incision to minimise the incidence of wound healing complications and infection is controversial. The primary parameters which determine wound healing is the alignment to Langer's lines, the amount of tension across the wound and the wound edge tissue oxygenation. There is presently confusion about the alignment of the skin cleavage lines around the knee and the alignment of the cleavage lines to the incisions commonly used.

Early mobilisation of the knee following joint replacement is undertaken to improve the early range of knee motion and therefore early function. It also reduces the incidence of venous thrombosis, and the duration of in-patient stay (Ritter and Campbell 1987). The effect of knee flexion on the skin wound is unknown. The vascularity of the prepatellar area has been demonstrated (Scapinelli 1967), but the oxygenation of the wound edges of each incision is unknown and therefore the incision with the best perfusion is unknown.

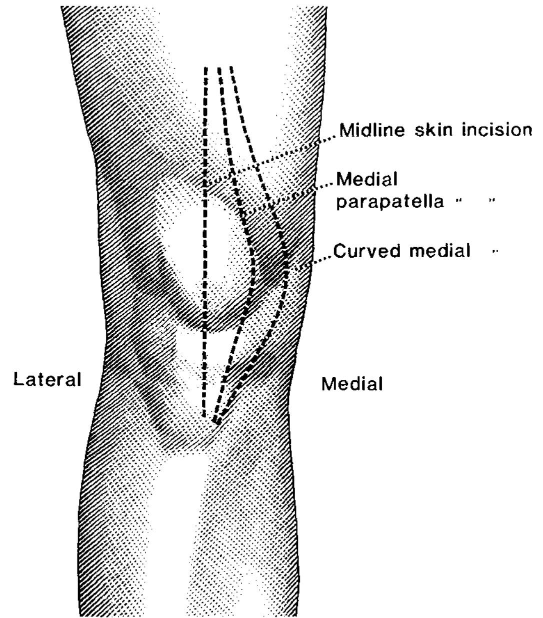

Figure 1. The three skin incisions used for knee arthroplasty; the anterior midline, the medial parapatellar, and the curved medial.

The type of knee implant used has an important effect on the incidence of infection. It has been demonstrated that hinged implants carry a higher infection rate than either total condylar or unicompartmental implants (Walker and Schurman 1984).

It has been suggested that knee prostheses with an increased antero-posterior diameter are associated with an increased incidence of wound breakdown (Simison Noble and Hardinge 1986). The effect of patella replacement on wound healing has not been evaluated.

Lateral retinacular release of the patella is often performed during surgery to correct abnormal tracking. The effect of dividing the supero-lateral geniculate vessels on infection, wound healing and devascularisation of the prepatellar skin has not previously been studied.

Postoperative factors

Valuable information about skin oxygenation in health and disease has been derived from experimental investigation of patients undergoing amputation for peripheral vascular disease. In healthy control groups there is no gradient down the limb of skin oxygenation similar to that found in peripheral vascular disease (Dowd et al. 1982, Franzeck et al. 1982).

At the front of the knee, the patella lies subcutaneously, there is no underlying muscle, the skin is of necessity mobile and the circulation depends upon the medial and lateral geniculate vessels running around

the knee from back to front. Thus, the front of the knee may be expected to be prone to local hypoxia, as predicted by studies using thermography (McCollum et al. 1985). During knee arthroplasty the tendency to elevate unnecessary skin flaps should be avoided. However, it is necessary to elevate a medial flap with an anterior midline incision in order to make the medial parapatellar entry through the joint capsule into the knee. The medial flap is much shorter with the straight medial parapatellar incision, than with the anterior midline incision. The oxygenation of the edges of these incisions in the postoperative period is unknown.

Many studies have demonstrated that it is possible to predict from preoperative transcutaneous skin oxygen tension ($TcPO_2$) measurements, the outcome of wound healing in peripheral vascular disease. None of these studies have attempted to study the wound hypoxia which might occur in the postoperative period (Burgess et al. 1982, Dowd, Linge and Bentley 1983, Bader and Gant 1985, Christensen and Klarke 1986). Analysis of the postoperative skin oxygenation may be able to detect the effect of operative factors such as surgical trauma, use of a tourniquet, effect of any wound hematoma, and any delay in restoration of the postoperative skin circulation. Postoperative evaluation of wound hypoxia may therefore give a much better correlation with the outcome of wound healing than preoperative evaluation.

Continuous passive motion (CPM)

The traditional postoperative management of the patient following total knee replacement has been to immobilise the operated knee for various periods of time, using bulky Robert Jones dressings, with or without plaster reinforcement (Skolnick, Coventry and Ilstrup 1976, Insall, Scott and Ranawat 1979, Murray and Webster 1981, Goodfellow and O'Connor 1986), or a cylinder cast (Insall et al. 1976, Finnerman et al. 1979). Range of motion exercises were begun on the third or fourth day (Finnerman et al. 1979), although some reports described starting as early as the first postoperative day (Fox and Poss 1981), or as late as the fourteenth postoperative day (Insall, Scott and Ranawat 1979).

The effect of CPM on wound healing and wound hypoxia has not previously been analysed. The optimal method of its use following knee arthroplasty has not been identified. It has been suggested that the elevation and constant motion which CPM produces, might reduce the incidence of deep venous thrombosis following knee arthroplasty. Unfortunately when the incidence of deep venous thrombosis was studied no significant effect was noted (Lynch et al. 1988).

Hypothesis

The present study evolved around the following hypotheses:

- The attainment of effective tissue levels of antibiotics, given prophylactically in knee arthroplasty, is critically dependant on the timing of antibiotic administration and tourniquet application.
- Following knee arthroplasty the wound is relatively hypoxic, and there are definable perioperative factors in the technique of knee arthroplasty which have an effect on oxygenation of the wound and wound healing.

Objectives

The following objectives were defined for this study:

- To establish the incidence of infection in the current practice of knee arthroplasty, to investigate the causes of infection and to assess the outcome at the end of treatment.
- To investigate the effect of inflation of the tourniquet on the pharmacokinetics of antibiotic prophylaxis, and to construct a protocol aimed at obtaining adequate antibiotic prophylaxis for knee arthroplasty, and also for simultaneous bilateral knee arthroplasty.
- To investigate the additional effect of the use of gentamicin containing cement on the incidence of infection following knee arthroplasty.
- To define the optimal incision for knee arthroplasty with respect to the orientation to Langer's lines, wound tension during knee flexion, and wound oxygenation.
- To investigate the role of wound hypoxia in infection and failed wound healing using the optimal incision. The technique of knee arthroplasty will be analysed so that specific preoperative, peroperative and postoperative factors which predispose to postoperative wound hypoxia may be identified.

The incidence of infection following knee arthroplasty

Many different methods have been used in reporting the incidence of postoperative infection; each has its own inaccuracies. In the series of Lidwell, reporting was by many individuals all with their own interpretation of infection (Lidwell et al. 1984). Alternatively, infection has been deemed to have occurred only when reoperation for sepsis is performed, thus excluding infections successfully treated by conservative means, or those infections suppressed by antibiotics and unsuitable for further surgery. The in-patient incidence of sepsis has even been used in some series. Inadequate length of follow-up may have resulted in delayed deep infections being missed; one cannot definitely rule out the possibility of a low grade infection presenting after some time from organisms implanted at the time of surgery (Ahlberg, Carlsson and Lindberg 1978). The reported incidence of infection is therefore a product of the quality and duration of follow-up (D'Ambrosia, Shoji and Heater 1976, Blomgren and Lindgren 1980).

Much of the research in prosthetic infection has concerned the hip joint. Extrapolations and inferences are frequently drawn from this work and applied to the knee. A much smaller volume of research is available specifically relating to the knee joint.

As the incidence of failure of knee arthroplasty due to the design of prostheses decreases, failure due to technique becomes increasingly more prominent. Failed primary wound healing is not a common problem after hip arthroplasty, but skin necrosis is an ever present hazard following knee arthroplasty. Poor wound healing includes marginal wound necrosis, skin sloughs, sinus tract formation, wound dehiscence and hematoma formation. The incidence of wound failure has been variously reported to be from 2% to 37% and probably averages about 165% (Insall, Lachiewicz and Burstein 1982, Mathews and Kaufer 1982, Simison, Noble and Hardinge 1986).

The most devastating complication of knee replacement is the development of deep wound infection. A review of adequately documented series in the world literature reveals 5866 cases with an incidence of superficial infection of 4.0% and deep infection of 3.2% (Table 1) with two-thirds occuring early. In this series infection was the largest single complication.

The incidence of deep infection following knee arthroplasty in reported series is higher than that in hip arthroplasty (Charnley and Eftekhar 1969, Walker and Schurman 1984); in unconstrained prostheses the average was 2.3% (range 0.8%–10.3%; Gunston and MacKenzie 1976, Skolnick, Coventry and Ilstrup 1976, Laskin 1976, Lacey 1978, Murray and Webster 1978, Moreland, Thomas and Freeman 1979, Kaufer and Matthews 1979, Habermann 1982, Walker and Schurman 1984, Goodfellow and O'Connor 1986); while the average in hinged prostheses was 6.2% (4.8%–12.5%; Bain 1973, Habermann, Deutsch and Rovere 1973, Freeman 1973, Arden 1974, Insall et al. 1976, Lettin et al. 1978, Hui and Fitzgerald 1978, DeBurge et al. 1979, Rand, Morrey and Bryan 1984, Walker and Schurman 1984). As in hip replacement the diagnosis of infection may be difficult. The diagnosis in the absence of wound breakdown may be made even more difficult because postoperative pain, swelling, knee effusion, and wound inflammation all occur frequently following knee arthroplasty.

Infection following knee arthroplasty is lower when associated with conventional turbulent flow operating theatres (Petty et al. 1976, Salvati et al. 1982), antibiotic prophylaxis (Lidwell et al. 1983a), unconstrained prostheses (Insall et al. 1976, Hood and Insall 1983, Poss et al. 1984), and primary compared with revision surgery (Cameron and Hunter 1982).

Treatment of the infected knee arthroplasty

Reports of the management of infected knee arthroplasty are sparse (Petty, Spanier and Shuster 1975, Hageman, Woods and Tullos 1978, Broderson et al. 1979, Insall, Scott and Ranawat 1979, Stinchfield et al. 1980, Ahlberg and Lindén 1981, Brause 1982, Thornhill, Dalzid and Sledge 1982, Eftekhar 1983, Bliss and McBride 1985, Rand et al. 1986, Borden and Gearen 1987, Rand and Fitzgerald 1989).

Treatment of an infected cemented knee prosthesis must aim to achieve a painless knee. Immediate exchange arthroplasty has proven to be unreliable (Rand et al. 1986); whereas two-stage reimplantation arthroplasty appears more promising (Borden and Gearen 1987, Rand and Bryan 1983, Insall, Thompson and Brause 1983). However, when removal of the prosthesis was followed by replacement after 2 weeks, painless walking was obtained in only 6 of 14 patients

Table 1. Literature review of the incidence and treatment of infection in knee arthroplasty

Author	Prosthesis	n	A	B	C	D	E	F	G	H	I	J	K	L	M
Petty 1975	Mixed	1045	1	4	2	21	–	–	8	3	7	1	0	0	2
Insall 1976	Mixed	193	2	7	9	6	3	3	1	3	1	0	1	0	0
Bargren 1976	Freeman	116	2	–	2	4	4	0	2	0	0	1	1	0	0
Deburge 1976	Guepar	292	2	–	18	19	9	10	5	4	3	7	0	0	0
Engelbrecht 1976	St Georg	534	2	–	–	6	6	0	4	0	2	0	0	0	0
Marmor 1976	Marmor	124	2	–	32	7	5	2	3	4	0	0	0	0	0
Ranawat 1976	Duo Condylar	109	2	–	8	0	0	0	0	0	0	0	0	0	0
Skolnick 1976	Polycentric	110	2	3	7	2	2	0	0	0	2	0	0	0	0
Watson 1976	Shiers	42	2	14	0	1	1	0	0	0	0	1	0	0	0
Wilson 1976	Walldius	44	2	–	–	3	0	3	1	1	0	0	1	0	0
Lacey 1977	UCI	100	1	4	1	2	2	0	1	1	0	0	0	0	0
Sonstegard 1977	Spherocentric	25	1	7	0	0	0	0	0	0	0	0	0	0	0
Lettin 1978	Stanmore	100	1	7	10	3	1	2	1	0	0	0	0	2	0
Sheehan 1978	Sheehan	157	1	–	2	1	1	0	0	0	1	0	0	0	0
Insall 1979	Total Condylar	461	2	10	9	6	4	2	0	1	2	0	0	0	3
Jones 1979	Guepar	112	1	7	9	9	4	5	1	4	1	1	1	0	1
Kaufer 1979	Spherocentric	134	1	–	–	3	3	0	0	0	0	0	2	1	0
Larsson 1979	Mixed	112	–	1	–	4	2	2	2	0	2	0	0	0	0
Schurman 1979	Guepar	66	–	5	–	6	3	3	3	0	0	0	0	0	3
Coventry 1980	Spherocentric	36	2	–	1	1	0	1	0	1	0	0	0	0	0
Goldberg 1980	Freeman	72	2	5	4	6	1	5	1	5	0	0	0	0	0
Hui 1980	Mixed	77	2	–	–	9	1	8	1	0	2	0	5	1	0
Wilson 1980	Mixed	87	2	3	–	4	0	4	3	0	1	0	0	0	0
Laskin 1981	Total Condylar	117	2	7	12	0	0	0	0	0	0	0	0	0	0
LeNobel 1981	Guepar	113	–	–	4	5	4	1	0	2	0	3	0	0	0
Murray 1981	Variable axis	55	2	–	7	2	2	0	1	0	0	0	1	0	0
Scott 1981	Unicondylar	100	2	2	1	1	1	0	0	0	0	0	1	0	0
Cameron 1982	Mixed	700	–	–	–	26	26	-	1	6	6	4	0	4	5
Eftekar 1983	Intramedullary	162	1	5	2	5	4	1	1	1	3	0	0	0	0
Johnson 1983	Mixed	471	1	3	23	25	18	7	3	8	5	3	2	4	0
Total		5866			163	186	107	58	43	44	38	21	15	12	14
Percentages					4.0	3.2	65	35	23	24	51	28	20	6.5	7.5

A Minimum follow-up (yrs)
B Days of immobilisation
C Superficial infection
D Deep infection total
E Early deep infection
F Late deep infection
G Successful salvage of prosthesis
H Failed salvage of prosthesis
I Bony arthrodesis
J Fibrous arthrodesis
K Failed arthrodesis
L Amputation
M Revision of arthroplasty

(Rand and Bryan 1983). A 2-week interval was therefore considered insufficient. When the prosthesis was replaced after 6 weeks, painless walking was obtained in 8 out of 11 cases (Insall, Thompson and Brause 1983) and in 80% of cases reported by Wilde and Ruth (1988). There is some evidence from a small number of cases reported by Freeman, that the treatment of infected uncemented knee arthroplasty may be more successful than the treatment of an infected cemented knee arthroplasty (Freeman et al. 1985).

Arthrodesis is traditionally the means of salvaging an infected knee arthroplasty. The success of fusion in noninfected failed knee arthroplasty depends upon the remaining bone stock. The success of fusion was 50% after removal of a hinged prosthesis, and 71% after removal of a nonhinged prosthesis (Hageman, Woods and Tullos 1978, Brodersen et al. 1979, Woods, Lionberger and Tullos 1983). Following infected knee arthroplasty, fusion was obtained in a smaller proportion of cases (Hageman, Woods and Tullos 1978). It has been reported that the technique of immobilisation with Charnley compression clamps is inadequate for arthrodesis following infected knee arthroplasty (Charnley and Baker 1952, Charnley and Lowe 1958, Wade and Denham 1984). However, a two-stage intramedullary nail appears to be the most successful technique (Knutson and Lidgren 1982, Knutson, Lindstrand and Lidgren 1985), although multiple operations with additional bone grafting is often required in order to obtain fusion (Potter 1969). The addition of pulsing electromagnetic fields has been suggested to increase the rate of fusion (Bigliani et al. 1983).

Despite the optimistic results of revision surgery, the spectre of amputation or even death remain a distinct possibility. Of 17 cases of infected hinged arthroplasty reported by Poss et al. (1984), 4 patients died and 4 required above-knee amputation. A mortality rate up to 7% has also been reported by Hood and Insall (1983), and by Grogan et al. (1986).

Bacteriology of prosthetic infection

The staphylococci remain the principal pathogens implicated in prosthetic infection. The ability of the staphylococcus to alter its structure has resulted in the epidemic of multiresistant *Staphylococcus aureus* and the emergence of *Staphylococcus epidermidis* which is now recognised as possibly the largest cause of postoperative implant infection. Once established this organism has proven extremely difficult to eradicate (Southwood et al. 1985). Gram-negative infections are usually found in association with chronic sinuses, and they normally represent secondary colonisation. Mackowiak et al. (1978) demonstrated that sinus cultures in chronic osteomyelitis bear little relation to culture results obtained during surgery. Thus deep joint aspiration or alternately capsule, cement or bone biopsy is a necessary diagnostic procedure. Fungal infections of prosthetic joints have also been reported (Goodman et al. 1983). The commensual flora usually present on the skin includes the *Staphylococcus aureus, Staphylococcus epidermidis* and diphtheroids. In the perineal region gram-negative bacteria, clostridia and pseudomonas may also be found (Kaul and Jewett 1981, Marples 1982); these organisms may be pathogenic in association with prostheses (Pollock 1979).

The correct method of specimen collection, and transport is important. Obligate anaerobes may be killed in transit if not inserted into aerobic and anaerobic containers and enriched culture media is often required especially if antibiotics have previously been administered. Despite these specialised techniques, in one series reported by Buckholz no organism could be identified in 80 of 667 infected hips (Buckholz et al. 1981).

Prosthetic infection has some specific characteristics. Although contamination often occurs at surgery, the postoperative onset of symptoms may be delayed by weeks, months or even years. The organisms implicated may be skin commensual organisms which in the presence of prosthetic materials can survive in the wound despite antibiotic prophylaxis (Bayston and Penny 1972, Stinchfield et al. 1980, Karchmer, Archer and Dismukes 1983, Peters and Pulverer 1984). There appears to be a particular association of *Staphylococcus aureus* and pseudomonas to metallic prostheses (Peters, Pulverer and Locci 1981), and an affinity of *Staphylococcus epidermidis* to polyethylene (Gristina 1987).

The nature of prosthetic infection was previously attributed to the large mass of foreign material embedded and the large dead space created in these elderly and often debilitated patients (Southwood et al. 1985). The recent theory of the role of the biofilm in prosthetic infection as described by Gristina may provide the explanation (Gristina and Costerton 1985, Gristina 1987). This theory stems from the knowledge that bacteria have an affinity to colonise the surface of most biomaterials and of damaged collagen fibres. When biomaterials are implanted there is a race for the surface between host cells and bacteria (Gristina Webb and Barth 1989). If the host cells initially coat the prosthesis then colonisation by bacteria is difficult and infection is rare (D'Ambrosia, Shoji and Heater 1976). However, if bacteria adhere to the surface, a time dependant bonding occurs which is increasingly difficult to displace (Gristina et al. 1988). This explains why antibiotic prophylaxis must be present in the wound at the time of surgery if it is to be effective. Antibiotic prophylaxis is progressively less effective thereafter (Burke 1961, Bowers et al. 1973, Blomgren and Lindgren 1980). Once infection is established, antibiotics have little effect because the bacteria involved have the ability to secrete a glycocalyx film over the colony, thus protecting it from the host defences and antibiotic attack infection may recur intermittently some time later when the host defences are reduced (Gristina and Costerton 1984a, 1984b). The bacteria with the greatest ability to form a biofilm are the staphylococcus aureus, epidermidis and pseudomonas; the same organisms found clinically in prosthetic infections (Gristina and Costerton 1984a, 1984b).

The biomaterials previously thought to be inert may present surfaces suitable for colonisation. Metal alloys such as stainless steel, titanium, vanadium and chrome cobalt present a surface with suitable anatomic geometry when cut or scratched, and a high surface energy when forged. Although polyethylene is inert, plasticisers incorporated into the surface during manufacture present a potent site for colonisation, particularly for *Staphylococcus epidermidis*. Methyl methacrylate has a porous surface with a monomer which leaches from its surface and is toxic to host cells including lymphocytes. Preparation of the bone, by reaming or power saws can fracture trabeculae and cause local bone necrosis. The subsequent heat of polymerisation of cement may cause further damage (Huiskes and Slooff 1981). Damaged collagen presents a potent site for bacterial adhesion (Gristina et al. 1985). Thus there is a zone around the bone-cement interface which is avascular, contains necrotic debris and where the host defences to bacteria are deficient (Charnley 1970, Chengar et al. 1981). It may be that this is why gentamicin cement is effective in reducing infection by leaching out into this avascular zone and by preventing bacterial colonisation (Josefsson, Lindberg and Wiklander 1981).

It is also recognised that the metallic ions of prostheses leach out into the tissues in very small concentra-

tions (Cracchiolo and Revell 1982). Ionic solutions of some ions such as iron, titanium, chrome, and nickel are known to produce activated bacterial metabolic activity (Gristina et al. 1988).

Prevention of prosthetic infection

Bacterial contamination of the operating environment is related to the number of people present and their rate of movement. There are inevitably large numbers of colony-forming units given off by all normal individuals at all times. At rest 100,000 particles are given off per hour; moderate movement increases this to 1,000,000 per hour; and full body movement increases emission still further to 2,000,000 per hour (Lidwell et al. 1983a, 1983b). Conventional operating gowns do little to suppress body emissions. Impervious body exhaust gowns can remove all of the body emissions (Whyte et al. 1983, Howorth 1986).

Following the multicentre trials run by the British Medical Research Council on ultra clean air in operating rooms, Lidwell concluded that in conventional operating rooms over 90% of the bacterial contamination of a surgical wound arises from bacteria in the air. Clean air reduces the risk of sepsis in hip replacement (Lidwell et al. 1983b, Salvati et al. 1982). If in addition, the surgical team wear total body exhaust suits, airborne infection can be virtually eliminated (Charnley 1982, Howorth 1989). However, horizontal laminar flow increases the risk of sepsis following knee replacement, presumably due to the position of the surgeon over the operative field (Salvati et al. 1982).

Prolonged preoperative hospital stay should be avoided as pathogenic hospital strains of staphylococci may be acquired (Cruse and Foord 1973). Resident commensual and transient organisms can effectively be removed from the surface of the skin with a number of antiseptic solutions. Transient organisms seeded onto the skin surface do not gain entry to the deeper layers of healthy skin. Once removed they do not reemerge within the prepared area (Ulrich 1982). Recolonisation of the skin surface occurs by resident commensual organisms progressively from these skin recesses within three hours of application of skin antiseptic (Lilly, Lowbury and Wilkins 1979). Preoperative showering or bathing is effective in lowering the skin surface bacterial counts and postoperative wound infection only if an effective antiseptic agent is used (Cruse and Foord 1973, Brandberg and Andersson 1981, Seeburg, Lindberg and Bergman 1981). Preoperative shaving causes multiple abrasions which become colonised by *Staphylococcus aureus* (Seroplan and Reynolds 1971, Powis, Waterworth and Arkell 1976, Court-Brown 1981).

There are conflicting reports about the possible benefits of adhesive plastic drapes. Some workers have found reductions in wound bacterial counts, but others have failed to show any benefit (Marples 1965, French Eitzen and Ritter 1976). Incorporation of iodine into the plastic adhesive drape has been shown to delay recolonisation of the skin and reduce the wound bacterial count (Fairclough, Johnston and Mackie 1976, Ulrich 1982, Johnston et al. 1987).

Patients and methods

A retrospective analysis of a consecutive series of 471 knee arthroplasties—431 primary and 40 revisions—with a minimum of one year's follow-up was undertaken (mean 2.8 years). Of the 431 primary knee arthroplasties studied, 293 were performed in patients with arthrosis, and 138 in patients suffering from rheumatoid arthritis (Johnson and Bannister 1986).

The patients were all routine admissions for knee arthroplasty. The operations were performed at Winford Orthopaedic Hospital, Bristol, over a five year period 1979–84. A conventional turbulent-airflow operating theatre was used for all patients. Antibiotic prophylaxis consisted of cephradine 500 mg by intravenous injection prior to surgery, though cephazolin 1 gm was used latterly. The dose was repeated 8 hours and 16 hours postoperatively. Subsequent analysis demonstrated that the first dose of antibiotic administered by the anesthetist was injected at various times prior to surgery, during the induction of anesthesia and commonly after inflation of the tourniquet and commencement of surgery. A variety of prostheses were used; constrained, semiconstrained and unconstrained, the outcome of infection being analysed for each type of prosthesis.

After surgery the wounds were inspected frequently and a swab taken if any evidence of wound infection was apparent. The presence of infection was defined as positive if clinical evidence of inflammation was substantiated by a positive culture from a wound swab; the records of all patients were reviewed and all surviving infected cases were personally examined.

It became apparent that some infections followed a benign course while others resulted in a failure of the arthroplasty; they have therefore been divided into two groups, superficial and deep. There has been no previous satisfactory definition of these terms. 'Superficial infection' was defined as having occurred when clinical evidence of extracapsular inflammation was substantiated by a positive culture from a wound swab. 'Deep infection' was defined as having occurred when clinical evidence of deep inflammation was substantiated by a

positive wound swab culture, and evidence from a sinogram, or operation findings that the infection had spread to involve the prosthesis. Four knees clinically suspected of having a superficial infection and two knees clinically suspected of having deep infection were excluded from the series because of repeatedly negative swab cultures.

Statistics; The chi-squared test was used for the statistical analysis of the incidence of infection associated with the various types of implants, and for the determination of the role of the superficial infection in the origin of deep infection. The range of knee motion between the patient groups was analysed with two sample t-tests.

Results

The incidence and outcome of infection

Superficial infection occurred in a total of 29 patients (6.7%; 17 arthrotic and 12 rheumatoid patients). Deep infection occurred in 19 patients (4.4%; 6 arthrotic and 13 rheumatoid patients). The presence of rheumatoid arthritis significantly predisposed to the development of deep infection ($P < 0.01$), but not to that of superficial infection ($P < 0.4$; Table 2).

Seven different types of prosthesis were used in the series. The incidence of superficial infection was found to be 9.4% in constrained prostheses, 8.6% in total condylar prostheses and 1.5% in unicompartmental. The incidence was significantly lower in unicompartmental prostheses than in total condylar ($P < 0.05$), and constrained hinged implants ($P < 0.01$; Table 3). The incidence of deep infection was found to be 8.4% in constrained implants, 1.9% in total condylar and 0.7% in unicompartmental implants. Constrained hinged implants therefore had a significantly higher rate of deep infection than total condylar implants ($P < 0.05$) and unicompartmental implants ($P < 0.01$; Table 3). Of the 19 cases of deep infection, 12 occurred in the perioperative period, and 7 occurred after initially successful primary wound healing.

The presence of superficial wound infection predisposed to the development of deep infection ($P < 0.001$). Progression of the infection from an initially localised, superficial wound infection, to a proven deep infection, was indicated by an initially negative sinogram or exploration, followed by a subsequent proven deep infection. Such progression occurred in 5 of the 12 cases of perioperative deep infection. Of these 5 cases, 4 suffered from rheumatoid arthritis and only 1 arthrosis. In 3 of the 5 cases the organism was the *Staphylococcus aureus*.

Of the 7 cases of deep infection that developed late, two had a bacteriologically proven source from which hematogenous spread of infection to a previously healthy arthroplasty occurred. One case followed a beta-hemolytic streptococcal sore throat, the other followed a *Staphylococcus aureus* urinary tract infection during transurethral resection of the prostate. Subsequently the corresponding organism was isolated from the joint in each case.

The infecting organism most commonly found, was the *Staphylococcus aureus*, although a variety of other bacteria were isolated (Table 4). The usual commensual organisms, *Staphylococcus epidermidis* and diphtheroids, were found to be pathogenic when found in association with a cemented prosthetic joint replacement.

During the study period 40 revision procedures of an aseptic failed knee arthroplasty were performed. Superficial infection occurred in one, and deep infection in 6. Analysis showed that the incidence of deep infection was nearly four times as great as that in primary knee arthroplasty ($P < 0.01$; Table 5). Because of the limited numbers of revision cases, only the primary knee replacements will be considered further.

Table 2. The incidence of infection in the arthrotic and rheumatoid patients undergoing primary knee replacement

Diagnosis	No of cases	Superficial infection n	(%)	Deep infection n	(%)
Rheumatoid arthritis	138	12	(8.7)	13**	(9.4)
Arthrosis	293	17	(5.8)	6	(2.0)
Total	431	29	(6.7)	19	(4.4)

**$P < 0.01$.

Table 3. The incidence of infection and the type of prosthesis inserted

Prosthesis	No of cases	Superficial infection n	(%)	Deep infection n	(%)
Stanmore	29	4	(14)	7	(24)
Deane	18	4	(22)	1	(5.5)
Sheehan	144	10	(6.9)	8	(5.6)
Hinged pr	191	18**	(9.4)	16**	(8.4)
Geomedic	4	1	(25)	0	(0)
Kinematic	101	8	(7.9)	2	(2)
Total condylar	105	9*	(8.6)	2*	(1.9)
St Georg	98	2	(2)	1	(1)
Charnley	38	0	(0)	1	(2.6)
Unicompartmental	135	2	(1.5)	1	(0.7)
Total	431	29	(6.7)	19	(4.4)

*$P < 0.05$, **$P < 0.01$.

Table 4. Organisms cultured from superficial and deep infections following primary knee arthroplasty

Organism	No of cases	Superficial infection n	(%)	Deep infection n	(%)
Number of cases		29	(6.7)	19	(4.4)
Mixed infections		1		4	
Total number of organisms		30		23	
Staphylococcus	Total	25		16	
aureus			12		9
epidermidis			13		7
pyogenes			0		0
Streptococci	Total	3		4	
anaerobic nonhaem			2		3
beta-haem			1		1
Diphtheroids		0		1	
Gram negative bacilli	Total	2			2
pseudomonas			1		1
proetus			1		1

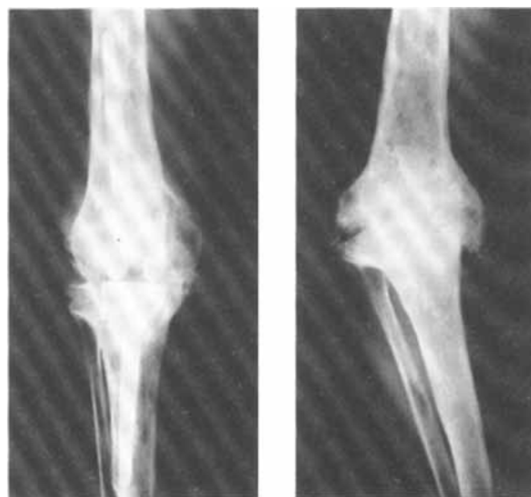

Figure 2. Radiographs of an infected Sheehan arthroplasty with the prosthesis in situ and following removal and arthrodesis. The result is a pain free stable but fibrous ankylosis.

Table 5. The incidence of infection in primary and revision surgery

Operation	No of cases	Superficial infection n	(%)	Deep infection n	(%)
Primary	431	29	(6.7)	19**	(4.4)
Revision	40	1	(2.5)	6**	(15)
Total	471	30	(6.4)	25	(5.3)

**$P < 0.01$.

The treatment of infected knee arthroplasty

Superficial wound infection was treated by rest and antibiotics. Wound debridement and secondary wound suture were performed as indicated. All these patients walked without pain within 5 months; they had a final mean fixed flexion deformity of 7° and a mean maximum knee flexion of 88°.

Deep infection was treated by knee immobilisation and antibiotic therapy in all cases. Flucloxacillin or sodium fucidate was the first-choice antibiotic. Alternative antibiotics or combination therapy was used when indicated by the sensitivity of the cultured organisms. The mean duration of antibiotic treatment was 1.3 (0.1–4.9) years. Only one patient had resolution of pain and discharge during this period. Thus long term antibiotic treatment was unsuccessful in 18 of the 19 cases.

In the treatment of deep infection, excision of a sinus tract was performed four times; in each case the sinus recurred. Joint debridement, leaving the prosthesis in situ, was performed 22 times; in every instance it failed. In an attempt to provide skin cover for an exposed prosthesis, split skin grafting was performed on two occasions, both were unsuccessful. However, a gastrocnemius musculocutaneous flap successfully provided permanent skin cover in two cases in which deep infection had been eradicated. A third case failed because of recurrent infection.

One stage exchange arthroplasty was attempted in two cases; in both the deep infection recurred. Subsequently one patient underwent an amputation and the other an arthrodesis. Amputation was undertaken in three of the 19 deeply infected cases. Subsequently all the amputees walked with the aid of a prosthesis. Arthrodesis was attempted in 10 cases by removal of the prosthesis and cement, followed by immobilisation with Charnley compression clamps supplemented by plaster. Subsequently additional bone grafting was required to obtain bony ankylosis in two cases. Of the 10 cases, bony ankylosis was obtained in 5 after a mean duration of 10 months immobilisation. More importantly, a painless knee during walking was achieved in 9 of the 10 cases; 4 of the 5 cases with fibrous ankylosis were painless (Figure 2) and one remained moderately painful while walking.

Thus, of the 19 cases of deep infection 3 came to amputation and 10 to arthrodesis. There remain 6 cases that have received long-term antibiotics and have not undergone amputation or arthrodesis. All these patients are handicapped by their knee and three have an intermittent discharge from the knee. Five have painful knees and one patient requires mechanical assistance in order to transfer from bed to wheelchair. These 6

patients had a mean fixed flexion deformity of 15° and a mean flexion of 60°; this is significantly worse than for those with a superficial infection ($P < 0.001$). Patients valued the ability to walk without pain more than joint movement or a pleasing cosmetic result. Of the 19 cases of deep infection, only 12 have achieved this. Of the 13 patients who have undergone major reconstructive surgery, 12 have obtained pain free walking. This contrasts with the 6 patients treated by long term antibiotics who are all handicapped by their painful knee.

Discussion

In the present study 19 out of 431 primary operations were followed by deep infection, an incidence of 4.4%. As in the series reported by Insall et al. (1976) and Walker and Schurman (1984), there was a significant association with the use of constrained prostheses; other predisposing factors were rheumatoid arthritis, a history of previous operations and the occurrence of postoperative superficial wound infection. It is the latter connection of superficial infection to deep prosthetic infection that is particularly relevant to this study.

Several of the 19 cases of deep infection, followed a superficial wound breakdown which developed into a superficial infection and subsequently progressed to become a deep infection. In 5 of these patients an initial sinogram or exploration was performed, which demonstrated that the initial infection was localised to the subcutaneous fat and did not involve the joint. In these patients a pattern of development was therefore identified; an initial wound breakdown which became colonised and formed a superficial infection. Subsequently the infection slowly progressed to become a deep infection with prosthetic involvement. Thus the initial failure of wound healing appeared to be an important factor in the development of deep infection

Failure of wound healing in rheumatoid patients is particularly disastrous as one-third progressed to deep infection. Insall's deep infection rate of only 1.4% (Insall et al. 1979) and that of 0.8% in the series of Goodfellow and O'Connor (1986), were associated with a postoperative regimen of immobilisation in extension of 10 and 7 days respectively, as a means of protecting against wound breakdown. These are much longer periods than that used in the present series, but they would seem to be justified for patients with rheumatoid arthritis.

Long-term antibiotics alone very rarely eradicate deep infection in a cemented prosthesis. They may suppress symptoms and reduce discharge but there is concurrent loss of bone stock, with persisting pain, discharge and functional disability. It is suggested that their use should be confined to patients who are too infirm for surgery and have limited life expectancy. It has not been determined whether long-term antibiotics are more successful for uncemented prostheses.

Table 6. Results of salvage procedures for infected arthroplasty of the knee

Procedure (Author)	Interval (weeks)	No of cases	Painfree ga n	(%)
Arthrodesis (Johnson)		12	11	92
Two-stage re-implantation (Rand et al. 1983)	2	14	6	43
Two-stage re-implantation (Insall et al. 1983)	6	11	8	73

Treatment of an infected cemented knee prosthesis must aim to achieve a painless knee. Excision of sinus tracts, wound debridement, split skin grafting and gastrocnemius musculocutaneous flaps all failed in the presence of continuing infection. Immediate exchange arthroplasty has proved to be unreliable. Two-stage reimplantation arthroplasty has therefore been developed and appears more promising. However, when removal of the prosthesis was followed by replacement after 2 weeks, painless walking was obtained in only 6 of 14 patients (Rand and Bryan 1983). These authors concluded that a two-week interval was insufficient. When the prosthesis was replaced after 6 weeks, painless walking was obtained in eight of 11 cases (Insall, Thompson and Brause 1983). Two-stage replacement merits consideration in patients able to withstand the rigors of the prolonged procedure and rehabilitation. It may be especially useful in patients with multiple joint involvement in whom loss of knee movement threatens their mobility and independence.

At present arthrodesis offers the best chance of long-term pain free gait (Wade and Denham 1984; Table 6). It should be remembered however, that arthrodesis results in bony ankylosis in only half the cases and also requires prolonged immobilisation.

Optimal use of salvage procedures can reduce the sequaele of deep prosthetic infection. More important is, however, prevention through optimal use of antibiotic prophylaxis, proper prosthesis selection, better understanding of the mechanism behind wound failure, notably its relation to incision, soft tissue handling and postoperative regime.

Antibiotic prophylaxis in knee arthroplasty

Antibiotic prophylaxis has been shown to reduce the incidence of infection following general surgery (Polk and Lopez-Mayo 1969, Evans and Pollock 1973), and hip arthroplasty (Ericson, Lidgren and Lindberg 1973, Brooks and Dent 1984, Lidwell et al. 1984, Marotte et al. 1987). A similar benefit may be expected in knee arthroplasty.

The choice of prophylactic antibiotic agent must be guided by the local experience of the bacteriology of joint infections and the sensitivity pattern of the causative agents. Cephalosporins can be used alone to provide antibiotic cover against the range of potential pathogens, including staphylococci, because of the resistance of the cephalosporins to ß-lactamase (Barry et al. 1977, Kunin 1977, Hughes et al. 1978). Cefamandole (Plaue et al. 1978), cefuroxime and cefoxitin (Wittman 1980) have all been shown to penetrate the bone and joint capsule well in hip arthroplasty (Parsons et al. 1976. Hughes et al. 1977. Schurman Hirshman and Burton 1980, Leigh et al. 1982. Hughes et al. 1982, Leigh et al. 1985. Davies et al. 1986). The methicillin resistant staphylococci and pseudomonas require additional antibiotics used in combination to provide an adequate prophylactic spectrum. Since the current contribution of these organisms in most centres to postoperative joint sepsis is small, the long term problems associated with additional prophylactic antibiotic use outweighs the potential benefits of their use (Quintiliani and Nightingale 1984).

Cefuroxime and cefamandole are the two most commonly used prophylactic antibiotics for joint arthroplasty. A three dose regime of cefuroxime is commonly chosen because of its efficacy (Chodak and Plaut 1977, Pollard et al. 1979), wide spectrum and low toxicity (Barry et al. 1977, Hughes et al. 1982). However, inexplicably low concentrations of the antibiotic have been noted in some patients undergoing knee arthroplasty (Hughes et al. 1977, Dash et al. 1982).

On the basis of the small defects in the spectrum of the cephalosporins, particularly towards pseudomonas, *Streptococcus faecalis* and some varieties of proteus, the adequacy of a single agent for prophylaxis after hip arthroplasty can be questioned. If in addition to a cephalosporin, a second agent is required, then an aminoglycoside would seem a reasonable choice. Aminoglycosides are bactericidal drugs and often act synergistically combined with ß-lactam antibiotics. Aminoglycosides do not show activity against bacteroides and clostridium (Martin, Gardener and Washington 1972, Finegold and Sutter 1971). However these organisms rarely cause prosthetic infection (Fitzgerald et al. 1977, Buckholtz et al. 1981, Kamme and Lindberg 1981). Prophylactic concentrations in serum and bone after parenteral administration of aminoglycosides are inadequate (Smilack, Flittie and Williams 1976).

Incorporation of aminoglycoside, usually gentamicin, into the acrylic cement (Buckholz, Elson and Lodenkamper 1979) can be undertaken. This achieves prolonged bactericidal concentrations which are maximal at the bone-cement interface, the most important site, while resulting in minimal serum concentrations (Wahlig and Dingeldein 1980, Elson et al. 1977). The amount and duration of antibiotic elution from methyl methacrylate cement is dependant on the antibiotic used, its concentration, the stability to the heat of polymerisation, the type of cement used, its granular size, its porosity and the surface area (Hill et al. 1977, Elson et al. 1977, Wroblewski 1977, Schurman et al. 1978, Wahlig and Dingeldein 1980, Linder 1981). Aminoglycosides used in this way can be effective against organisms usually resistant to the levels attained by parenteral administration because of the very high local concentration. Prophylactic use of gentamicin-containing cement has resulted in a reduction in the incidence of infection following hip arthroplasty both in the short and the long term (Buckholz, Elson and Lodenkamper 1979, Josefsson, Lindberg and Wiklander 1981, Blomgren and Lindgren 1981, Murray 1984, Petty, Spanier and Shuster 1988). Using gentamicin impregnated cement Rottger et al. (1979) reported a reduction in the incidence of sepsis following hip arthroplasty from 5% to 0.2%. Carlsson was able to demonstrate that the incidence of aseptic loosenings was reduced (Carlsson, Josefsson and Lindberg 1978). However, animal studies have not proven that gentamicin impregnated cement provides long term protection against hematogenous infection (Blomgren 1981). Infections in the presence of gentamicin cement may become resistant to gentamicin (Bernard 1975).

Without prophylactic therapy, the mean incidence of deep infection in total hip replacement performed in conventional operating rooms is approximately 6% (Nelson 1977, Carlsson, Lidgren and Lindberg 1977). Systemic antibiotics will reduce this figure to between 0.5% and 3% (Marotte et al. 1987). The mean incidence using antibiotic-containing bone cement is 0.5–1%

(Josefsson, Lindberg and Wiklander 1981), as it is when the operation is performed in an ultra-clean room without the administration of antibiotics. The lowest incidence of 0.5% is reported in the series where ultra-clean room and body exhaust suits were used combined with prophylactic antibiotics (Lidwell et al. 1984).

In knee arthroplasty it is usual to use a tourniquet after elevation or exsanguination of the knee. This effectively renders the limb ischemic for the duration of the operation, though the tissues can survive this period, the hypoxic environment created is to the advantage of any contaminating organisms since the host defences are inhibited. In addition, exsanguination or elevation of the limb removes most of the blood from the limb. Any prophylactic antibiotics given immediately beforehand may also be removed, before adequate tissue uptake has occurred. Thus, the pharmacokinetics of antibiotic prophylaxis in knee surgery may differ considerably from that in hip arthroplasty. The pharmacokinetics of antibiotic prophylaxis in relation to the increasingly popular technique of simultaneous bilateral knee arthroplasty have not been determined (Hardaker et al. 1978, Gradillas and Volz 1979).

Patients and methods

Timing of prophylactic antibiotics in knee arthroplasty (Johnson 1987)

A randomised prospective trial was undertaken of 22 patients undergoing knee arthroplasty. The patients were all routine consecutive admissions for knee arthroplasty. The patients were randomised into four groups receiving their intravenous prophylactic injection of cefuroxime (1.5 g) at 5, 10, 15 and 20 minutes prior to inflation of the tourniquet. The groups were found not to differ significantly in their ages, weights or their renal function. Therefore the volumes of distribution of the drug and the renal clearance can be assumed to be the same in each of the patient groups.

At the time of inflation of the tourniquet a sample of peripheral venous blood was taken and the serum separated. Throughout each operation small samples of subcutaneous fat were excised from the wound at regular intervals. Samples of bone were collected when available, the time and site of excision of each sample being noted. The serum and tissue samples were stored at –40 °C, prior to the samples being assayed for antibiotic concentration.

The antibiotic was extracted from the bone and fat samples by the method described by Dash et al. (1982). The serum was prepared for assay by precipitation of the serum proteins by the addition of an equal volume of 5% perchloric acid. The solutions obtained were assayed by high performance liquid chromatography using a column (10 cm x 4.6 cm) filled with spherisorb packing (Spherisorb ODS2 5μ). The mobile phase (12% acetonitrile in 0.05M ammonium phosphate adjusted to pH 3.0 with phosphoric acid) was allowed to flow through the column at 2 mL/min at room temperature. The cefuroxime was detected by ultraviolet absorbance at a wavelength of 260 nm. The results of the cefuroxime concentration in the samples were corrected by colorimetric estimation for the presence of any blood contamination.

Antibiotic levels in sequential bilateral knee arthroplasty (Johnson and Donell 1988)

Six patients undergoing sequential bilateral knee arthroplasty were assessed for their age, weight, hemoglobin and renal function. The mean age of the six patients undergoing simultaneous bilateral knee arthroplasty was 70 (63–75) years, their mean weight was 74 (56–85) kg and all had normal renal function. The interval between inflation of the first and the second tourniquet averaged 109 (90–135) min. The subsequent analysis of the preceding study revealed that in order to obtain optimal tissue concentrations an interval of 10 minutes was required between injection of the antibiotics and inflation of the tourniquet. Therefore in this study cefuroxime (1.5 g) was given by intravenous injection 10 minutes prior to inflation of the first tourniquet. A sample of peripheral venous blood was taken when each tourniquet was inflated. During both procedures tissue samples were collected, stored and assayed as previously described.

Statistics. Two sample t-tests were used to evaluate the ages, weights and renal function of the patient groups. Tissue samples from the patient groups were analysed with two sample t-tests for the comparison of timing of antibiotic and tissue type. Adequacy of prophylaxis above the required concentration was further analysed using contingency table analysis. An estimation of the cefuroxime half-life in the bone and fat in the limb isolated from the general circulation was made. This was calculated from the slope coefficient of the values of relating the time each sample was taken after the tourniquet was applied, to a natural logarithm.

Staphylococcus aureus is the principal cause of postoperative infection following knee arthroplasty in Bristol. The minimum inhibitory concentration (MIC) of cefuroxime for *Staphylococcus aureus* is 0.5–1.0 μg/mL (Barry et al. 1977). The minimum bactericidal concentration (MBC) is the level usually presumed to be adequate for antibiotic prophylaxis. This is conventionally assumed to be four times the MIC (Quintilliani

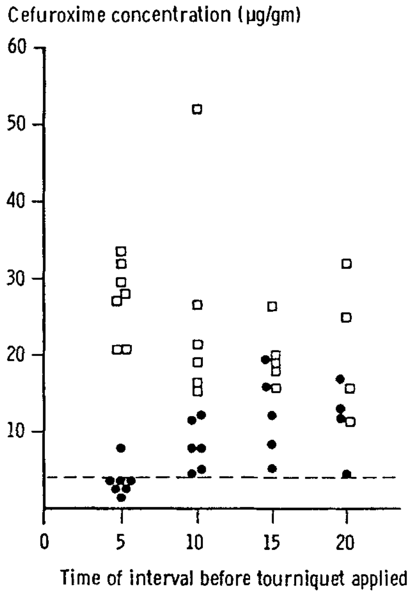

Figure 3. A comparison of the cefuroxime assay results upon the bone (▫) and subcutaneous fat (l) samples obtained for patients given intravenous injection 5, 10, 15 or 20 minutes before application of the tourniquet. – – – MBC.

Table 7. Mean tissue cefuroxime concentrations, *SD*, and range in bone and subcutaneous fat grouped according to the duration after intravenous injection prior to application of the tourniquet

Interval	No. of patients	Antibiotic conc. (μg/g) In bone			In fat		
5 min	7	27	*5*	21–33	3	*2*	1–8
10 min	6	25	*13*	16–52	8	*3*	5–12
15 min	5	20	*4*	15–27	12	*6*	5–20
20 min	4	21	*9*	11–32	11	*5*	4–17

Table 8. Mean tissue cefuroxime concentrations, *SD*, and range in bone and subcutaneous fat during sequential bilateral knee arthroplasty

Knee arthroplasty	Antibiotic conc. (μg/g) In bone			In fat		
First	21	*6*	15–33	8	*4*	5–15
Second	14	*4*	9–17	5	*3*	2–10

and Nightingale 1984). For the purpose of this study an average tissue concentration of 4.0 μg/g is considered to constitute adequate prophylaxis.

Results

Timing of prophylactic antibiotics in knee arthroplasty

The results of the antibiotic assays of the samples of *subcutaneous fat* taken from the wound during surgery demonstrated that, after an interval of 5 minutes, 6 of 7 patients obtained inadequate antibiotic penetration into the subcutaneous fat. When an interval of 10 minutes or more was allowed, all the 15 patients obtained adequate tissue concentrations ($p < 0.001$; Figure 3, Table 7). In 2 patients where the interval was 10 minutes or more, some assay concentrations in subcutaneous fat samples were lower than 4 μg/g, although the average concentration exceeded 4 μg/g. Both these patients weighed over 80 kg.

The results of the antibiotic assays of the *bone* samples (mean 23 μg/g) demonstrated significantly higher concentrations than those found in the fat (mean 9 μg/g; $p < 0.0001$). All of the patients obtained adequate antibiotic prophylaxis in the bone even after the shortest interval of 5 minutes (Figure 3, Table 7) The mean antibiotic concentrations in the femur (22 μg/g) were not significantly different from those found in the tibia (24 μg/g) or patella (24 μg/g). This suggests that the antibiotic rapidly penetrates all of the bones equally.

The calculation of the *half-life of cefuroxime* in the subcutaneous fat demonstrated no significant reduction in the concentration during the period of surgery. The half-life in the bone isolated from the general circulation was prolonged from 80 minutes to 121 minutes.

The early clinical results were good with no inpatient sepsis being recorded. No conclusion was drawn from the lack of infection as the numbers involved were inadequate for such an analysis.

Antibiotic levels in sequential bilateral knee arthroplasty

The results of the antibiotic assays on the *serum* samples taken at the time of inflation of each tourniquet, demonstrated that the serum antibiotic concentration upon inflation of the first tourniquet (118 μg/g) was significantly higher than the concentration on inflation of the second tourniquet (44 μg/g; $p < 0.01$).

The concentration of antibiotic in the *bone* samples was significantly higher in the first procedure (mean 21 μg/g) than in the second procedure (mean 14 μg/g; $p < 0.05$; Table 8). Despite a reduction in the antibiotic concentration in the bone samples between the first and

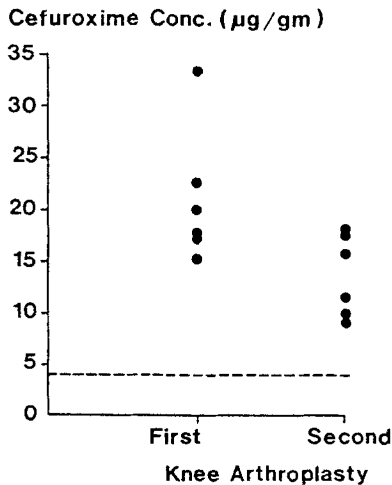

Figure 4. The mean tissue cefuroxime concentration in the bone samples of each patient during the first and second of sequential bilateral knee arthroplasty. – – – MBC.

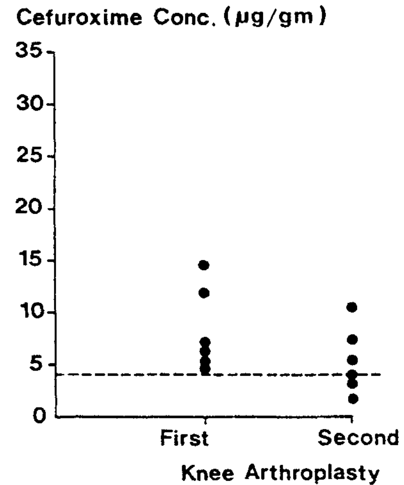

Figure 5. The mean tissue cefuroxime concentration in the subcutaneous fat samples of each patient during the first and second knee arthroplasty of sequential bilateral knee arthroplasty.

second procedures averaging one third, all patients maintained adequate concentrations during both procedures (Figure 4). The antibiotic bone concentrations in the femur were slightly higher than in the tibia though the differences were not significant.

The antibiotic concentrations in the samples of *subcutaneous fat* taken from the wound demonstrated significantly lower concentrations than in the bone samples ($p < 0.01$), both during the first and second procedure (Table 8). The concentrations in the subcutaneous fat were higher during the first procedure (mean 8 µg/g) than during the second (mean 5.4µg/gm), the mean concentration being reduced by one third. This resulted in 3 of the 6 patients having inadequate antibiotic concentrations in the subcutaneous fat of the wound during the second procedure (Figure 5).

Discussion

One of the most effective ways of reducing the risk of postoperative wound infection is by the prophylactic use of systemic antibiotics (Quintiliani and Nightingale 1984). It is self-evident that antibiotics must be given by a suitable route, in sufficient concentration and for a sufficient period of time, to ensure adequate tissue levels during and immediately after surgery (Burke 1961, Bowers Wilson and Green 1973, Hughes et al. 1978, Quintiliani and Nightingale 1984). What has not been sufficiently recognised is that the correct timing of antibiotic administration is essential in operations involving the use of a tourniquet. Moreover, it should also be appreciated that different tissues absorb antibiotics at different rates. For example, cefuroxime penetrates bone in adequate concentrations within 5 minutes of intravenous injection but it takes 10 minutes to reach adequate tissue levels in subcutaneous fat. This is presumed to be due to the poor lipid solubility of cephalosporins. Conversely cefuroxime levels, once established, remain high for much longer in fat than in bone. This may be due to the absence of any appreciable circulation through subcutaneous fat whilst the tourniquet is inflated.

The half-life of cefuroxime in bone in the isolated limb is 121 minutes. Since the drug is not metabolised in the body to any significant extent, the reduction in concentration must be due to re-distribution between the tissues of the leg or elution via the intramedullary circulation.

From the foregoing it may be deduced that;

- The high incidence of superficial infection which was found in this study may result from inadequate antibiotic concentration in the subcutaneous fat rather than in bone.
- The timing of the antibiotic injection prior to tourniquet inflation should take account of the relatively slow uptake of cefuroxime into the subcutaneous fat as compared with bone. Differences in the protocol of antibiotic administration in different centres may account for the wide differences in the incidence of infection following knee arthroplasty. A similar protocol of admin-

istration is recommended for antibiotic prophylaxis in elbow, ankle or other joint replacement performed under tourniquet control. Lower tissue concentrations were achieved in patients weighing 80 kg or more, and these patients may benefit from a larger dose of antibiotic.

Sequential bilateral knee arthroplasty is increasingly popular as it reduces the period of hospitalisation; only one period of mobilisation and rehabilitation is necessary and there may be a benefit to the functional result (Hardaker et al. 1978, Gradillas and Volz 1979).

If only a single injection of antibiotic is used prior to sequential bilateral knee arthroplasty, it should be injected 10 minutes before the first tourniquet is inflated. The antibiotic tissue concentration was found to be adequate during the first procedure. However, during the second procedure the antibiotic concentrations in the bone and subcutaneous fat were significantly reduced, and were below the required concentration in half the cases. This was due to the continued renal excretion of cefuroxime lowering the tissue concentrations ($T_{1/2}$ = 80 min). When the second tourniquet was inflated 2 hours after the first, the antibiotic concentration in the blood perfusing the limb had fallen significantly ($p < 0.01$), and as a consequence the antibiotic concentration in the tissues was also significantly lower ($p < 0.05$).

In order to obtain effective antibiotic prophylaxis in both the bone and the subcutaneous fat of the wound during sequential bilateral knee arthroplasty, it has been proposed that cefuroxime (1.5 g) should be administered 10 minutes prior to inflation of the first tourniquet, and again 10 minutes prior to inflation of the second.

Skin incision for knee arthroplasty

Skin cleavage lines were first described by Dupuytren in 1834. He noticed that the wound resulting from a circular knife was longitudinal rather than circular. The skin cleavage lines are commonly referred to as Langer's lines. Langer in fact wrote his monumental work 27 years after the skin cleavage lines were first described, and he disagreed with some of Dupuytrens' findings (Langer 1978). Cox wrote a thesis on skin cleavage lines which also disagreed with some of the previous patterns (Cox 1941). One of the areas of greatest disagreement has been around the knee.

The importance of skin cleavage lines lies in the influence that they have on wound healing: incisions made parallel to the cleavage lines heal faster, gain strength faster, accumulate collagen faster and result in a neater scar (Ksander, Vistnes and Rose 1977). The confusion about the alignment of the skin cleavage lines around the knee remains.

The skin cleavage lines as documented by thrusting a circular needle through the skin, must not be confused with the skin crease lines which differ in their orientation from the skin cleavage lines in some areas. The skin crease lines have not been demonstrated to have an influence upon the speed of wound healing.

Excessive tension in a healing wound has long been known to have a detrimental effect (Mulliken and Healey 1979, Irvin 1981). Measurement of tension across a wound was first described by Sandblom et al. (1953). Initially wound dehiscence is resisted only by the suture material. Subsequently collagen is produced which forms the fibrous scar. Excessive wound tension on immature or ischemic wounds may result in wound dehiscence. Physiological loads across a mature wound results in earlier maturation of the collagen. The collagen also becomes orientated to resist the load applied (Langrana et al. 1986). The effect of knee flexion in the early postoperative period and the amount of wound tension this generates is unknown, as is the difference in wound tension between the different incisions.

Although the vascularity of the patella has been defined (Scapinelli 1967), a direct inference to wound edge viability cannot be made. The lateral wound flap created by the medial parapatellar incision is longer and relies for its circulation on the superio-lateral geniculate vessels, whereas the lateral skin flap of the anterior midline incision is shorter. If the longer lateral flap of the medial parapatellar incision was hypoxic, this incision would be undesirable.

Material and methods

Langers' lines

The skin overlying the knees of 6 fresh postmortem specimens aged 60–70 years was excised. This gave 12 specimens for analysis. None of the specimens was from patients affected by arthritis or any other pathology in the lower limbs. Using a wooden board, a 2-mm diameter pin of circular profile was used to penetrate the skin. Multiple holes were made over the specimen approximately 3 mm apart. Blue ink was then rubbed over the specimens to reveal the alignment of the resulting small 2-mm slits. The patterns found were recorded onto a chart. There were only minor variations between the alignment in the different specimens. The differences between the specimens were compared, and the 12 charts combined into a single diagram showing the most commonly occurring arrangement of the skin cleavage lines around the knee. The three skin incisions commonly used for knee arthroplasty are; the anterior midline incision, the straight medial parapatellar incision and the curved medial incision. The alignment of these incisions to the skin cleavage lines was studied.

Wound tension

In 6 fresh postmortem specimens aged 60–70 years, each knee was studied, making 12 knees available for testing. None of the specimens was from patients affected by arthritis or any other pathology in the lower limbs. An anterior midline incision was made in one knee of each specimen and a medial parapatellar incision in the other knee (Figure 1). The wounds were left unsutured. The side chosen for each incision was randomly allocated. For the measurement of wound tension during knee flexion the skin tensionmeter described by Sandblom was unsuitable (Sandblom, Petersen and Muren 1953). Therefore a simple tensionmeter was designed using two steel footplates which were glued to the skin either side of the midpoint of each incision. In order to glue the footplates in position the skin needed to be degreased with an alcohol swab. Cyanoacrylic glue was used to fix the footplates in position. The footplates were connected, via a specially constructed cam system, to a Mecmesin force dial which was able to measure up to 10 N (Figure 6). The tensionmeter was positioned across an experimental incision. In full knee extension the force required to

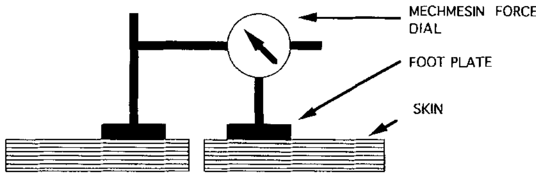

Figure 6. The skin tensiometer designed and constructed for the measurement of tension across the skin incisions during knee flexion.

maintain the skin edges in apposition, as measured on the force dial, was recorded. Repeated measurements were made while the knee was progressively flexed in 10° intervals from full extension to 110° of flexion.

The results were subjected to statistical evaluation using the paired *t*-test to compare the means of each position of the knee, between the two patient groups.

Wound edge hypoxia (Johnson 1988a)

Fourteen knees in 12 patients undergoing total knee replacement for arthrosis were investigated to determine the viability of the wound edges in the perioperative period. The patients were consecutive routine admissions for total knee arthroplasty. The patients were assessed for their age and the presence of any previous scars around the knee. Hematologic assessment included a full blood count and renal function tests. The knees were randomly allocated to one of the three incisions; an anterior midline incision, a curved medial incision or a medial parapatellar incision (Figure 1).

The proposed incision was marked on the skin. Transcutaneous skin oxygen tension measurements ($TcPO_2$) were taken preoperatively from the medial and lateral wound edges adjacent to the midpoint of the proposed incision. Each of the procedures was performed under antibiotic prophylaxis of 1 gram cefuroxime administered 10 minutes prior to application of the tourniquet, in a conventional turbulent flow operating theatre. At surgery, the skin incision was made as marked out. Gentamicin-containing cement was used in all cases. Interrupted 3.0 nylon mattress sutures were used for skin closure. Skin fixation rings for the transcutaneous oxygen electrode were then sterilised in Cidex, irrigated in sterile saline and fixed to the marked sites on the skin after wound closure. The wounds were dressed with Mepore adhesive dressing with holes cut out over the fixation rings. The knees were lightly bandaged in a wool and crepe bandage. The knees were kept immobilised in extension for 7 days to optimise the traditional conditions for wound healing of rest, immobilisation and elevation, and to avoid the wound tension associated with knee flexion.

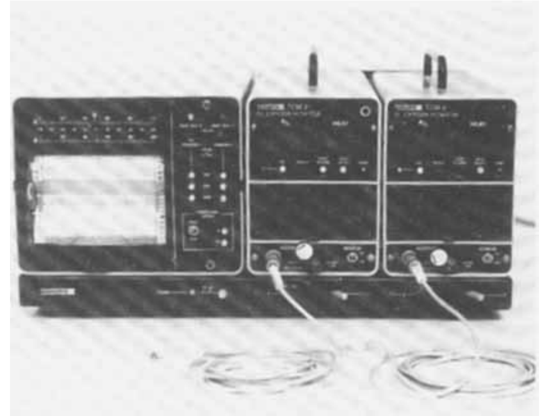

Figure 7. The radiometer TCM 204 oxygen monitor for the transcutaneous measurement of skin oxygen tension with the chart recorder.

In order to obtain postoperative recordings, a hole was cut through the wool and crepe bandage to gain access to the fixation rings. Recordings could then be taken throughout the postoperative period without necessarily exposing the wound. Recordings were taken preoperatively and on the first and eighth postoperative day. The wounds were inspected daily, and the site and severity of any wound healing problems noted. If any wound discharge was present a bacteriological culture swab was taken.

Throughout this study and subsequent studies the technique of $TcPO_2$ measurement was standardised, using the Radiometer TCM 204 oxygen monitor, with a chart recorder (Figure 7), and the E5242 $TcPO_2$ electrode (Figure 8). During the measurements the patients were placed supine, with pillows to support the head comfortably, resting in a warm room above 21 °C for at least 30 minutes prior to the start. The skin was prepared by cleaning with an alcohol wipe. A plastic self adhesive fixation ring was attached to the skin, a drop of contact fluid was placed on the skin and the electrode screwed into the fixation ring (Figure 9). The electrode heated the skin to a measured 44 °C causing maximal dilation of the cutaneous capillary network, and this temperature was then automatically maintained. The power necessary to maintain the electrode temperature was displayed on the monitor. After an interval of approximately 15 minutes an equilibrium was achieved between the cutaneous capillary network and the oxygen electrode. The heater power used diminished to a steady constant figure, and a short while later the oxygen tension measurement would also reach a steady constant recording. The skin oxygen tension was then noted. The electrode heater power and the oxygen tension were also automatically recorded on to a chart recorder, by the Radiometer TCM 204 monitor.

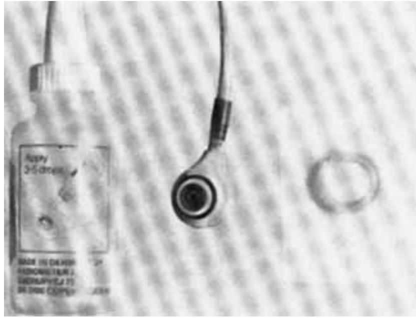

Figure 8. The radiometer E5242 $TcPO_2$ electrode for the transcutaneous measurement of skin oxygen tension, the electrode fixation ring which sticks onto the skin, and the electrode fluid, a few drops of which are placed inside the fixation ring prior to the electrode being screwed in place.

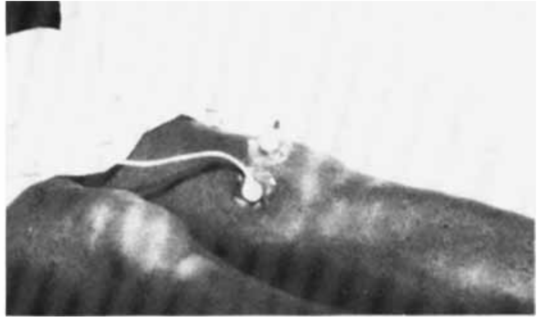

Figure 9. A volunteer demonstrating the method of recording with the patient resting supine. The electrode fixation rings are stuck onto the skin either side of the midpoint of the incision. The electrodes are screwed into position and connected to the TCM 204 oxygen monitor and chart recorder.

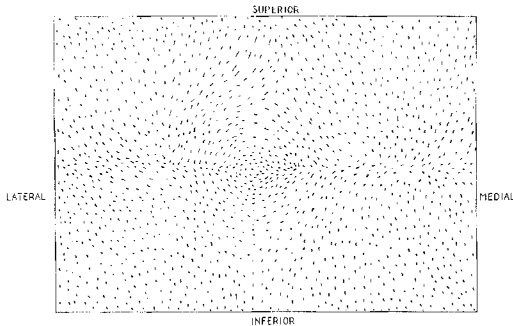

Figure 10. The alignment of the multiple small puncture holes in the skin removed from around a cadaveric knee.

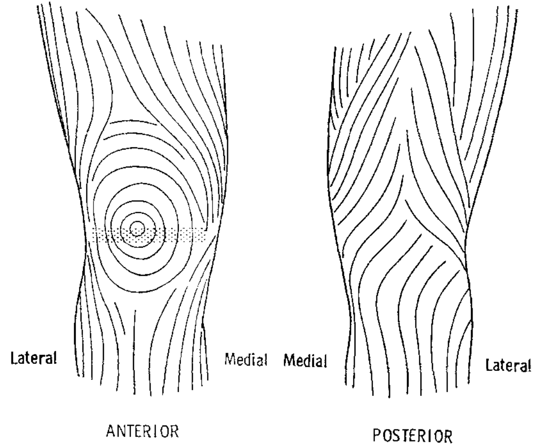

Figure 11. Anterior and posterior view of the right knee showing the pattern of skin cleavage lines. The shaded area represents the area of chaotic inconsistent orientation.

Statistics. The postoperative changes in the skin oxygenation was subjected to statistical analysis. The 'between group' differences were analysed using two way analysis of variance. Further analysis to identify the significant relationships in the data was performed by two-sample and paired *t*-tests. 'Within patient' comparison of the wound-edge skin oxygenation on sequential days was performed using paired *t*-tests. The presence of wound healing problems in the groups was analysed using contingency table analysis.

Results

Langer's lines

The pattern of cleavage lines found around the knee differed from that reported by previous authors (Figure 10). The arrangement of the skin cleavage lines as recorded on the charts was very similar for all of the 12 specimens. The oblique alignment found above the knee on the thigh continued down around the sides of the knee before converging below it. A circular pattern was found around the patella. The only variability in alignment was at the level of the joint line, where a zone of skin around the knee at the level of the tibiofemoral joint line was found to contain a chaotic and inconsistent pattern of lines (Figure 11).

The alignment of the skin cleavage lines was then compared to the three commonly used incisions for knee arthroplasty (Figure 1). It was clearly apparent that the anterior midline incision across the front of the knee was perpendicular to the alignment of the skin cleavage lines for the vast majority of its length. The straight medial parapatellar and the curved medial incision were aligned parallel or nearly parallel to the cleavage lines over their entire length (Figure 11).

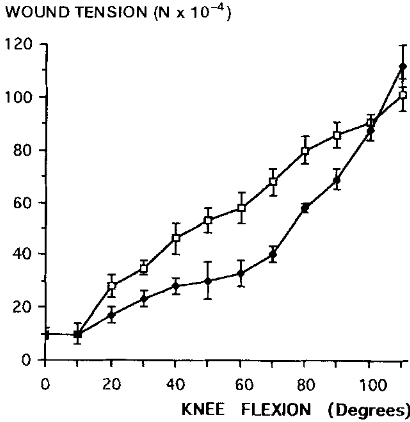

Figure 12. The mean wound tension and SD generated at each 10° of knee flexion for the anterior midline (□) and the medial parapatellar (●) incisions.

Table 9. Mean $TcPO_2$ (mmHg) and *SD* in the three incisions studied over the perioperative period

Side/Incision	n	Preoperative		Postoperative Day 1		Postoperative Day 8	
Medial wound edge							
Anterior midline	5	65	*17*	37	*18*	61	*14*
Medial parapatellar	5	52	*16*	29	*10*	45	*10*
Curved medial	4	55	*13*	32	*14*	62	*15*
Mean	14	58	*15*	33	*14*	56	*13*
Lateral wound edge							
Anterior midline	5	59	*19*	24	*16*	51	*11*
Medial parapatellar	5	47	*16*	17	*9*	40	*11*
Curved medial	4	53	*11*	18	*13*	41	*14*
Mean	14	53	*15*	20	*13*	44	*12*
Overall mean	14	55	*15*	26	*14*	50	*13*

Wound tension (Figure 12)

When the knee was fully extended or was flexed to 10° the wound tension was minimal and the same for the two incisions. However, during knee flexion from 10° to 90° the anterior midline incision was subjected to a progressive increase in wound tension which had a disrupting effect upon the wound.

In contrast there is only a small increase in tension across the medial parapatellar incision when knee flexion was below 60°. The tension increased from 0.01 N at 10° of knee flexion, to 0.034 N at 60° of knee flexion. Further flexion resulted in an exponential increase. If limited knee flexion of only 40° was performed following a medial parapatellar incision only minimal tension was generated. The anterior midline incision was meanwhile subjected to a gradual increase throughout the range of flexion, and until 90° of knee flexion was exceeded the tension in the anterior midline incision was greater. The tension across the anterior midline incision was 0.57 N at 60° of knee flexion. The difference in the tension measured across the two incisions between 10° and 90° of knee flexion was significant ($p < 0.001$).

Wound edge hypoxia

The $TcP0_2$ measurements demonstrated that there was a significant reduction in the oxygenation of the wound both of the medial and lateral wound edges. The reduction measured on the first postoperative day averaged over 60% of the preoperative value ($p < 0.01$). The oxygenation of the wound improved during the postoperative period such that the $TcPO_2$ measurement on the eighth postoperative day was not significantly different from the preoperative value, though it still averaged approximately 15% less (Table 9).

When the medial and lateral sides of the incisions were compared in the preoperative period, the $TcPO_2$ of the medial wound edge was not different from that of the lateral wound edge. In the postoperative period, the oxygenation of the lateral wound edge was significantly reduced as compared to the medial wound edge ($p < 0.01$; Table 8).

Although the absolute values for the oxygenation of the anterior midline incision were marginally higher than the values for the other incisions, there were no significant differences between the $TcP0_2$ measurements on the medial side of the incisions. Assessment of the lateral wound flap skin oxygenation demonstrated higher $TcP0_2$ values in the smaller lateral wound flap of the anterior midline incision than in the larger lateral wound flaps of the other incisions. Once again the differences were marginal and not significant ($p > 0.3$).

Of the 14 cases clinical evidence of a delay in wound healing occurred in only 2. In both cases there was discolouration of the central part of the lateral wound edge following a curved medial incision. In each case, wound healing occurred after a period of immobilisation. The preoperative $TcPO_2$ measurement was of no value in the prediction of these wound healing problems. However, both patients were found to have very low $TcPO_2$ measurements in the lateral wound edge on the first postoperative day. Even in this small study the largely abandoned curved medial incision appeared to be associated with a higher incidence of wound healing problems and poor oxygenation of the lateral wound flap.

Discussion

Langer's lines

Primary wound healing is of paramount importance following arthroplasty of the knee as wound breakdown and superficial infection have been demonstrated to predispose to deep infection and failure of the arthroplasty. Mobilisation was undertaken early in the postoperative course in order to attain a good range of knee flexion without the need for manipulation, and to reduce the incidence of venous thrombosis. If mobilisation was undertaken before the wound was soundly healed, it may slow down wound healing or the wound may be disrupted.

There are three primary incisions for knee arthroplasty; the curved medial incision, the straight medial parapatellar incision and the anterior midline incision (Figure 1). The old fashioned curved medial incision has largely fallen into disrepute because it was associated with a high incidence of wound breakdown and infection. The two other incisions are commonly used.

This simple study has shown that whilst an anterior midline incision lies perpendicular to the cleavage lines for much of its length, a medial parapatellar incision lies parallel to the lines. The medial parapatellar incision can therefore be expected to heal faster, gain strength faster, accumulate collagen faster and to heal with a neater scar (Ksander, Vistnes and Rose 1977). In order to help prevent wound breakdown progressing to a deep infection, it is helpful to site the skin incision so that it does not lie over the capsular incision. Though it is closer to the capsular incision, the medial parapatellar incision need not lie directly over it (Figure 13). The medial parapatellar incision does not restrict the surgeon, as exposure of the lateral compartment may easily be obtained by careful wound retraction.

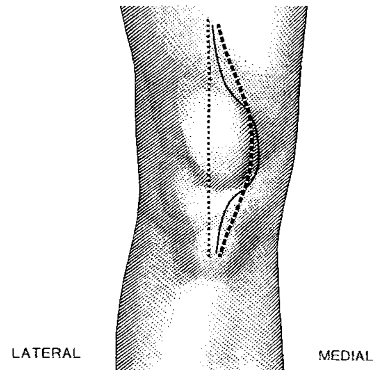

Figure 13. The anterior midline incision and the medial parapatellar incision in relation to the capsular incision. The medial parapatellar incision need not overlie the capsular incision.

Wound tension

This study has demonstrated that during the early postoperative period, while the wound was susceptible to disruption, the medial parapatellar incision was subjected to significantly less tension and therefore experienced lower disruptive forces than an anterior midline incision. If the medial parapatellar incision is used, knee flexion to 50° results in only a small increase in wound tension .

Wound edge oxygenation

The oxygenation of the skin over the anterior and medial aspects of the knee was poor preoperatively compared to the skin oxygenation over the hip, the chest wall and elsewhere on the extremities in such sites as: the forearm, the hip, the front of the thigh, the front of the tibial and on the dorsum of the foot (Rooth et al. 1976, Rooth Hedstrand and Ogren 1979, Dowd, Linge and Bentley 1983). The skin oxygenation in all the wounds was dramatically reduced in the early postoperative period and it did not fully recover to normal by the eighth postoperative day. The hypoxic wound can be expected to heal slowly, and to be prone to wound breakdown and infection. Knee flexion during this early postoperative period may further delay wound healing and increase the risk of wound breakdown and infection. This postoperative wound hypoxia may be the major factor causing knee arthroplasty to be more susceptible to a failure of wound healing and wound infection than hip arthroplasty.

The lateral edge of the wound has been found to have a significantly lower oxygenation and viability than the medial side throughout the postoperative period. When the oxygenation of the long lateral skin flap of the medial parapatellar incision was compared with the shorter lateral skin flap of the anterior midline incision, the medial parapatellar incision showed no significant reduction in wound oxygenation. On the basis of alignment to the skin cleavage lines and wound tension, the medial parapatellar incision was preferred for knee arthroplasty.

The lateral parapatellar incision though minimising the size of the lateral skin flap has certain disadvantages. Exposure of the medial side of the joint is restricted. If a lateral parapatellar capsular incision is also used the capsular incision lies directly under the skin incision. If a medial parapatellar capsular incision is used a large medially based skin flap is created. If in addition a lateral release is necessary the knee joint and the exposed prosthesis will lie directly beneath the skin suture line. Therefore the oxygenation of the lateral parapatellar incision was not studied.

Wound hypoxia—the effect of knee surgery

Metabolic factors in wound healing

The constant process of synthesis and lysis of tissue collagen is greatly exaggerated in healing wounds. During the first 48-hour phase of wound healing there is minimal synthesis of collagen. Continued collagen lysis reduces the collagen content in the wound edges. Subsequently collagen synthesis increases rapidly accompanied by an increase in the mechanical strength of the wound. The collagen initially produced in healing wounds is of type-III collagen. This type of collagen is usually present only in minute quantities in skin. The synthesis of type-III collagen requires the amino acids methionine and cystine, which are not required in the synthesis of the proline and lysine-rich alpha chains. The presence of ferrous ions, ascorbic acid, alpha-ketoglutarate, several co-enzymes and molecular oxygen are also required.

A large number of factors, within both the patient and the environment, have been alleged to alter the course of wound healing. Wound infection disturbs the metabolism of collagen resulting in an increased collagen lysis via polymorphonuclear leucocytes (Irvin 1976), and a depressant effect on fibroblasts (Smith and Enquist 1967, Segree et al. 1970, Irvin 1976, Irvin and Hunt 1984). The amino acids methionine and cystine are essential in the synthesis of type-III collagen and their deficiency accounts for the delay in wound healing associated with hypoproteinemia (Udupa, Woessner and Dunphy 1956). Diabetes (Goodson and Hunt 1979), jaundice (Irvin et al. 1978) and uremia (McDermott, Nayman and DeBoer 1971) all have a detrimental effect on fibroblast function and wound healing. Anemia, however, has very little effect on wound healing, as long as the blood volume is maintained and hypotension does not occur (Hunt 1970). Hypotension results in diminished peripheral circulation with detrimental effect on wound healing (Levenson, Birkhill and Waterman 1950).

The environmental temperature affects the speed of wound healing. When the ambient temperature is reduced the rate of accumulation of collagen diminishes and vice versa (Hunt and Zederfeldt 1969). These effects are abolished by prior denervation. Therefore the effect of ambient temperature is mediated by the sympathetic control of skin circulation.

Zinc is an essential co-enzyme in association with DNA-polymerase and reverse transcriptase. In zinc deficiency cellular proliferation in the wound does not occur and healing is delayed. Vitamin C is essential for the synthesis of collagen and formation of scar tissue (Dunphy, Udupa and Edwards 1968). In a similar way vitamin E significantly retards wound healing and collagen production. Vitamin A, in high doses, promotes wound healing and has the ability to reverse the detrimental effects of corticosteroids and vitamin E (Ehrlich and Hunt 1968, Salmela and Ahonen 1981).

Most commonly used corticosteroids tend to inhibit wound healing in laboratory animals (Hinshaw, Hughes and Stafford 1961), and also in the clinical setting (Lindstrum et al. 1977). Nonsteroidal anti-inflammatory agents have a similar action to corticosteroids on wound healing (Salmela and Ahonen 1981). The effect on delaying wound healing and collagen accumulation is dose dependant, with very little effect at therapeutic concentrations.

Oxygen and wound healing

The growth of new granulation tissue, and therefore connective tissue healing, is critically dependant on the formation and extension of new blood vessels into the wound space. It is a matter of common observation that new vessels grow towards the centre of a wound and thus towards hypoxic regions (Silver 1973, Remensnyder and Majno 1968). Until recently it was not clear what controlled this directional angiogenesis. The macrophages are now known to be directed into the centre of a wound by the oxygen tension gradient, the hypoxic macrophages secrete an angiogenic factor, and angiogenesis is then directed by the gradient of angiogenic factor (Knighton, Silver and Hunt 1981). The angiogenic factor is not secreted in normal oxygen tensions nor in completely anoxic environments. Thus stimulation of angiogenesis is dependant on a finely balanced series of gradients. If the normal wound oxygen tension gradient is eliminated artificially, by local oxygen therapy to the wound or hyperbaric oxygenation, angiogenesis may be inhibited temporarily or permanently (Banda, Dwyer and Bechman 1985). Conversely, if inspired oxygen therapy results in circulating hyperoxia, then the oxygen gradient from the capillaries to the centre of the wound is greater, and enhancement of angiogenesis and wound healing may be expected (Hunt and Pai 1972, Niinikoski, Hunt and Dunphy 1972, Hunt and Dunphy 1980). Under anoxic conditions neither cellular movement nor cell division

occur, but cells can survive for periods of up to seven days at body temperature in a vegetative state (Medawar 1947).

The importance of oxygen in wound healing has not been universally appreciated in clinical practice, although it is well established that certain elements in tissue repair are oxygen dependant (Hunt and Pai 1972, Niinikoski 1977, Bucknall 1984, Silver 1985, Kaufman and Alexander 1988). It is also a common observation that wounds heal poorly at high altitude where the oxygen tension is low (Monge and Lui 1983). Conversely, they are difficult to infect, and heal quickly in oxygen enriched atmospheres (Niinikoski 1977).

Starr (1932) was the first to apply oxygen therapy to intractable wounds when he introduced the 'oxygen boot' for the treatment of gangrene of the feet. It is only relatively recently that oxygen has been used systemically in various ways to improve healing of simple and indolent wounds. An investigation into the effects of oxygen enriched atmospheres on several aspects of wound healing have demonstrated that the speed of healing can be improved by raising the tissue oxygen tension (PO_2) of the wound (Niinikoski and Kulonen 1970, Hunt and Dunphy 1980, Hunt et al. 1984). This appears to be partly due to the enhancing effect of raised oxygen tension on the ability of phagocytes to destroy invading micro-organisms, and partly to the improved energy supply provided by oxidative as opposed to glycolytic metabolism. Molecular oxygen is also required in the synthesis of collagen (Niinikoski 1977).

It has been demonstrated that wound strength, and collagen accumulation in experimental wounds, is accelerated when oxygen tension is raised; and diminished when it is lowered (Niinikoski Hunt and Dunphy 1972, Hunt and Pai 1972, Kivisaari and Niinikoski 1975). Most local factors such as wound hematoma or contusion are mediated through poor tissue oxygenation and have an adverse effect on wound healing (Sharp 1987). In the absence of infection, malnutrition or metabolic abnormalities, tissue oxygen tension is the rate limiting factor of wound healing (Knighton, Silver and Hunt 1981, Silver 1985).

Fibroblasts are aerobic cells, and require oxygen for both division and collagen synthesis (Pikkareinen and Kulonen 1973). They may easily be damaged, especially when in the growth phase, by a hostile hypoxic microenvironment such as they encounter in wounds during hypovolemic shock (Silver 1973). Collagen synthesis and the consequent development of early wound strength has been shown to be critically dependant on oxygen supply (Hunt and Pai 1972). Fibroblast activity is stimulated by moderately elevated tissue oxygenation, is maximal at 70% oxygen environment. It is reduced if the tension is increased further to 100%, or to increased atmospheric pressure in a hyperbaric oxygen environment (Niinikoski 1977). This activity may be associated with the reduced blood supply and substrate limitation which occurs in hyperoxygenated tissue. Fibroblast synthesis of collagen is deficient in quantity and quality in tissues where the local tissue oxygenation is below 20 mmHg. As the wound tissue oxygen tension is reduced below 20 mmHg, the quantity of collagen is initially diminished; and the disulphide cross linkage, which confers the strength of collagen, is absent. When further local tissue hypoxia occurs, and the wound tissue oxygen tension falls to less than 10 mmHg, collagen synthesis is absent (Goodwin and Heppenstall 1977, Niinikoski 1977).

Macrophages are probably the key cells in the initiation and maintenance of connective tissue repair, and interact with a very wide range of other cells, such as the fibroblasts. They are also the primary agents in debridement of debris and bacteria in the wound. They secrete proteolytic enzymes as well as chemotatcic and mitogenic agents. Their microbiocidal activity is dependant on both oxidative and anaerobic systems. The most effective is the oxidative microbiocidal system. This involves the oxidative generation of free radicals such as superoxide (O_2-), singlet oxygen and hydroxyl radicals. These are oxygen dependant systems and require molecular oxygen to recharge them when they have been used. Generation of these free radicals for aerobic bactericidal action is deficient in tissues where the local tissue oxygenation is below 20 mmHg, and is absent in tissues where the tissue oxygenation is below 10 mmHg. However, the macrophage migrates into wounds where the oxygen tension is as little as 5 mmHg, although the bactericidal action in these tissues is absent (Niinikoski 1977). A supply of oxygen to wound macrophages ensures their maximum efficiency. The nonoxidative bactericidal function is not effective against the staphylococci and the E. Coli bacteria, therefore these organisms are particularly virulent in hypoxic tissues (Niinikoski 1977).

Oxygen is therefore a necessary component for rapid and effective wound healing, and oxygen gradients across a wound edge are important in ensuring the correct growth patterns. Excessive amounts of oxygen in the centre of the wound, which eliminate the gradients, inhibit connective tissue repair. Conversely, systemic hyperoxia, which increases the oxygen gradients, enhances repair (Silver 1985).

It has recently been demonstrated by Dodds (1989) that patients following joint replacement under general anesthesia, have a surprising degree of arterial desaturation. This may have many causes, such as pulmonary ventilation-perfusion mismatch, pulmonary shunting

due to local atelectasis or possibly central respiratory depression. Hyperbaric oxygen elevates the systemic oxygen tensions, but also elevates the local oxygen tensions in open wounds. The net effect upon the wound edge oxygenation is not resolved. In the clinical setting hyperbaric oxygenation can only be used for one or two hours per day; and therefore only has a very temporary effect. The oxygen tension in the peripheral blood may easily be increased by the addition of inspired oxygen. This has been shown to be the most efficient clinical means of increasing macrophage and fibroblast function and to promote wound healing (Niinikoski 1977).

Measurement of tissue oxygen tension

The clinical assessment of wound healing and infection is notoriously difficult and beset with inaccuracies and observer error. The desire for an objective measurement of peripheral vascular disease without the necessity to resort to invasive arteriography with its associated complications, has led to the development of noninvasive techniques. These noninvasive measurements of ischemia have been applied to the prediction of amputation stump healing, skin flap survival and neonatal intensive care.

Oxygenation of the skin can be assessed indirectly by measuring cutaneous blood flow using radioisotope clearance, venous occlusion plethysmography, laser doppler, skin perfusion pressure, pulse oximetry or thermography. The radioactive Xenon-133 clearance technique requires the facilities of a nuclear medicine department, has significant exposure to radioactivity, and is not uniformly reliable (Moore et al. 1981). Skin perfusion pressure measurement involves the invasive injection of labelled antipyrine into ischemic areas and lacks predictive value (Holstein, Sager and Lassen 1979, Holstein, Dovey and Lassen 1979). Venous occlusion plethysmography can be undertaken in the digits or perhaps limbs, but it is not applicable to other more central sites (Abramson 1967). Laser doppler techniques are being assessed for their ability to measure cutaneous blood flow, and indirectly, skin oxygenation. Pulse oximetry is useful in anesthetic practice, but is limited to measurement of a digit or ear lobe. Thermography has been used to assess patients in the preoperative period for the level of amputation and the optimum type of skin flaps (Spence et al. 1981, McCollum et al. 1985). However, the technique of thermography is time consuming and the need for stable reproducible testing conditions means that the results are not uniformly reliable and the technique has not found widespread application.

Alternatively oxygenation of the skin may be measured directly by the use of oxygen microelectrodes. This technique is invasive and cannot be repeated (Silver 1973). The very fine microelectrodes require shielding from electromagnetic fields, and measurements usually require a Faraday cage as stray currents may also cause irregularities. Other problems include the alteration of the microenvironment due to the consumption of oxygen by the probes. Nevertheless, these probes have the ability to undertake single cell investigations (Silver 1973). Implanted wicks, or more recently oxygen sampling chambers, provide the ability to estimate the subcutaneous oxygen tension but not that of the skin. Measurement of skin oxygen tension, rather than subcutaneous oxygen tension is important as it is skin which is the least viable part of the healing wound (Silver 1985, Kaufman and Alexander 1988). Following the development of a transcutaneous skin oxygen electrode the transcutaneous estimation of skin oxygen tension ($TcPO_2$) is now possible.

Transcutaneous measurement of skin oxygen tension

The technique of transcutaneous skin oxygen tension measurement ($TcPO_2$) was first introduced into pediatric practice by Huch et al. (1969). This technique has now been used in the monitoring of respiratory function in neonates and also in many other areas of pediatric practice (Rooth et al. 1976. Lofgren et al. 1978). In the neonate, the estimation of $TcPO_2$ gives an accurate assessment of arterial oxygen tension, except when wide variations occur in blood pressure (Huch, Huch and Lubbers 1969). Although $TcPO_2$ has proven useful in adult intensive care, the measurements are inaccurate immediately following a general anesthetic containing Halothane. The technique has therefore been somewhat superseded by the pulse oximeter in anesthetic practice (Rooth, Hedstrand and Ogren 1979).

Dowd performed many verifications and comparisons between $TcPO_2$ and other means of assessing the ischaemic limb (Dowd 1982, Dowd et al. 1982). The technique of $TcPO_2$ estimation was found to be safe, free of complications, easy to use, noninvasive, reliable and repeatable (Huch, Lubbers and Huch 1972, Dowd 1982. Mani et al. 1988). Dowd and others consider the technique to be superior to other methods of measuring skin viability for determining the capacity of the local circulation to deliver oxygen to the skin (Dowd 1982. Franzech et al. 1982). $TcPO_2$ is an accurate measurement of the oxygen tension in the local dermal arterioles (Rooth et al. 1976), and the technique is rapidly responsive to changes in local circulation (Burgess et al. 1982, Bader and Gant 1985). It has been demonstrated that there is no diminution of the $TcPO_2$ values with age (Dowd 1982). There is no gradient along the lower

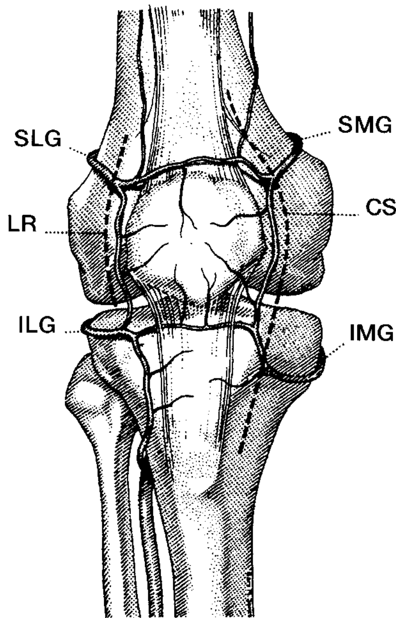

Figure 14 The vascularity of the front of the knee and around the patella. The medial parapatellar capsular incision (CI) divides the superior (SMG) and inferior (IMG) medial geniculate vessels. A lateral release (LR) divides the superior lateral geniculate vessels (SLG).

limb in normally perfused limbs (Matsen et al. 1980, Dowd, Linge and Bentley 1983, Clyne et al. 1982). However, these studies measured sites on the thigh, calf and dorsum of the foot; and not areas of the extensor surfaces such as greater trochanter, knee and sole which might be expected to be less well vascularised. A progressive decrease in $TcPO_2$ down a limb with peripheral vascular disease has been reported (Clyne et al. 1982, Franzeck et al. 1982, Christensen and Klarke 1986).

In peripheral ischemia, $TcPO_2$ has proved effective in the prediction of amputation stump healing, where a preoperative $TcPO_2$ above 40 mmHg is consistent with successful wound healing (Dowd et al. 1982, Christenson and Klarke 1986). Though at 20–40 mmHg amputation stump healing may occur, wound breakdown is common (Wyss et al. 1988). Wound breakdown can be reliably predicted at $TcPO_2$ less than 20 mmHg (Franzeck et al. 1982, Dowd Linge and Bentley 1983, Christenson and Klarke 1986). $TcPO_2$ has also been used for monitoring skin flap survival in plastic surgery (Aucher, Black and Litke 1980), and in the investigation of venous ulceration (Mani et al. 1988).

Certain conditions such as diabetes and rheumatoid arthritis present a restriction to diffusion of oxygen from the capillaries to the cells. In rheumatoid disease there is often vasculitis, perivascular fibrosis or amyloidosis; all of which increase the diffusion distance to the cells, thus reducing the oxygen tension at the cellular level. These factors are constant in individual patients. The $TcPO_2$ technique also relies upon diffusion from the dermal capillaries once they are maximally dilated, and therefore integrates these factors into the measurement. The technique of $TcPO_2$ assesses the oxygen supply to the cells; rather than the arteriolar oxygen tension which may be misleading. In this respect $TcPO_2$ is the most accurate assessment of oxygen tension at the cellular level (Dowd 1982)

Wound edge hypoxia following lateral release of the patella

Lateral retinacular release of the patella is often performed during surgery to correct abnormal tracking. This may be performed in one of three ways; through a separate lateral incision, via an extracapsular prepatellar approach reflecting the lateral skin flap, or by the intracapsular route prior to capsular closure. The superio-lateral geniculate vessels are usually divided to provide adequate release of the lateral retinaculum. Division of the superio-medial geniculate vessels by the incision and of the superio-lateral geniculate vessels by the lateral release may devitalise the patella and prepatellar skin (Figure 14; Scapinelli 1967, Wetzer et al. 1985, Scuderi et al. 1987, Kayler and Lyttle 1988). This devascularised area may be detrimental to the oxygenation of the lateral edge of the wound and so lead to wound healing problems and infection.

Patients and methods

The role of wound edge hypoxia in failed wound healing and infection (Johnson 1988b)

Forty-seven consecutive primary knee replacements were performed over a 6 month period on 44 patients, whose mean age was 70 (46–85) years. Of the 47 cases 37 were performed for arthrosis (20 Kinematic total knee replacements and 17 unicompartmental), and 10 for rheumatoid arthritis (all Kinematic). Previous incisions around the knee were present in 7 of the 47 knees; 6 medial parapatellar incisions for menisectomy or synovectomy and one transverse incision for a high tibial osteotomy. All patients had normal renal function and the pre- and postoperative blood pressure and hemaglobin concentrations were within normal limits.

The 30 Kinematic replacements alone were used for comparison of wound viability between arthrosis and rheumatoid arthritis.

To determine whether any differences existed between the wound viability in patients receiving unicompartmental (n 17) and total knee replacements (n 20), only patients with arthrosis were analysed.

$TcPO_2$ recordings were taken preoperatively from the chest wall, hip and both sides of the proposed medial parapatellar incision in both the knee undergoing surgery and the other knee as a control. For the $TcPO_2$ estimations the radiometer TCM 204 oxygen monitor, E5242 $TcPO_2$ electrode and chart recorder were used, and the measurements recorded as previously described.

All of the arthroplasties were performed under antibiotic prophylaxis of 1 gram cefamandol, administered 10 minutes prior to application of the tourniquet, in a conventional turbulent flow operating theatre. The operation was carried out through a medial parapatellar skin incision. Gentamicin-containing cement was used in all cases. Interrupted 3.0 nylon mattress sutures were used for skin closure. Sterilised $TcPO_2$ electrode holders were attached to the skin adjacent to the mid-point on either side of the wound so that the $TcPO_2$ electrode could be connected to the holders postoperatively and the $TcPO_2$ measured at the same sites throughout the postoperative period. An occlusive dressing and a wool and crepe bandage were applied. Patients were immobilised for seven days in a knee splint to optimise the traditional conditions for wound healing of rest, immobilisation and elevation, and to avoid the wound tension associated with knee flexion.

The clinical state of wound healing was assessed. Wounds were inspected daily during the in-patient stay and intermittently for a period of 12 months postoperatively for evidence of discolouration, dehiscence, discharge or infection. Any discharge was subjected to bacteriological swabbing and identification of any organisms present.

$TcPO_2$ measurements were taken repeatedly from the same sites on either side of the wound on the 1st, 3rd 5th, 7th, 10th, and 14th postoperative day and at subsequent review. Additionally patients were studied while breathing inspired oxygen at a concentration of 24%. In order to determine the effect of the type of arthritis, and the effect of using a unicompartmental prosthesis rather than a total condylar prosthesis, each of these factors was analysed in isolation.

For comparison, 15 patients undergoing hip replacement were analysed in the same way. $TcPO_2$ recordings were taken pre- and postoperatively from the anterior and posterior edges of the wound of a direct lateral incision.

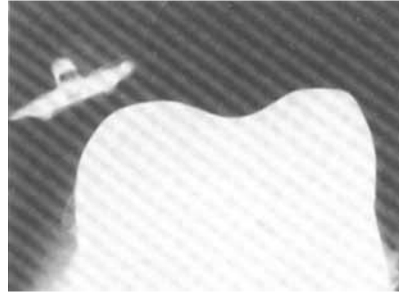

Figure 15. Skyline radiograph of a knee in flexion demonstrating patella subluxation onto the lateral condyle of the femoral component.

The effect of lateral patella release on infection and wound viability

This study included 56 knees in 51 patients undergoing primary total knee replacement with the Kinematic prosthesis of which 35 knees were arthrotic, and 21 had rheumatoid arthritis. All the patients were routine admissions for knee arthroplasty. The mean age of the patients was 69 (36–85) years. Intraoperative lateral release was performed in 8 of the 56 cases. Of these cases 4 had rheumatoid arthritis and 4 arthrosis. The mean age was 64 (52–82) years.

The limb alignment and range of motion were carefully measured with a goniometer preoperatively. At surgery, patellar tracking was assessed in all cases prior to capsular closure using one finger's pressure to aid correct patellar tracking. If deemed necessary, lateral release was performed by the intra-capsular technique. The superior lateral geniculate vessels were not preserved.

The preoperative antibiotic prophylaxis, surgical procedure, postoperative management and $TcPO_2$ measurement routine were the same as previously decribed. However, patients were allowed to mobilise on the third postoperative day if wound healing appeared satisfactory.

Postoperative follow-up was for 2 years in all cases, with examination of wound healing, measurement of the range of motion and alignment. Radiological examination included skyline patella radiographs. Patello-femoral subluxation was defined as clinical or radiographic evidence that the patella was displaced from its groove onto or beyond the top of the lateral femoral facet during knee flexion (Figures 15 and 16).

Statistics

All the results were analysed in conjunction with the statistical services unit of the University of Sheffield, and further calculations were performed using a Stat

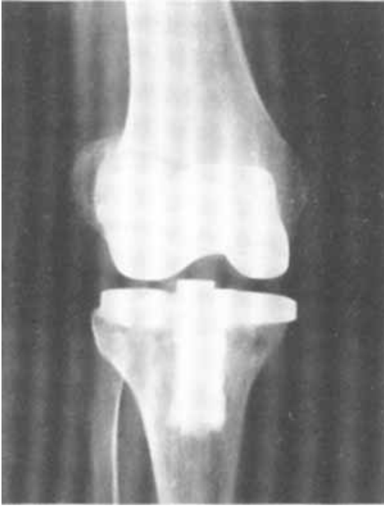

Figure 16. An antero-posterior radiograph of a knee demonstrating a subluxed patella superior to the short femoral flange during knee extension.

View 512+ statistical program and an Apple Macintosh microcomputer. Two-way analysis of variance was used when a comparative analysis of several patient groups was required; where differences were found, further *t*-test analysis was undertaken to identify the significant relationships within the data. Paired *t*-tests were used for 'within patient' comparisons. This included comparative analysis of: the wound edge oxygenation on each postoperative day and the preoperative value; the operated and unoperated knee; and the effect of additional inspired oxygen. Two-sample t-tests were used for the comparative analysis of the statistical effect of the type of arthritis on wound oxygenation, and the effect of knee replacement as compared to hip replacement. Linear regression was used to analyse the dependence of parameters such as wound oxygenation to continuous factors, including age and length of tourniquet time. The correlation coefficient was calculated to determine the correlation between wound edge oxygenation in patients having unicompartmental prostheses and total condylar prostheses.

The relationship between the occurrence of wound healing problems and other factors such as: the patient age, the type of arthritis, the type of prosthesis, and the length of tourniquet time was investigated by linear logistic regression. In the case of binary factors such as arthritis and the type of prosthesis this is equivalent to contingency table analysis.

In the statistical analysis of the effect of a lateral patella release paired *t*-tests were used for 'within patient' analyses, two-sample *t*-tests were used for analysis of lateral release and wound oxygenation and

Table 10. Mean $TcPO_2$ (mmHg) and *SD* preoperatively from the medial aspect of the forearm, the chest wall, the trochanteric region, the knee to be operated on and the contralateral knee

Site		n	$TcPO_2$	
Chest		46	59	*12*
Medial forearm		25	58	*16*
Trochanter		46	52	*14*
Contralateral knee,	medial	46	54	*15*
	lateral	46	42	*10*
Ipsilateral knee,	medial	46	52	*16*
	lateral	46	43 ***	*12*

*** $p < 0.001$.

contingency table analysis was used for analysis of wound healing problems and the effect of lateral release on wound edge oxygenation.

Many statistical tests were undertaken on this data, therefore three working rules have been adopted: For lateral, medial and mean comparisons of wound oxygenation significance will only be declared for the average comparison and only if this comparison proves positive will the lateral and medial wound edges be discussed individually. For comparisons involving wound healing problems statistical significance will only be declared when seen for problems overall and only at that stage will the individual problem areas be described. Tests which form part of a series of comparisons in time, such as will occur when looking at several postoperative days, will be undertaken at the 1% level.

Results

Wound edge hypoxia following knee surgery

In the postoperative period, the wound became discoloured and looked ischemic in 7 cases; of these, 3 became superficially infected ($p < 0.01$). Superficial infection occurred in a total of six cases (13%); there was one case of aseptic wound dehiscence and 5 cases of aseptic wound discharge after the third postoperative day. Thus failed primary wound healing, superficial infection, dehiscence or wound discharge occurred in a total of 12 cases (26%). There were no cases of deep infection. Of the 6 superficial infections, the organisms cultured were *Staphylococcus aureus* in one, *Staphylococcus albus* in 4, and *Streptococcus faecalis* in one.

Objective measurement of skin viability performed by $TcPO_2$ estimation demonstrated a gradient between the chest (59 mmHg), peripherally to the trochanteric region of the hip (52 mmHg) and to the antero-medial aspect of the knee (48 mmHg; $p < 0.001$; Table 10). The

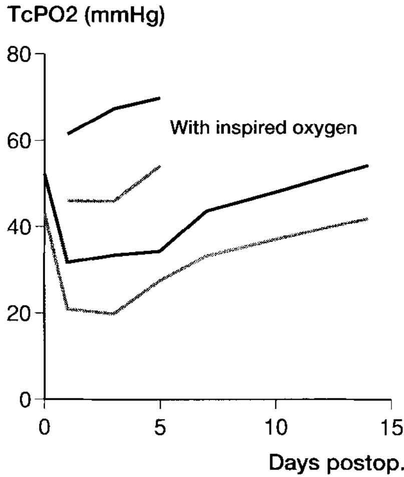

Figure 17A. The transcutaneous skin oxygen tension on the medial (black) and lateral sides (gray) of the wound, with and without breathing 24% oxygen.

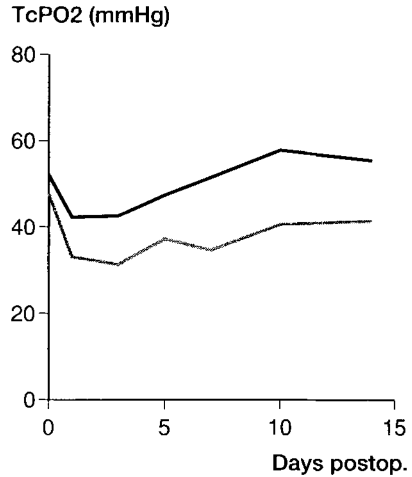

Figure 17B. The transcutaneous skin oxygen tension on the anterior (black) and posterior sides (gray) of the wound after hip arthroplasty through a straight lateral incision.

oxygen tension in the skin overlying the front of the knee was poor, and reflected a level similar to that found in ischemic limbs with peripheral vascular disease (Dowd et al 1982). The operated and unoperated knee, did not differ in their skin oxygenation as might be predicted (Table 10).

However, even preoperatively the medial wound $TcPO_2$ was significantly higher than that of the lateral wound edge (43 mmHg; $p < 0.001$; Figure 17). A low preoperative $TcPO_2$ recording did not significantly predispose to postoperative failed wound healing and infection.

The $TcP0_2$ recordings repeated on the first postoperative day demonstrated a significant fall in skin viability of the knee undergoing replacement (26 mmHg) compared with the preoperative measurements (48 mmHg; $p < 0.001$), and to the contralateral knee ($p < 0.001$). The lateral wound edge (21 mmHg) was significantly less well oxygenated than the medial side (32 mmHg; $p < 0.001$; Figure 17). At some time in the first 3 days, 44% of patients had a period where the wound oxygen tension was below the critical 20 mmHg level. Those cases having severe or prolonged wound hypoxia in the first seven days were associated with wound discolouration, infection ($p < 0.01$) and aseptic wound healing problems ($p < 0.05$; Figure 18). The effect of inspired 24% oxygen was to increase the wound oxygen tension within 5 minutes to a level greater than the preoperative level ($p < 0.001$), in both the medial (61 mmHg) and lateral (46 mmHg) wound edges (Figure 17). This effect of inspired oxygen was apparent throughout the early postoperative period.

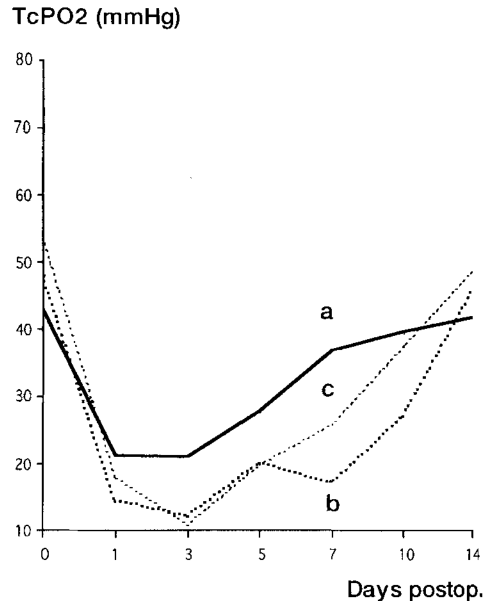

Figure 18. Wound edge skin oxygenation in those patients with (a) normal wound healing, (b) those with wound discolouration, and (c) those with superficial infection.

The wound oxygen tension steadily improved in the postoperative period. However, it remained significantly lower than preoperatively until the 10th postoperative day in the medial wound edge, and until the 14th postoperative day in the lateral wound edge (Figure 17). Subsequently, over the next 12 months, the wound

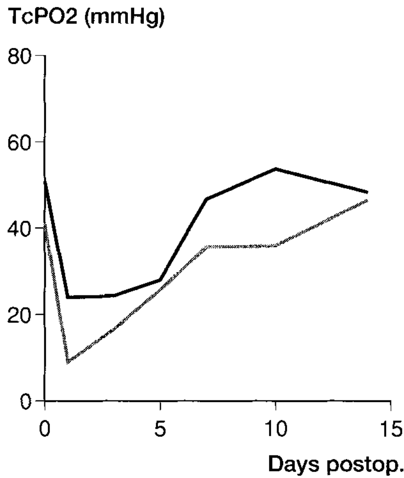

Figure 19A. Transcutaneous skin oxygen tension in the medial (black) and lateral (gray) wound edges of rheumatoid arthritic knees treated with Kinematic total knee replacements.

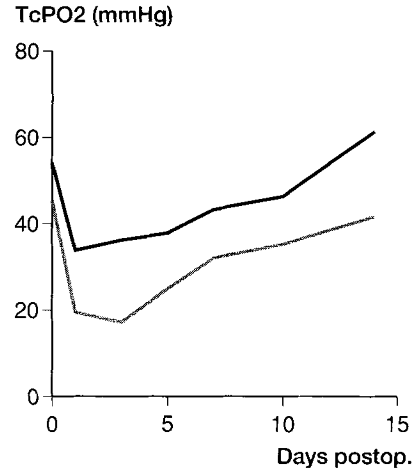

Figure 19B. Transcutaneous skin oxygen tension in the medial (black) and lateral (gray) wound edges of arthrotic knees treated with Kinematic total knee replacements.

oxygen tension did not increase further. Increasing age, and the presence of previous incisions did not significantly alter wound oxygen tension preoperatively or postoperatively, nor did they increase the incidence of problems with wound healing. The 13 patients who had a prolonged tourniquet time of over 120 minutes suffered some slight diminution in the oxygen tension in the wound edges, but no increase in the incidence of infection.

Of the 30 patients receiving Kinematic total prostheses, 10 suffered from rheumatoid arthritis and 20 from arthrosis. Wound discolouration occurred in 2 of the rheumatoid patients and 2 arthrotic patients. Superficial infection occurred in 2 of the rheumatoid patients and one arthrotic.

$TcPO_2$ measurement preoperatively demonstrated no differences between the groups of patients ($p > 0.9$). The mean preoperative measurement was 46 mmHg in rheumatoid patients, and 50 mmHg in arthrotic patients. The $TcPO_2$ recordings on the first postoperative day demonstrated a reduction in the wound viability in all patients. However, the skin oxygenation was significantly less in the rheumatoid patients (mean 17 mmHg) than in the arthrotic patients (mean 27 mmHg; $p < 0.01$; Figure 19). This difference was also present on the third postoperative day, when $TcPO_2$ was 20 mmHg in the rheumatoid patients and 27 mmHg in the arthrotic patients. The differences between rheumatoid and arthrotic patients was particularly apparent in the oxygenation of the lateral wound edge. On the first postoperative day, $TcPO_2$ in the lateral wound edge of rheumatoid patients was lower (mean 9 mmHg) than in the arthrotic patients (mean 20 mmHg; $p < 0.001$). The skin oxygenation on the medial side of the wounds in the rheumatoid patients was lower (mean 24 mmHg), than in the arthrotic patients (mean 34 mmHg) but the differences was not significant ($p < 0.09$). The differences were most marked on the first postoperative day, thereafter the differences diminished (Figure 19).

There were 17 arthrotic patients in whom unicompartmental arthroplasties were performed and 20 in whom Kinematic total implants were inserted. Wound discolouration occurred following 3 unicompartmental arthroplasties, and 2 Kinematic arthroplasties. Superficial infection occurred in 3 unicompartmental arthroplasties and one Kinematic arthroplasty.

$TcPO_2$ measurement of wound viability demonstrated no significant difference in the preoperative wound viability. Wound viability on the first postoperative day averaged 30 mmHg in the unicompartmental arthroplasties and 27 mmHg in the total knee arthroplasties; there being no significant difference. Similarly on the third postoperative day the wound viability was identical in the two groups of patients (mean 27 mmHg; Figure 20). At no time in the postoperative period was the wound oxygenation, as measured in the medial or lateral wound edge, or the mean of the two measurements, significantly different between patients in whom different prostheses had been inserted. Statistical analysis revealed the correlation coefficient to be 0.928 between the wound viability of those patients receiving unicompartmental and Kinematic total condylar arthroplasties (Figures 20 and 21). Therefore for subsequent analyses the wound viability will be considered as not

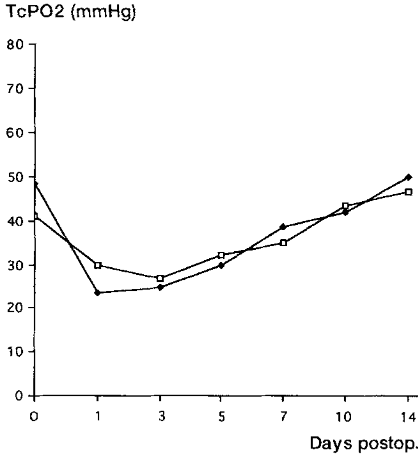

Figure 20. Transcutaneous skin oxygen tension in the wounds of patients receiving unicompartmental (◆) and total (□) knee prostheses.

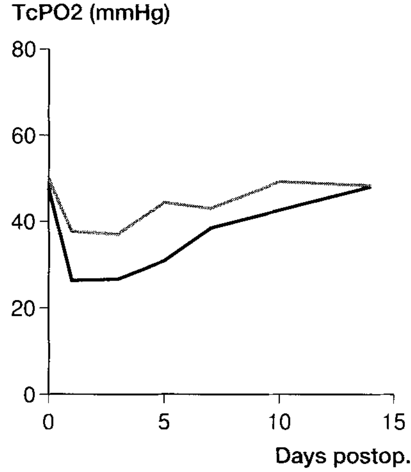

Figure 22 Transcutaneous skin oxygen tension in the wound edges following knee arthroplasty (black) and hip arthroplasty (gray).

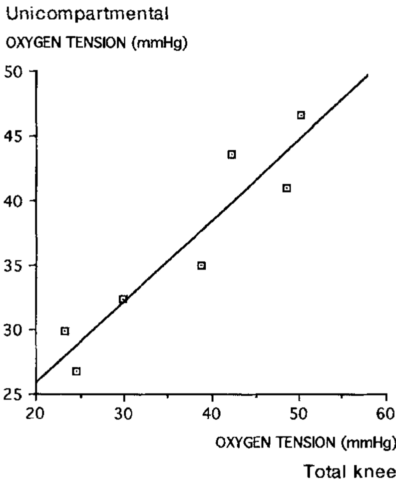

Figure 21. The correlation (0.928) between the skin oxygen tension in patients receiving unicompartmental and total knee prostheses.

being influenced by the choice of a unicompartmental or a total condylar prosthesis.

Increasing age and the presence of previous incisions did not significantly alter wound oxygen tension preoperatively or postoperatively, and did not increase the incidence of wound healing problems. The 13 patients who had a prolonged tourniquet time of over 120 minutes suffered some diminished oxygen tension in the wound edges, but no increase in the incidence of infection.

The average age of the 15 arthrotic patients undergoing Charnley total hip replacement through a lateral approach was 71 (60–86) years. The $TcPO_2$ measurements from the midpoint of the anterior and posterior wound edges demonstrated that preoperatively there is no difference in the anterior and posterior skin oxygen tension. During the postoperative period the anterior wound edge never suffered any hypoxia. The posterior wound edge had only a minor degree of hypoxia during the period from the 1st to the 7th day ($p < 0.05$), though the skin oxygen tension remained safely above 30 mmHg; significantly higher than found in the knee arthroplasty wound ($p < 0.001$; Table 10, Figure 22).

The effect of lateral patella release on infection and wound viability

Lateral wound edge discolouration occurred in 8 of the 56 knees. Of the 8 cases having a lateral patella release 4 sustained wound discolouration ($p < 0.01$). No deep infection occurred in this series. Superficial wound infection occurred in a total of 5 of the 56 knees (9%). Of the 8 cases having lateral release, 3 suffered superficial infection (40%), whilst only 2 of the 48 cases not having a lateral patella release suffered superficial infection (4%; $p < 0.01$). The organisms cultured were *Staphylococcus epidermidis* in 4 and *Staphylococcus aureus* in one. All of the wound infections settled with wound debridement, immobilisation and antibiotics.

Patella subluxation occurred in 3 of the 48 knees with stable patella tracking during surgery without patella release. In an additional 9 knees a minor degree

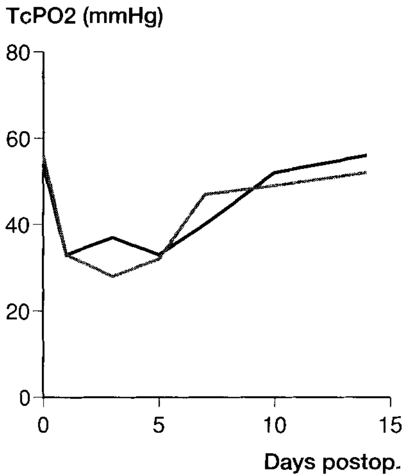

Figure 23A. The transcutaneous skin oxygen tension in the medial wound edge perioperatively in patients who had had a lateral release (black), and in those not having had a lateral release (gray).

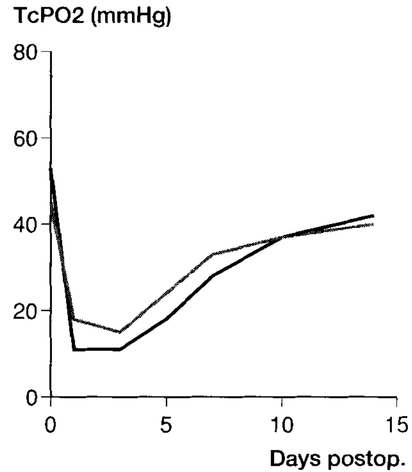

Figure 23B. The transcutaneous skin oxygen tension in thelateral wound edge perioperatively in patients who had had a lateral release (black), and in those not having had a lateral release (gray).

of lateral patella tracking was noted during early flexion, which spontaneously corrected beyond 30° of flexion. Of the 8 knees having lateral patella release because of patella instability at operation, none suffered patella subluxation postoperatively.

Postoperatively, the mean range of knee flexion was 103° in those patients having lateral release, where as it was only 99° in those not having a lateral release. The fixed flexion and extensor lag deformities were similar in the two groups. The Hospital for Special Surgery (HSS) knee assessment score was calculated for all patients at the final review (Insall et al. 1985). The score averaged 78 points, while those patients having lateral release averaged slightly higher at 84.

The lateral wound edge had a significantly lower $TcPO_2$ than the medial wound edge both preoperatively ($p < 0.001$), and postoperatively ($p < 0.001$). Lateral release, dividing the superior lateral geniculate vessels, resulted in a significant further reduction in the oxygenation in the skin of the lateral wound edge ($p < 0.02$; Figure 23).

Lateral patella release was performed in 4 of the 35 cases with arthrosis. Of these 4 cases, 2 wounds became discoloured, of which one became superficially infected. Of the 31 cases not having a lateral release, 4 wounds became discoloured and 2 sustained a superficial infection. In these arthrotic patients the postoperative $TcPO_2$ was reduced by a lateral patella release. The lateral skin edge oxygenation was 12 mmHg in the 4 patients who had lateral release and 15 mmHg in those who had not. Patello-femoral subluxation did not occur in any of the 4 patients with patello-femoral instability at surgery, but was present in 3 of the 31 cases without.

Four of the 21 cases with rheumatoid arthritis underwent lateral patella release. Of these, 2 became discoloured and superficially infected. Of the 17 cases not having a lateral release one case suffered wound discolouration, but none sustained superficial infection ($p < 0.05$). Lateral release in rheumatoid patients resulted in a significant reduction in the oxygenation of the lateral wound edge. The skin oxygenation had a mean of 7 mmHg in those cases having a lateral patella release, whereas it was 19 mmHg in those cases who did not ($p < 0.02$). Postoperative patello-femoral subluxation was not detected in any of the rheumatoid patients postoperatively.

Discussion

Wound hypoxia and the effect of knee surgery

Failed primary wound healing following knee arthroplasty results in delayed mobilisation and reduced range of motion, and may progress to deep prosthetic infection. In this study failed primary wound healing was found to occur in 23% of cases. In the presence of normal wound metabolism, nutrition and the absence of infection the rate of wound healing was found to be tissue oxygen-tension dependant (Knighton, Silver and Hunt 1981). I therefore set out to assess wound skin edge hypoxia following knee arthroplasty and to ana-

lyse its relationship to infection and failed primary wound healing. In addition these results were compared to the situation following hip arthroplasty.

The results demonstrated that the hip arthroplasty wound was well oxygenated preoperatively. Postoperatively, only the posterior wound edge was subject to slight hypoxia for the first 7 days. A tissue oxygen tension of 20 mmHg is necessary for normal macrophage and fibroblast function, therefore the cellular function in the wound following hip arthroplasty was not diminished by postoperative wound hypoxia. The situation in hip arthroplasty compares favourably with knee arthroplasty where the skin overlying the knee was hypoxic preoperatively. The levels recorded were similar to those experienced in ischaemic limbs. Postoperatively following knee arthroplasty, the viability of the wound edges was further reduced and did not recover to the preoperative level for 10 days. This wound hypoxia was particularly marked on the lateral wound edge. The skin oxygenation fell to below the critical level of 20 mmHg in 44% of cases. This can be expected to result in reduced cellular function in the early postoperative period. It is not therefore surprising that wound healing problems have been reported to occur in a higher proportion of cases following knee arthroplasty than following hip arthroplasty (Walker and Schurman 1984).

Contrary to the experience in amputation stump healing it was not possible to predict preoperatively the outcome of subsequent wound healing using $TcPO_2$ (Dowd, Linge and Bentley 1983, Christensen and Klarke 1986). However, those patients suffering failed primary wound healing were noted to have a greater degree and a more prolonged period of postoperative wound hypoxia, which did not start to recover until the 7th day. In contrast, patients who subsequently went on to primary wound healing had a less marked degree of postoperative wound hypoxia which lasted for a shorter period of between one and 3 days.

If postoperative wound hypoxia and reduced cellular function do indeed predispose to wound healing problems, then how could this practically be reversed? Local skin perfusion can be increased by a regional sympathetic block using intravenous infusion of guanethidine. This was used successfully to treat one of the patients with aseptic wound dehiscence, but because of the potential side effects it is impractical as a routine prophylactic procedure. The oxygen tension in the peripheral blood may easily be increased by the addition of inspired oxygen. This has been shown to be the most efficient means of increasing macrophage and fibroblast function and to promote wound healing (Niinikoski 1977). The addition of 24% inspired oxygen in this study has been demonstrated to reverse detrimental postoperative wound hypoxia. Subsequently I have routinely used 24% inspired oxygen by nasal cannula as a prophylaxis against failed wound healing. It is used for 24 hours postoperatively and then at night for the first 3 nights. I have also used inspired oxygen therapeutically for wound healing problems with some success.

Other factors were analysed for their effect on postoperative wound viability. The duration of tourniquet time was found not to have a significant effect on wound hypoxia even when prolonged beyond 120 minutes. However, measurements taken some 18 to 24 hours after surgery may have missed any short period of reactive wound hypoxia produced by prolonged tourniquet time.

The underlying disease seems to have an important influence on wound viability. Patients with rheumatoid arthritis developed significantly more wound hypoxia in the early postoperative phase than those with arthrosis. This may be one of the many factors causing increased wound healing problems in rheumatoid patients.

Other situations commonly affected by failed wound healing are: ankle or elbow arthroplasty and internal fixation of the tibia, ankle or foot, particularly if the skin has been crushed and devitalised. These sites may similarly be affected by postoperative wound hypoxia, and helped by postoperative inspired oxygen, but this requires further investigation.

The effect of lateral patellar release on infection and wound viability

Lateral division of the extensor retinaculum has been shown to be effective in preventing patellar subluxation in patients with unstable patellar tracking at the time of surgery. Of those patellae considered to be stable using one finger's lateral pressure, approximately 6% were found to develop postoperative patella subluxation. A lower threshold to performing lateral release therefore appears to be necessary. Instead of the technique where one finger's pressure is allowed to aid patellar tracking, a "no finger technique" is suggested, with lateral release performed more frequently than in the 14% of cases recorded in this study .

It was shown that lateral release reduced the incidence of postoperative anterior knee pain and was associated with an increase in the HSS knee score of an average 5 points. This increase was primarily due to the absence of patellar subluxation and to a slight improvement in the range of knee flexion.

Lateral patellar release, in which the superior lateral geniculate vessels were divided, resulted in a significant increase in the incidence of postoperative wound

discolouration and superficial wound infection. When a medial capsular incision is used, and the infrapatellar fat pad is partially or wholly resected, the superior lateral geniculate vessels are then the major blood supply to the patella and prepatellar skin (Scapinelli 1967. Kayler and Lyttle 1988). If a lateral patellar release is performed, dividing the superior lateral geniculate vessels at the superior lateral pole of the patella, reduced viability of the patella and prepatellar skin might be expected. This was confirmed by the present study. Postoperative analysis of wound edge oxygenation demonstrated that performing a lateral release, in which the superior lateral geniculate vessels are divided, resulted in a further significant reduction in the viability of the prepatellar skin.

Several modifications of surgical technique are available to preserve the viability of the patella and prepatellar skin during lateral patellar release. Of the three approaches to lateral release, a separate lateral incision should be discouraged because the medial and lateral patellar skin incisions would further devascularise the prepatellar skin. The extracapsular route raises a large lateral skin flap and is therefore also inadvisable. The preferred technique is by eversion of the patella and intracapsular division of the retinaculum. The superior lateral geniculate vessels should be identified at the superior lateral pole of the patella, approximately 5 mm inferior to the lower border of vastus lateralis, and carefully protected by a sling placed around the vessels to retract them while the lateral retinaculum is divided.

Wound hypoxia—the effect of continuous passive motion

Movement and wound healing

The traditional conditions for successful wound healing are clearly stated by Hugh Owen Thomas in 1876; "... a combination of enforced, uninterrupted, and prolonged rest; the first gives relief of pain; the second added to the first, enables the case steadily to progress to a cure; the third secures that which has been gained." This is contrasted by those who believed the opposite, 'mouvement dose' or prudent motion, methodical motion as championed by Lucas Championniere in 1879. This is as yet an unsolved dichotomy. It is clear that if early function and mobility can be restored without detrimental effects upon wound healing or promoting infection, the major problems of prolonged immobilisation could be avoided.

Prolonged immobilisation has been experimentally studied in animals (Evans et al. 1960) and in humans (Enneking and Horowitz 1972). Immobilisation results in contracture of muscles and capsule, proliferation of intracapsular connective tissue, adhesions and cartilage degeneration (Evans et al. 1960, Enneking and Horowitz 1972). These changes result in a stiff knee, but most of the changes are reversible if immobilisation is not prolonged. Intra-articular changes of fibrosis and adhesions may be expected to be much more rapid in their onset following knee surgery (Dunphy and Udupa 1955).

The goal of postoperative rehabilitation is early function. The swing phase of normal gait requires 65°–70° of knee flexion, ascending stairs requires 90°, descending stairs requires 100°, and for rising easily from a low chair requires 105° of knee flexion (Kettlekamp et al. 1970, Fox and Poss 1981). The range of knee motion therefore determines the functional abilities and the resulting success of the arthroplasty (Ritter and Campbell 1987).

Manipulation under anesthesia has been used to gain additional knee flexion. However, manipulation has been associated with various complications including; supracondylar fractures and patella tendon avulsion (Insall, Scott and Ranawat 1979), wound dehiscence and hemarthrosis (Fox and Poss 1981), or death due to anesthetic complications (Riley and Hungerford 1978). Fox and Poss (1981) evaluated the results of manipulation and found that the ultimate range of flexion was no different for those patients who were manipulated compared with those who were not.

Continuous passive motion (CPM)

It has been shown experimentally in animals that continuous passive motion (CPM) promotes healing of full thickness articular cartilage defects, improves cartilage nutrition and improves the range of joint motion following surgery (Salter and Edholm 1955, Salter and Ogilvie-Harris 1979, Salter, Bell and Keeley 1981). Clinical application of CPM was first reported by Salter (Salter et al. 1975). Attention was initially concentrated on the ability of CPM to promote healing of full thickness cartilage defects in rabbits (Salter et al. 1980). The technique of CPM has been applied to the management of articular fractures particularly of the acetabulum and knee (Salter et al. 1980), septic arthritis (Salter, Bell and Keeley 1981), tendon healing (Salter and Bell 1981), and flexor tendon repair in the hand (Gelberman, Amid and Gonsalves 1981). CPM has also been used in the postoperative period to restore movement after knee arthroplasty (Coutts et al. 1982).

Salter concluded from his studies on immature rabbits that CPM had no detrimental effect on wound healing (Salter and Ogilvie-Harris 1979, Van Royen et al. 1986). When the wounds in rabbits were tested after three weeks, CPM resulted in stronger wounds with a greater concentration of collagen (Salter and Bell 1981). This might be expected from physiological loading of a vascular wound during its maturation. Unfortunately the anatomy of the cutaneous circulation is very different in man. Extensive skin flaps may be raised in the rabbit without any risk of skin necrosis. There are great differences in the anatomy of the skin vasculature in man. In clinical knee surgery skin necrosis is an ever present hazard (Insall 1984). Therefore the effect of motion on the knee arthroplasty wound in man may not be comparable to the situation in the rabbit.

CPM has been used in the postoperative period following knee arthroplasty to restore movement particularly during the first few days when patients were reluctant to participate in active exercises (Coutts et al. 1982). Following knee arthroplasty CPM also improves the clearance of blood from the joint (O'Driscoll, Kumar and Salter 1983), and reduces the requirement for analgesia (Goletz and Henry 1980), but it has no effect on the incidence of deep venous thrombosis (Lynch et al. 1988). Recent reports have suggested that CPM might have an adverse effect upon wound healing

following knee arthroplasty (Goletz and Henry 1980). The effect of knee flexion and CPM on the viability of the wound and wound healing is unknown. The optimal regime of CPM is unknown as is the optimal speed. Many different regimes have been suggested but the relative efficacy of these protocols is unknown. It has been shown that CPM is most effective in improving the range of motion when used for the first seven days rather than for longer periods (Salter et al. 1980).

Patients and methods

A prospective, randomised and controlled study was undertaken in 92 patients undergoing knee arthroplasty (Johnson 1990). 21 patients suffered from rheumatoid arthritis and 71 patients had arthrosis. 45 (34 arthrotic) patients received CPM and 47 (37 arthrotic) patients were immobilised. The prostheses used comprised 35 unicompartmental (18 with CPM) and 57 unconstrained total knees (27 with CPM). The CPM (n 45) and immobilisation (n 47) groups did not differ significantly in the content of prostheses used.

The patients were assessed for the presence of any factors that might adversely affect wound healing (diabetes, peripheral vascular disease, corticosteroid therapy). The patients were also assessed for their age, type of arthritis and the presence of any previous scars around the knee. Hematologic assessment included a full blood count and renal function tests. $TcPO_2$ recordings were taken preoperatively from both sides of the proposed medial parapatellar incision.

The preoperative extensor lag, fixed flexion and range of flexion were measured with a goniometer. A standard operative protocol was designed which included a three dose regimen of prophylactic antibiotic (cefamandole 1 gram), the use of a medial parapatellar incision, and the use of gentamicin-containing cement. The wounds were closed with one drain in the joint cavity, one in the subcutaneous fat, and interrupted nylon mattress sutures for the skin. Sterilised $TcPO_2$ electrode holders were attached to the skin adjacent to the mid-point on either side of the wound so that postoperatively the $TcPO_2$ electrode could be connected to the holders and the $TcPO_2$ measured from the same sites throughout the postoperative period. The knee was lightly bandaged with a wool and crepe bandage.

Patients were randomly assigned to one of two groups: those receiving immediate postoperative CPM and those immobilised in a splint. CPM was used for the first 7 days as this is the period during which it has been shown to be most effective. Patients used the machine for 20 hours per day for 3 days and then for 16 hours per day for 4 days. The initial range of motion was 0°–40° and this was increased each day by 10° up to 90° on the 6th day; the apparatus was removed on the 7th day. Twice daily full extension exercises off CPM were performed under the supervision of a physiotherapist. Weight bearing was begun on the third day, but no active flexion was allowed until the 7th day.

Patients on the immobilisation regimen kept the splint on for 7 days. Straight-leg raising exercises were performed twice daily. Weight bearing started on the third postoperative day, but no flexion was allowed until the 7th postoperative day.

All wounds were inspected regularly throughout the postoperative period and the range of motion was recorded on the seventh, tenth and fourteenth day. Failure of primary wound healing was considered to be present if infection, or aseptic wound dehiscence occurred; or if an aseptic discharge continued after the fifth postoperative day. All patients were subsequently reviewed at six weeks, six months and one year, when measurement of the range of motion was undertaken, and the wounds inspected.

$TcPO_2$ was estimated using the Radiometer TCM 204 oxygen monitor and skin electrode as previously described. Measurements were made on either side of the midpoint of the proposed wound preoperatively and on alternate days throughout the postoperative period until the 14th postoperative day. For patients on CPM, recordings were taken in flexion and extension, and additional measurements taken while the range of motion was slowly increased from 0°–20°, to 0°–90°.

From subsequent analysis of the results of this trial, a protocol for the use of CPM could be identified which minimised the detrimental effects of knee flexion on the viability of the wound. This protocol included restricting knee flexion on CPM to 0°–40° in the first 3 postoperative days; then progressively increasing the range of knee motion daily to 60°, 80°; reaching 90° on the 6th postoperative day. The machine was removed on the 7th. A cycle speed of one cycle per minute was used.

Using this 'optimal' protocol a further group of 59 patients undergoing knee replacement was studied. These patients' results were analysed in an identical way to the original group; with review at 6 weeks, 6 months and 1 year.

Statistics. The statistical analysis was performed in association with the statistical services unit of the University of Sheffield. Further calculations were performed using a Stat View 512+ statistical program and an Apple Macintosh microcomputer. Statistical analysis included paired *t*-tests for 'within patient' analyses of wound edge oxygenation between sides, on sequential days, and in knee flexion and extension. Two-sam-

Table 11. Fixed flexion, extension lag, and flexion for the immobilised group, CPM group, and for those receiving the "optimal" CPM protocol

Measurement	Protocol	7 d	10 d	2 wks	6 wks	3 m	6 m	1 year
Fixed flexion	Immobilised	4	5	3	3	2	2	4
	CPM	4	4	3	4	3	2	4
	Optimal CPM	4	4	3	4	1	0	4
Extension lag	Immobilised	7	3	5	3	3	2	0
	CPM	8	6	5	2	1	1	0
	Optimal CPM	5	5	3	2	2	0	0
FLexion	Immobilised	55	64	70	84	96	93	97
	CPM	71	77	80	92	101	100	106
	Optimal CPM	64	74	77	90	93	100	106

ple t-tests were used for the analysis of the effect of CPM and immobilisation on wound oxygenation. Contingency table analysis was used for the analysis of wound healing problems and the influence of CPM.

Results

No case of deep infection was recorded in this series. Superficial infection occurred in 9 cases (10%): 3 (7%) of these were in the CPM group, and 6 (13%) in the immobilised group. Though the incidence was marginally higher in rheumatoid and immobilised patients the differences were not significant. Delayed wound healing occurred in 12 cases (13%); 5 (11%) in the CPM group and 7 (13%) in the immobilised group. Here again although the incidence was higher in rheumatoid and immobilised patients, the differences were not significant. The only complication of CPM was the development of buttock pressure sores in 2 patients early in the study; subsequently extra nursing vigilance prevented this problem.

The length of stay in hospital averaged 15 days for the CPM group and 21 days for the immobilised group ($p < 0.01$). This reduction in in-patient stay was particularly marked in rheumatoid patients.

Fixed flexion deformity was not significantly different in the two groups at any time in the postoperative period. Fixed flexion decreased from 4° at 7 days, to 2° at 6 months, most of the improvement occurring after discharge from hospital. Although there was a slight increase in the extension lag after CPM, the difference between the two groups of patients was not significant and had disappeared by the 14th day. The extension lag diminished from 7° at seven days to 2° at 6 months and to zero at one year (Table 11).

The range of flexion achieved with CPM was significantly greater than with immobilisation at 7 days ($p < 0.001$), 10 days ($p < 0.01$), 14 days ($p < 0.01$) and 6 weeks ($p < 0.05$). The ultimate range of flexion at one year was 9° greater with CPM ($p < 0.02$; Table 11).

The effect of CPM was further analysed by studying the group of 36 patients with arthrosis who underwent Kinematic knee replacement. 16 of these 36 patients received CPM while 20 were immobilised. The ultimate range of knee flexion at one year was 105° for those patients receiving CPM, while only 93° for those which were immobilised for one week ($p < 0.01$). CPM was therefore demonstrated to result in a significant increase in both the early and late range of knee flexion ($p < 0.01$).

The relationship of arthritis on the range of knee flexion with the use of CPM was further studied using the 26 patients which underwent a Kinematic total condylar arthroplasty with CPM. This study included 16 arthrotic patients and 10 rheumatoid patients. The average range of knee flexion produced in the arthrotic patients was 77° at 14 days, 101° at 6 months, and 105° after one year. In rheumatoid patients the average range of knee flexion at 14 days, 6 months and one year was 74°, 107° and 107°, respectively. There was no significant difference in the range of knee motion in rheumatoid and arthrotic patients.

$TcPO_2$ measurement performed on the first postoperative day, when the CPM range of motion was 0°–40°, was not significantly different in the two groups of patients. However, by the third postoperative day, when the CPM range was 0°–60°, skin viability was significantly reduced on the medial wound edge ($p < 0.02$) and on the lateral wound edge ($p < 0.01$) for the patients having CPM compared with those immobilised. Again at 5 days, when the CPM range was 0°–80°, the lateral wound edge had reduced viability. After 7 days, when CPM was stopped, there was no longer any significant difference in wound viability in the groups of CPM patients and immobilised patients (Figure 24).

The postoperative oxygenation of the wound was compared between those patients receiving CPM and those receiving immobilisation. It has previously been

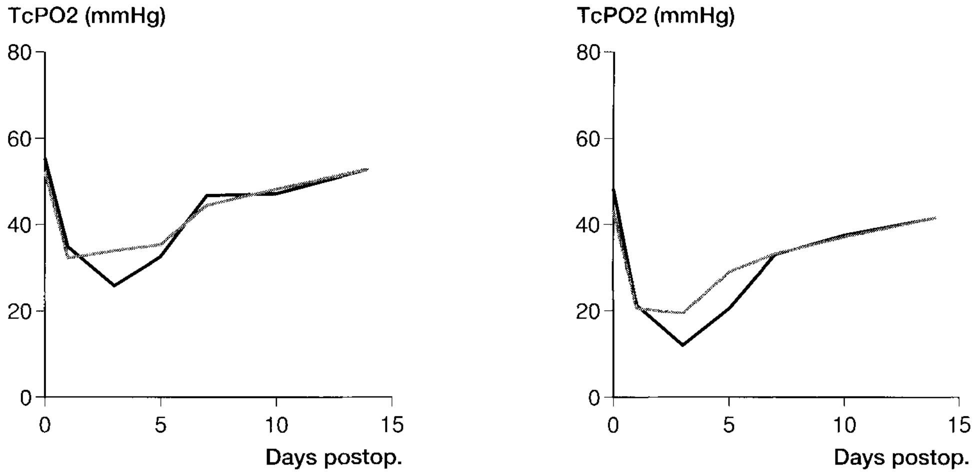

Figure 24. The transcutaneous skin oxygen tension of the medial (left) and lateral (right) wound edge in the early postoperative period for patients receiving continuous passive motion and immobilisation

Table 12. Mean $TcPO_2$ (mmHg) and *SD* in rheumatoid and arthrotic patients during CPM and knee immobilisation

Diagnosis	Protocol	n	Day 1		Day 3	
Arthrosis	CPM	34	25	*13*	20	*10*
	Immob.	37	28	*11*	26	*14*
Rheumatoid ar.	CPM	11	24	*18*	18	*10*
	Immob.	10	17	*7*	21	*12*

Table 13. Mean $TcPO_2$ (mmHg) in the medial and lateral wound edges in flexion and extension with the knee moving on CPM in a pre-set range

Side/Direction	20°	30°	40°	50°	60°	70°	80°	90°
No of cases	7	11	11	11	10	5	2	1
Medial/Flexion	44	43	45	43	43	38	20	5
Medial/Ext.	48	47	48	49	50	52	41	42
Lateral/Flexion	31	32	30	26	25	17	22	7
Lateral/Ext.	33	36	36	35	33	35	39	40

demonstrated that the presence of a unicompartmental or a total condylar prosthesis does not influence the postoperative wound oxygenation (correlation coefficient 0.928). Therefore the use of CPM will be analysed in groups separated into patients suffering from rheumatoid arthritis and arthrosis. However, because of the correlation previously determined, the patients will not be further subdivided for the study of wound oxygenation into those receiving unicompartmental prostheses and total condylar prostheses.

There were 52 patients in this study, of whom 25 had rheumatoid arthritis and 27 arthrosis. In the arthrotic patients, CPM reduced the wound viability as measured upon the first postoperative day ($p < 0.05$; Table 12). In the rheumatoid patients, the reduction in wound viability observed following the use of CPM was not significant (Table 12).

When the two phases of CPM were analysed, the flexion phase was found to diminish the viability of the lateral prepatella skin ($p < 0.001$), and to a lesser extent the medial wound edge. This was further analysed by slowly increasing the range of flexion on CPM in 10 patients from a range of 0°–20° to 0°–90° while recording the wound oxygenation. The oxygenation of the medial wound edge rapidly decreased beyond 0°–60° ($p < 0.05$), while the oxygenation of the lateral wound edge decreased beyond 0°–40° ($p < 0.01$). Flexion to 40° was not accompanied by any significant reduction in wound viability (Table 13).

The effect of the speed of CPM was analysed, by measuring the wound edge viability whilst the CPM speed was adjusted from one cycle in 30 seconds, to one cycle per minute and to one cycle in 2 minutes (slow, med, fast settings). The range of knee flexion remained constant at 0°–40°. The speed of one cycle per minute gave marginally superior readings for oxygen tension but the differences were slight and not significant (Table 14).

A regimen of CPM was constructed based upon these results, to 'optimise' the viability of the wound. A limited range of flexion of 0°–40° for 3 days was followed by daily increases of 20°, 20° and 10° to reach 90° by the sixth day. The CPM machine was removed on the seventh day. Knee flexion was thereby limited in the

Table 14. $TcPO_2$ (mmHg) of the wound edges in knees moved on CPM through a range of motion of 0°–40° at various speeds

Side/Direction	Slow	Medium	Fast
No of cases	10	10	10
Medial/Flexion	44	44	44
Medial/Ext.	48	50	48
Lateral/Flexion	28	30	29
Lateral/Ext.	37	37	33

first 3 postoperative days, when the viability of the wound was poor. As viability improved during the fourth, fifth and sixth days the range of flexion was increased.

Subsequently, another 59 patients undergoing knee arthroplasty were studied using this 'optimal' CPM protocol. In this group the incidence of superficial infection was further reduced from 6% with the original CPM protocol, to approximately 3% with this less aggressive 'optimal' protocol.

Measurement of the resulting range of motion demonstrated that this less aggressive 'optimal' regimen did not increase the fixed flexion deformity or extensor lag. The range of knee flexion was reduced by 7° at 7 days, though the difference had reduced to an insignificant 4° by 14 days, and the ultimate range of flexion at one year was identical to the previous more aggressive CPM regimen (Table 11).

Discussion

Several studies have shown that CPM, used postoperatively following knee arthroplasty, significantly increased the range of knee flexion during the early postoperative phase (Coutts et al. 1982, Lynch et al. 1988). This method, in one routine or another, is now widely used in the postoperative management of patients after knee arthroplasty. This is justifiable only if it can be shown that CPM and the early knee flexion it produces has no detrimental effects on wound healing.

Salter concluded, from his studies on immature rabbits, that CPM had no detrimental effect on wound healing (Salter and Ogilvie-Harris 1979. Van Royen et al. 1986). Unfortunately the anatomy of the cutaneous circulation is very different in man. Enormous skin flaps may be raised in the rabbit without risk of skin necrosis. However, due to differences in the anatomy of the skin vasculature, skin necrosis is an ever present hazard in clinical knee surgery (Insall 1984). Problems with wound healing and superficial infection may progress to deep infection with dire consequences for the patient.

A conservative CPM regimen specifically designed to obtain the maximum effect of CPM on joint mobility whilst minimising the potentially deleterious effect of knee flexion on wound healing was studied. A prospective, randomised and controlled trial was performed in two groups of patients which were comparable, particularly in terms of the prosthesis used and the type of arthritis. No difference in the incidence of infection or wound healing was demonstrated when a regimen of CPM was compared with a regime of postoperative immobilisation. This is in contrast to the results of more aggressive CPM regimes (Goletz and Henry 1986). Therefore if used in a controlled way CPM did not increase the incidence of wound healing problems, but it significantly increased the range of early knee flexion. This improvement was maintained compared to immobilised patients at one year. When the CPM regimen included initial full knee extension, with daily quadriceps exercises, there was found to be no increase in the fixed flexion deformity or the extensor lag.

The clinical assessment of wound healing and infection is notoriously difficult and inaccurate. However, since wound edge oxygenation is related to wound healing (Niinikoski 1977), an objective method of measuring wound viability is readily to hand. $TcPO_2$ measurement of patients having CPM demonstrated that knee flexion beyond 40° progressively reduced the wound viability. This reduction is particularly marked during the first three days and is more pronounced on the lateral than the medial wound edge. Therefore excessive early flexion on CPM is to be avoided as reduced wound viability will result. The speed of CPM made little difference to the wound viability, though a setting of one cycle per minute optimised wound oxygenation without causing the patient the discomfort associated with the faster settings.

The 'optimal' CPM regimen was designed to maximise the benefits whilst obtaining the maximum wound edge viability and limiting the detrimental effects. The initial knee flexion was limited to 40° for three days and subsequently gradually increased to 90°. When tested it was indeed successful in further reducing the incidence of superficial wound infection and failed wound healing. The range of early knee flexion was slightly reduced compared to more aggressive CPM regimes but the differences were quickly regained. A more aggressive regimen resulted in diminished wound viability, and increased the incidence of wound healing problems and infection, without improving the eventual range of knee flexion (Goletz and Henry 1980).

Conclusion

Introduced changes to the technique of knee arthroplasty

From the results of this series of studies a protocol which seems optimal for knee arthroplasty can be designed. This could be expected to reduce the incidence of deep infection to a minimum. Indeed, the measures already introduced in Winford Orthopaedic Hospital Bristol as a result of the studies described, has resulted in a reduction of the incidence of infection following knee arthroplasty. The incidence of deep infection has been reduced from the 5% initially recorded, to a percentage of zero in the 151 consecutive primary knee replacements used in the later studies. In a similar way the incidence of superficial infection has been reduced from 6% to 3% when the 'optimal' regimen of CPM was subsequently used.

The changes producing this effect are:

- The medial parapatellar incision.
- Allowing 10 minutes to elapse after injection of the antibiotic before the tourniquet is applied.
- Gentamicin-containing cement has been used.
- The proportion of hinged prostheses used in this period has diminished (even so the incidence of deep infection with the Kinematic total condylar knee has fallen from 2%, to less than 1%).
- Postoperative CPM has been used in a carefully controlled way.
- More aggressive treatment of superficial infection has been undertaken.
- The preferred technique of knee arthroplasty.

Further measures to reduce the clinical incidence of wound healing problems and infection have been suggested by the results of this study; these have been described in Table 15.

Table 15. Perioperative protocol for knee arthroplasty to prevent infection and wound healing problems

PREOPERATIVE	POSTOPERATIVE
ANTIBIOTIC INJECTION Intravenous injection of cefuroxime 1.5 gm, 10 minutes prior to application of the tourniquet.	DAY OF SURGERY Application of C.P.M. in recovery room, range 0-40°. Inspired 24% oxygen by mask or nasal cannula. Two subsequent injections of cefuroxime 1.5gm, 8 hours and 16 hours after surgery.
PEROPERATIVE	
INCISION Medial parapatellar incision, do not undermine the lateral skin flap. Preserve the infrapatellar fat pad.	DAY 1–3 CPM 0°–40°. Remove CPM twice for 1 hour of straight-leg raise and quadriceps exercises. Inspired 24% oxygen at night.
CEMENT Use gentamicin-containing cement.	DAY 4 CPM 0-60°. Remove CPM during the day from 8 am to 4 pm for mobilisation, straight-leg raise and quadriceps exercises. No active knee flexion.
LATERAL RELEASE Intra-capsular division of the lateral patellar retinaculum. Preservation of the superio-lateral geniculate vessels.	DAY 5 CPM 0°–80°. Remove CPM during the day from 8 am to 4 pm for mobilisation, straight-leg raise and quadriceps exercises.
DRAINAGE Use one or two drains in the knee joint and one along the subcutaneous fat.	DAY 6 CPM 0°–90°. Remove CPM during the day from 8 am to 4 pm for mobilisation, straight-leg raise and quadriceps exercises.
DRESSINGS Use an adhesive occlusive dressing, split and overlapped in the centre to allow free knee flexion.	DAY 7 CPM stopped. Active knee flexion is begun.
BANDAGE Use a lightly applied wool and crepe if desired, do not bandage over the patella so as to allow free unrestricted knee flexion.	

Conclusions

This program of research has considered many aspects of infection and wound healing following knee arthroplasty. The following conclusions were reached:

- Deep infection following knee arthroplasty was a significant problem in the initial part of this study, occurring in 4.4% of patients. Predisposing factors are rheumatoid arthritis, a history of previous operations, and the presence of a postoperative superficial wound infection, particularly if the infecting organism is *Staphylococcus aureus*.
- Superficial wound infection predisposes to deep infection. Progression of superficial infection to a deep infection accounted for at least one third of the deep infections. Primary wound healing is therefore of paramount importance.
- Long-term antibiotics do not eradicate established deep infection of a cemented knee arthroplasty, though they may suppress the signs and symptoms in patients unsuitable for further surgery.
- Arthrodesis was successful in eradicating the symptoms of infection and providing pain free walking, though bony ankylosis was only obtained in half the cases so treated.
- The most effective and practical way of reducing the risk of infection is by giving prophylactic antibiotics. The timing of antibiotic injection in relation to the time the tourniquet is inflated is a critical determinant of the tissue antibiotic concentrations achieved. The antibiotic absorption into the subcutaneous fat is slower than uptake into bone. For adequate tissue uptake of cefuroxime an interval of 10 minutes is necessary after intravenous injection prior to application of the tourniquet. A lower tissue concentration of antibiotic was found in patients weighing over 80 kg, and in these patients a larger dose of cefuroxime is necessary.
- In sequential bilateral knee arthroplasty a second dose of cefuroxime is necessary 10 minutes prior to inflation of the second tourniquet.
- Since primary wound healing is so vital for the prevention of infection, it is essential to establish optimal peroperative and postoperative conditions for wound healing. The medial parapatellar incision is preferred for knee arthroplasty as it is (a) aligned parallel to the skin cleavage lines, (b) subjected to significantly less disrupting wound tension during knee flexion. Knee flexion to 50° results in only a small increase in wound tension across the medial parapatellar incision. Moreover, the lateral wound edge is not subject to any significant reduction in wound viability compared to the effect of an anterior midline incision.
- Oxygenation of the wound over the anterior aspect of the knee is poor, and the oxygenation of the knee arthroplasty wound is significantly reduced postoperatively.
- Following knee arthroplasty the lateral wound edge is significantly less well oxygenated than the medial wound edge. The oxygenation of the wound is below the critical 20 mmHg level in 44% of cases.
- The addition of 24% inspired oxygen rapidly reverses the postoperative wound hypoxia.
- The oxygenation of the wound following hip arthroplasty is significantly better than the wound oxygenation following knee arthroplasty.
- Patients at risk of failed wound healing could not be identified by diminished wound oxygenation preoperatively. Patients in whom failed wound healing occurred suffered a greater degree and a more prolonged period of postoperative wound hypoxia than patients in whom normal wound healing occurred.
- Lateral patellar release is effective in preventing postoperative patellar subluxation, but lateral release dividing the superior lateral geniculate vessels results in a significant increase in the incidence of failed wound healing and infection. This is due to a significant reduction in the viability of the lateral wound edge. Lateral patellar release should be performed by the intra-capsular route with preservation of the superior lateral geniculate vessels.
- Continuous passive motion (CPM) results in a significant increase in the range of early and late postoperative knee flexion. When a regimen of initial full extension and early static quadriceps exercises is used, CPM does not result in any increase in the fixed flexion or extensor lag. CPM also results in earlier discharge from hospital.
- A conservative regimen of CPM with limited knee flexion in the early postoperative period did not increase the incidence of wound healing problems, nor did it reduce the viability of the wound edges. Knee flexion beyond 40° diminished wound viability particularly on the lateral side of the wound. This is particularly marked in the first three postoperative days when the wound is most hypoxic. The speed of CPM makes little difference to the wound viability, but a speed of one cycle per minute optimised wound oxygenation without the discomfort associated with faster speeds.
- An optimal CPM protocol was designed which minimised the detrimental effect on wound viability. This protocol resulted in a reduction of the incidence of failed primary wound healing to 3%, whilst maintaining the advantages of increased range of knee flexion and early discharge from hospital.

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