The total cost of hip-joint replacement; a model for purchasers

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Summary
A computer-based model is used to investigate the total cost of primary total hip-joint replacement. The model takes into account the probability of prosthesis failure, death and re-revision. The results emphasize the importance of age at insertion, demonstrating that the expected life-span of the patient has a major influence on the total cost for a given prosthesis. The discussion considers the idea of a 'lifetime care package' to encapsulate the concept of quality when considering the purchasing of total hip replacements. If it is assumed that a primary replacement episode costs £3500 and revision surgery costs twice as much, then the additional premium on the best implant currently available would be £630. The premium payable on the same patient using the worst design would be £3080. This difference reflects the importance of quality in total hip replacement surgery.

Keywords: joint replacement, quality, cost, survival

Introduction
Total hip replacement (THR) is now a common operation, over 40,000 being performed in the UK alone each year. It is most often used to relieve the pain of arthritis of the hip in the elderly. It is a dramatically successful operation, initially offering complete relief of pain and greatly increased mobility in over 99 per cent of cases. The operation of THR is still relatively new and the numbers being performed are still rising. Its real value in social terms is probably still not fully appreciated and each year more resources have been made available for more operations. Even when the number of THRs per year reach a plateau (when the backlog is cleared and all patients developing symptoms severe enough to warrant THR do in fact receive one) the number of people with a THR in situ will continue to rise for some time until, eventually, a steady state will be reached when the number of patients receiving THR equals the number dying with THR in place.

Hip replacements fail after a period of time by breaking, loosening, wearing or by becoming infected. When they fail they usually become painful and sometimes unstable. Hip-joint replacements can be revised (the old one removed and a replacement fitted securely into the old bone bed) but the operation requires considerable skill and expertise, takes longer to perform than a primary THR and involves a longer stay in hospital for the patient. The overall cost of a revision is approximately twice that of a primary THR and, it should be noted, the operation competes for the same limited resources currently allocated to primary total joint replacement. Revision THRs do not last as long as primary THRs and when they fail they may need to be revised again. As the number of patients with THRs in situ rises, the number failing also rises. This is creating an epidemic of patients requiring revision operations, a veritable iatrogenic tidal wave. The size of this wave and its timing depend on several factors, in particular, the life expectancy of patients at the age they receive their first hip replacement and the longevity of the implant. There is no evidence that patients are receiving THR any younger today than they were a decade ago but patients are living longer, so the number of patients 'at risk' with hips in place is rising even faster than might be predicted from the number of primary operations being performed. Some THRs appear, as a result of their design, to last longer than others by a very significant amount. The skill, competence and experience of the operating surgeon may also be of great importance, but the magnitude of this effect has not yet been measured. If THRs could be designed to last longer than the life expectancy of the
patients receiving them, revision operations would not be required, apart from the occasional accident, when an implant is broken by a fall or when infection occurs. The shorter the life expectancy of any THR design in relation to the longevity of patients receiving it, the greater the number of patients likely to require revision THRs in the future.

In the purchaser-provider environment it is clearly advantageous for the purchaser as well as the patients represented by that purchaser to obtain total hip replacements from a unit which provides hips which last as long as possible. Every revision which must subsequently be purchased when a primary THR has failed is, in effect, the purchaser paying a second time to treat the same condition. There are also costs to the patient in terms of the distress and pain.

Information on the longevity of many implants is not available to purchasers and therefore, at the moment, they can only buy on price and not quality. The information required can in fact only be obtained by providers and then only after considerable effort, using clinical audit.

If purchasers decided to buy not just a simple total hip replacement, but a care package for that hip for the rest of the patient's life, the price agreed would have to take account of the chance of the hip failing in the lifetime of the patient. The less the chance of a revision being required, that is, the longer the primary hip lasts, the lower the price which could be quoted would be. This paper explores this model (Fig. 1) using information already known about the survival of different designs of implant. It attempts to show that the issue of quality (as measured by the longevity of the implant) has a profound effect on price and could be used to make purchasing decisions mainly on quality rather than simple cost.

**Material and methods**

The model was developed and tested using the ‘C’ programming language. The program uses a simple iterative loop to solve this time-dependent problem. A more formal explanation of the actual calculation may be found in the Appendix.

**Failure rate of the primary replacement**

The basis for modelling the failure of the primary arthroplasty is the authors’ own experience with survival analysis of Charnley prostheses inserted over the last 25 years\(^9\) and McKee–Farrar prostheses inserted over the period 1965–1973\(^10\) (Fig. 2a). The data from Ref. 8 have been used to model a hip prosthesis with a poor outcome, namely the Christiansen arthroplasty. The latter prosthesis was commonly used in Sweden during the period 1967–1987, with results that showed a 62 per cent failure within 10 years of insertion.

It should be noted that the survival curve usually used in descriptions of replacement surgery represents a cumulative probability.\(^11\) For the purposes of this model, the probability of failure each individual year, given an arthroplasty survives to a particular year, is required (Fig. 2b). In the case of the Christiansen results, these probabilities have been derived from the survival curve published in Ref. 8.
FIGURE 2 (a) Curves representing the cumulative survival data for a variety of hip prostheses. These data are from Carter et al., 9 August et al. 10 and Ahnfelt et al. 8 for the Charnley, McKee-Farrar and Christiansen prostheses, respectively. The survival data-points are estimated over a period of one year; the time axis represents the end-time of this period. (Note that the Christiansen data have been extrapolated from the eleventh to the twentieth year.) (b) The corresponding proportion of failures in any given year.
Mortality rate
The predicted death rates are based on data kindly supplied by the Office of Population Censuses and Surveys for England and Wales. The probability of death at a given age for males and females is shown in Fig. 3. For simplicity, the sexes are not distinguished in the model and a mean rate is used.

Some patients have bilateral joint replacements; on average, 30 per cent of the populations studied had bilateral replacements, thus the mortality rate is multiplied by 1.2 to obtain the number of prostheses removed from each pool as a result of patient mortality.

Failure rate for revision surgery
There is far less published literature on the failure rates of revision surgery than for primary arthroplasty. Kavanagh and Fitzgerald emphasized that four and a half years after revision 45 per cent of patients show evidence of radiographic loosening. Sources consulted for survival data on revision surgery are summarized in Fig. 4. For the model, the re-revision rate is assumed to be constant with time and with the degree of re-revision (i.e. secondary, tertiary, etc.).

Summary of assumptions
The model has the following known assumptions:
(1) A mean death rate from both sexes is used.
(2) The sex of the patient does not affect outcome.
(3) The re-revision rate is constant.
(4) The patient's age at primary insertion does not affect the failure rate.
(5) Cross-boundary outflow is assumed to match inflow.
(6) The Christiansen data have been extrapolated to 20 years.
(7) The values for probability of death have been extrapolated from 86 to 90 years.

Results
The results presented below investigate the effects of varying the time-dependent parameters on the final number of revisions.
The effect of survival rate of primary replacement

Figure 5 shows the effect of various survival data on the cumulative number of revisions. The survival probabilities illustrated in Fig. 2b have been used for the failure rate. The probability of death used is the mean mortality rate shown in Fig. 3. Figure 5a illustrates the annual proportion of revisions incurred and Fig. 5b depicts these revisions integrated to form a cumulative plot.

The effect of age at the time of primary replacement and mortality considerations

Figure 6 shows the effect of applying a mortality correction to the data. The number of revisions is reduced because of death. That is, if there was no patient mortality, eventually all hips would come to revision and subsequently all revisions would also come to re-revision. If other factors, such as patient activity, are ignored then changing the age at primary operation represents merely a shift in the applied mortality probabilities demonstrating that the younger the patient the more revision procedures will eventually be needed. The influence of mortality on survival data has been emphasized by other workers.22

The effect of re-revision rate

Published re-revision rates were mentioned above (Fig. 4). Figure 7 illustrates that these rates do not, in fact, have a large influence on the final number of revisions over the small magnitudes in question.

Re-revision appears to have little effect on the total number of revisions required if the primary failure rate is low. However, if the primary failure rate is high re-revisions start to make a significant contribution to the resource implications.

Discussion

The cumulative number of revisions using different designs of hip prosthesis can be compared with this
model. Comparative data and cost benefits of THRs have been modelled by other groups; however, specific data from the UK are not known to have been modelled. It is estimated that at least 40,000 primary hip prostheses are being inserted annually in England alone. Although more THRs are being performed each year, it does seem that there is a trend to insert proportionally more into the older age group (Fig. 8) thus reducing the risk of revision (Fig. 6) but increasing the morbidity. If, for example, the age-related data of

FIGURE 5 (a) The modelled proportion of revisions with a primary insertion age of 60 years and a re-revision rate of 0.02 per year. Thus if 100 primary hips were inserted at time zero, the number of revisions would be obtained by multiplying the values on the ordinate axis by 100. (b) The same data plotted in a cumulative form.
Ref. 2 are used, then the expected number of revisions at 10 and 20 years can be predicted from the model (Table 1). It should be borne in mind that these results represent an underestimate, as the mean death rate for both sexes has been used, whereas, in reality, women have more THRs than men. It is not clear whether this is merely because they live longer or because they have a greater susceptibility to osteoarthritis than men.
FIGURE 8 The reported age of insertion of primary THRs. The McKee–Farrar and Charnley data relate to operations over 20 years up to 1980s; the data from Williams et al.\(^2\) are for 1989–1990.

TABLE 1 The application of the model to the age-related data of Williams et al.\(^2\)

<table>
<thead>
<tr>
<th>Age group</th>
<th>No. of hips</th>
<th>Charnley 10 yr</th>
<th>Charnley 20 yr</th>
<th>McKee 10 yr</th>
<th>McKee 20 yr</th>
<th>Christiansen 10 yr</th>
<th>Christiansen 20 yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 45</td>
<td>866</td>
<td>71</td>
<td>176</td>
<td>88</td>
<td>636</td>
<td>340</td>
<td>890</td>
</tr>
<tr>
<td>45–54</td>
<td>1764</td>
<td>141</td>
<td>331</td>
<td>177</td>
<td>1129</td>
<td>675</td>
<td>1663</td>
</tr>
<tr>
<td>55–64</td>
<td>5208</td>
<td>387</td>
<td>794</td>
<td>494</td>
<td>2391</td>
<td>1838</td>
<td>3958</td>
</tr>
<tr>
<td>65–74</td>
<td>9613</td>
<td>607</td>
<td>962</td>
<td>809</td>
<td>2173</td>
<td>2829</td>
<td>4701</td>
</tr>
<tr>
<td>75–84</td>
<td>9477</td>
<td>409</td>
<td>409</td>
<td>603</td>
<td>603</td>
<td>1801</td>
<td>1801</td>
</tr>
<tr>
<td>&gt; 84</td>
<td>2768</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>29696</td>
<td>1614</td>
<td>2672</td>
<td>2171</td>
<td>6933</td>
<td>7483</td>
<td>13011</td>
</tr>
</tbody>
</table>

The columns indicate the number of revision procedures that may be expected in 10 and 20 years using the survival data for three different prostheses used at the time of primary THR. Death rates beyond the age of 90 years are not considered, thus only the first 10 years are used for the 75–84 age group. All those over 84 years are assumed to die before revision.
Although the possibility of failure is always a concern to both the surgeon and patient, it is felt that the long-term financial consequences beyond the initial cost of the primary procedure have not been previously appreciated. The financial costs of a potential cascade of revision surgery are considerable. One of the factors that affect the final cost of hip replacement is the known survival of the implant. Many orthopaedic surgeons are interested to try new techniques and thus implants which do not have the benefit of long-term reviews and are of unknown durability. Such implants may be more successful than the current best available implant; certainly this is what the manufacturers would have us believe. In fact, many implants have been introduced onto the market only to be withdrawn as it has become apparent that they do not have sufficiently good survival to compete with established designs.

A primary hip replacement may be financed as a

### TABLE 2 The percentage premium which would have to be added to the primary cost of a THR assuming that a revision THR costs twice as much as a primary THR; the data are calculated from the 20 year revision figures

<table>
<thead>
<tr>
<th>Age groups (yr)</th>
<th>Charnley (%)</th>
<th>McKee (%)</th>
<th>Christiansen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 45</td>
<td>41</td>
<td>147</td>
<td>205</td>
</tr>
<tr>
<td>45–54</td>
<td>37</td>
<td>128</td>
<td>188</td>
</tr>
<tr>
<td>55–64</td>
<td>31</td>
<td>92</td>
<td>152</td>
</tr>
<tr>
<td>65–74</td>
<td>20</td>
<td>45</td>
<td>98</td>
</tr>
<tr>
<td>75–84</td>
<td>9</td>
<td>13</td>
<td>38</td>
</tr>
<tr>
<td>&gt; 84</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Average</td>
<td>23</td>
<td>71</td>
<td>114</td>
</tr>
<tr>
<td>Average excluding under 45 yr</td>
<td>19</td>
<td>56</td>
<td>95</td>
</tr>
</tbody>
</table>
result of a contract between purchaser and provider. The subsequent revisions may well be the subject of a second contract. Financial provision for the costs subsequent upon a primary hip replacement should be considered at the time of initial referral. An alternative to the purchaser entering a second contract would be for the provider to issue a warranty with the primary arthroplasty contract for the life of the patient. If 5 per cent of all primary hip arthroplasties eventually require revision surgery, perhaps 5 per cent of the cost of the revision surgery should be included as a premium in the cost of the primary contract. Thus the total cost of the initial contract would reflect the success of hip arthroplasties at that institution. The purchaser could therefore compare the results of differing surgical techniques and the use of different prosthetic designs before agreeing the initial arthroplasty contract. This would introduce a 'premium on quality' in the purchaser-provider costing process.

This scheme does have the drawback of limiting the use of prosthetic designs to those with established survival studies. Currently, newly introduced prostheses, which are therefore experimental in terms of their survival, with unknown financial implications, are financed by the purchaser. The use of such implants should not be withdrawn, but perhaps the possible consequences of untried designs should be made known to both the patient and the purchaser, with either the manufacturer or the institution performing the arthroplasty agreeing to fund any excess expenditure beyond that expected for an established prosthesis. In these circumstances, the financial consequences of such surgery should be defined and perhaps funded by the provider, the manufacturer and research funding bodies. It would be the responsibility of the institution and financiers to ensure that a proper trial was established using reliable measures to assess the outcome of the treatment.26

All orthopaedic units would also want up-to-date information on survival of implants, and it would thus be in everyone's interest to contribute to a national register where each unit alone would know how well their implants were surviving. Hence a useful side-effect of a lifetime care package would be a national register set up by the NHS trusts.

The use of hip arthroplasties in a fitter population with an increasing life expectancy (Fig. 8) will have large financial consequences in the future. Serious consideration should be given to the choice of implant and techniques used.27-29 A successful joint replacement is one in which the patient dies with the original prosthesis in situ. Patients with a long life expectancy may outlive their prosthesis and be condemned to a process of possibly recurring revision surgery. It is suggested that the purchaser could ensure reliable surgical techniques and appropriate implant designs are used by demanding a lifetime guarantee with the purchase. The provider would underwrite the guarantee by incorporating a proportion of the cost of revision in the contract for the primary surgery.

If it is assumed that, on average, revision surgery costs twice as much as primary surgery, then the additional cost per primary episode can be calculated (Table 2). This shows that for the younger patients (less than 45 years) the premium is 41 per cent for Charnley prosthesis and a staggering 205 per cent for one with the predicted Christiansen rate of failure. If, on the other hand, a general premium is to be charged for a 'lifetime care package', then the same calculation can be done on the total figures from Table 1. Thus for a Charnley prosthesis after 20 years, 2672 (9 per cent) revision episodes will have occurred in the population of 29 696 primary replacements. Similarly, in the case of the McKee-Farrar and Christiansen-like prostheses the values are 23 per cent and 44 per cent, respectively. Currently, the cost of a primary hip procedure carried out in an NHS hospital in the UK is approximately £3500. At this price for the 'lifetime care package', £4130 should be charged for hip replacement surgery that uses a prosthesis with the properties of the Charnley design whereas £6580 would need to be charged for the package if a prosthesis followed the Christiansen survival pattern.

Summary

If, when negotiating contracts between purchasers and providers, a price for a ‘lifetime care package’ for the hip replacement was calculated, rather than a single one-off price for the primary replacement, the following advantages would result:

1. The quality of the primary operation (as measured in how long the hip would last) would be reflected in the price quoted.

2. There would also be a strong incentive for providers to monitor survival of implants within their own unit to ensure that their figures were as good as, or better than, generally published figures so that they could remain competitive.

3. The purchaser should demand accurate information about the survival of the implant so that the purchase price of the entire package is clearly defined at the time of the initial contract.

4. There would be a strong disincentive to publish over-optimistic results, which, although they might make the implant or unit appear good, would produce pricing levels that would be out of balance with the actual costs incurred by the lifetime package.
(5) Using current figures for three implants, the premium payable on quality would vary from 18 per cent to 88 per cent of the quoted cost of the primary surgery. In young patients the premium would be between 41 per cent and 205 per cent.

References


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Appendix

We consider the model to be in two parts: Stage 1, the changes to the population of primary hips; Stage 2, the changes to the revised population. It would, of course, be
possible to have additional stages reflecting secondary, tertiary, etc. revisions; however, as no data are available on the survival, it is assumed the probabilities are the same for all re-revisions.

**Stage 1**

Figure A1 summarizes the stochastic process applied to the primary-hip population.

We let $A_{u_{i-1}}$ be the number of hips alive and unrevised at the start of an interval $i$; then $A_{u_i}$ is the number of hips alive and unrevised at the end of the interval $i$ [that is, at the start of the next $(i+1)$ interval]. $D_{u_i}$ is the number of hips unrevised but dead at the end of interval $i$, $D_r$ the number of hips revised but dead at the end of interval $i$, $p_r$ the probability of revision during interval $i$, $p_d$ the probability of death at the age in interval $i$. For convenience, we let $T_{d_i}$ and $T_{a_i}$ denote the total number of hips dead and total alive, respectively, at the end of the interval $i$; thus,

$$A_{u_{i-1}} = T_{d_{i-1}} + T_{a_{i-1}}$$

Then the outcome of the $A_{u_{i-1}}$ hips during interval $i$ is as follows:

$$T_{d_i} = A_{u_{i-1}} \times p_d$$

We assume that of those hips who die in the $i$th interval only half will be exposed to the risk of failure; thus

$$D_r = T_{d_i} \times p_r \times 0.5$$

and therefore

$$D_{u_i} = T_{d_i} - D_r$$

Now,

$$T_{a_i} = A_{u_{i-1}} - T_{d_i}$$

$$A_{r_i} = T_{a_i} \times p_r$$

$$A_{u_i} = T_{a_i} - A_{r_i}$$

where $A_{r_i}$ represents the number of hips alive and revised at the end of interval $i$.

**Stage 2**

This stage has exactly the same form of stochastic model but with the probabilities adjusted for the re-revision situation (see Fig. A2).

The situation is more complicated, from a computational point of view, when dealing with this stage. As the probabilities are time dependent, for each iteration where a re-revision occurs a new iteration must be started, and from within this new iteration for every re-revision that occurs a further sequence of iterations must be started again. This type of problem is resolved computationally by recursive calls to the Stage 2 calculations.