LABORATORY TESTS ON TOTAL JOINT REPLACEMENT PROSTHESSES

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Total joint replacement is becoming a clinical commonplace. The hip is now often replaced, the knee and finger joints on a smaller but increasing scale, and widening interest is being shown in designs of implants for the total replacement of the elbow and shoulder joints. The largest experience (considering both numbers of patients and lengths of service) has been obtained with the hip, in which it is now known that more than one design will give at least eight years' service and that, supposing extrapolation of the rates of wear observed in clinical use to be permissible, at least twenty years of working life should often be obtainable. Whether such extrapolation is permissible is a separate question to which attention is being devoted. Nevertheless, on the assumption that prostheses of present and foreseeable designs will not wear out in less than the time for which many patients will require them, it is wise to consider the other factors which may limit the useful life of a total replacement implant. On the basis of recorded clinical experience (Girzadas, Geens, Clayton and Leidholt 1968; Kitridou, Schumacher, Sbarbaro and Hollander 1969; Arden, Taylor and Ansell 1970; Charnley 1970; Stinchfield and White 1971; Arden and Ansell 1971; Patterson and Selby Brown 1972; Safi and Schreiber 1972; Wilson, Amstutz, Czerniecki, Salvati and Mendes 1972) and theoretical possibilities, these factors may be listed as infection, trauma, loosening and biological damage from wear or corrosion products. The prevention of infection is primarily a matter of surgical technique and facilities, and this topic will not be considered in detail in this paper. It may however be noted that the design of an implant can theoretically influence the development and consequences of infection by making insertion possible with minimal dissection and the creation of the smallest possible implant-tissue interface, and by making removal simple and not mutilating. Such factors contributed to the design of a total replacement knee by two of the authors (Freeman, Swanson and Zahir 1972; Swanson and Freeman 1972).

Similarly, the occurrence of trauma is not a matter for laboratory testing, although by the choice of materials and the mechanical design of an implant it is possible to limit the damage that might be caused by incidental trauma.

Loosening must be assumed to be influenced by, amongst other factors, the magnitude of the frictional forces and moments in the prosthetic joint although other factors may well be relevant. Wilson and Scales (1970) discussed the loosening of femoral head components of total hip replacements and Andersson, Freeman and Swanson (1972) the loosening of prosthetic acetabula.

The possibility of biological damage to the tissues obviously depends on the nature and quantity of the wear or corrosion products, which in turn will depend on the materials used for the bearing and the mechanical design of the implant.

The tests described in this paper were designed to investigate the performance of a selection of currently used prosthetic hips and knees, and also some combinations of materials not yet in clinical use, particularly with respect to friction and the wear and corrosion products. When these tests were started, published measurements of frictional moments had given only relative and not absolute values (Scales, Duff-Barclay and Burrows 1965). Also, whereas the presence of metallic ions in tissues close to non-wearing cobalt-chrome implants had been recognised (Müller, Allgöwer and Willenegger 1965), no work had been published dealing with the wear or corrosion products to be expected from total joint replacement prostheses.
MATERIALS AND METHODS: WEAR AND FRICTION TESTS

The following test apparatus was used.

**Hip and knee simulator**—A machine was designed and constructed in which implants could be tested in the laboratory under chemical, thermal and mechanical conditions simulating those encountered in life. This machine offers the following facilities. 1) The prosthesis under test can be implanted in bone and the bone held in the machine. 2) The prosthesis can be surrounded by a liquid (normally Ringer's solution) at a controlled temperature which has no contact with any metal other than that of the prosthesis. 3) Either constant or cyclically varying loads up to 4,450 Newtons (1,000 pounds force) can be applied to the prosthesis. 4) Flexion-extension movements, the total range of which is adjustable up to 90 degrees and whose speed can be varied, can be applied cyclically while the prosthesis is under load. This is the only movement essential to a knee joint; movements about the other two axes (medial and lateral rotation, and adduction and abduction at a hip joint) are provided but were not used in the tests to be described. 5) The forces transmitted through the prosthesis are recorded continuously in such a way that at any chosen instant both the total force and the moment can be calculated. The sudden changes in the transmitted moment at the instants of reversal of movement show the effect of friction in the prosthesis, and the frictional moment can be calculated.

The following notes may be of interest to those concerned with the technical aspects of such testing apparatus.

The two components of the joint to be tested are set (either directly or after having been implanted in the appropriate portions of bone) in an epoxy resin, so that in full extension the long axis of the leg would be inclined at 45 degrees to the horizontal. The femoral component is below the tibial (if a knee) or acetabular (if a hip) component, and is supported in a fixed position by three load cells. The upper component (tibial or acetabular) can be moved through a maximum of 90 degrees, so that in 90 degrees of flexion the long axis of the tibia (or the corresponding line in the pelvis) would be inclined at 45 degrees to the vertical. This movement of ±45 degrees about the vertical was adopted so that the metallic parts holding the upper component need never dip into the liquid surrounding the joint. This liquid is retained by a “Perspex” bath having a flexible polyethylene dust cover. A thermocouple and electric heater (both sheathed with non-metallic materials) connected to a temperature controller enable the temperature of the liquid to be kept constant.

The three load cells supporting the lower component of the joint under test are arranged symmetrically about the load axis, in such a way that at any instant the sum of two of their readings minus the third represents the moment about the flexion-extension axis of the joint, while the sum of all three readings naturally represents the total load being transmitted through the joint. To reduce the number of calculations needed, the additions and subtraction are done electrically. For this purpose each load cell (which is a spring steel member fitted with electrical resistance strain gauges) is provided with two independent sets of strain gauges, and the two groups of three sets are connected as necessary, each as one Wheatstone bridge. A standard oscillator-amplifier-demodulator and ultra-violet paper recorder are used to make a simultaneous record against time of the load and of the moment, on which can be superimposed marks to show the instants of reversal of movement in the joint.

Constant loads are applied by means of a dead weight, acting through a lever and a cantilever arm able to rotate in a pair of ball bearings which allow the flexion-extension movement to be applied while the load acts. The axis of a knee joint, or the centre of a hip joint, must be set at the start of a test to coincide with the axis of these ball bearings. Cyclically varying loads are applied by means of a cam acting on the same lever system through springs. In principle, different shapes of cam could be made, but in the tests to be described only an approximately sinusoidal variation of load with time has been used.

The whole is driven by a 1 horse-power (750 watt) electric motor, which might be necessary if a prosthesis on the point of seizure were to be tested under 1,000 pounds force of load, but is much more powerful than is needed for most prostheses. The speed can be controlled; 1-5 cycles of flexion-extension per second is a possible speed, but vibrations tend to introduce unwanted fluctuations into the loads at higher speeds, and the tests to be described were performed at about one cycle per second, which represents a brisk walking pace.

**Stanton pendulum**—As an independent check on the values obtained for frictional moments, some prostheses were tested while forming the fulcrum of a Stanton pendulum originally constructed for experiments on synovial joints, and already described in that connection (Little, Freeman and Swanson 1969). The pendulum is displaced by hand and then allowed to oscillate freely, having the joint or bearing under test as its pivot. The oscillations of the pendulum are recorded continuously, and from their decay the frictional moment exerted by the joint under test is calculated. In the present tests this pendulum was used with a total load of 956 Newtons (215 pounds force) supported by the joint under test, and at a frequency of about 0-9 cycles per second.
Quantities measured—The forces and moments transmitted through the prostheses were calculated from the records obtained from the testing machine, as indicated above.

The Ringer's solution was removed at suitable intervals and any remaining particles washed from the bath with distilled water. Particles, which were only obtained from prostheses composed entirely of cobalt-chrome alloy, were separated by filtration through Whatman No. 40 filter paper and weighed. Then the filtrate was analysed for chloride ions (as a check on the concentration of the Ringer's solution, by comparison with the chloride ion content of the new solution), and for cobalt, chromium, manganese and molybdenum by a spectrographic method.

The particles, having been washed free of soluble salts, were used for one of three purposes: 1) examination of size and shape by transmission electron microscopy, following dispersion; 2) spectro-chemical analysis for cobalt, chromium, manganese and molybdenum (the results from which were compared with the results of corresponding analyses of small pieces removed from the prostheses before testing); or 3) injection into rats as described below.

The chemical analyses were performed by a commercial laboratory approved for such purposes by the Air Registration Board and similar bodies.

Specimens of the Ringer's solution as put into the bath at the start of each test were subjected to the full analysis to discover whether any part of the content of metallic ions found after testing was present before testing.

Prostheses and specimens tested—Results from the following are given in this paper. 1) A Shiers knee prosthesis in cobalt-chromium-molybdenum alloy; 2) a Walldius knee prosthesis in cobalt-chromium-molybdenum alloy; 3) two McKee-Farrar hip prostheses in cobalt-chromium-molybdenum alloy tested in the simulator, and a third one tested in the pendulum; 4) a Charnley hip prosthesis in stainless steel and polyethylene; 5) a specimen having a 23-millimetre diameter ball in titanium alloy (IMI 318) bearing against a cup in high-density polyethylene; 6) a specimen similar to the last, but having the ball in a different titanium alloy (IMI 680).

### TABLE I

<table>
<thead>
<tr>
<th>Prosthesis</th>
<th>Cobalt</th>
<th>Chromium</th>
<th>Molybdenum</th>
<th>Manganese</th>
<th>Iron</th>
<th>Nickel</th>
<th>Silicon</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shiers knee</td>
<td>65.3</td>
<td>26.9</td>
<td>6.11</td>
<td>0.36</td>
<td>d</td>
<td>d</td>
<td>d</td>
<td>0.25</td>
</tr>
<tr>
<td>Walldius knee</td>
<td>63.5</td>
<td>28.0</td>
<td>5.53</td>
<td>0.81</td>
<td>d</td>
<td>d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McKee hip (1)</td>
<td>64.5</td>
<td>28.2</td>
<td>5.2</td>
<td>0.76</td>
<td>0.25</td>
<td></td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Charnley hip (femoral component)</td>
<td>17.18</td>
<td>26.1</td>
<td>26.1</td>
<td>1.60</td>
<td>66.5</td>
<td>11.18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RESULTS OF WEAR AND FRICTION TESTS

Composition of alloys—These are shown in Table I.

Corrosion or wear products—Each of the cobalt-chromium-molybdenum prostheses, when tested in the simulator, produced a readily visible change in the appearance of the fluid in the bath. Typically this became cloudy and brown-coloured, and a brown deposit could be seen on all the upward-facing surfaces in the bath. When bone fat or synovial fluid was present between the bearing surfaces, the discolouration of the bulk fluid took place more slowly; a smear of dark grey coloured paste was seen to accumulate at those parts of the margins of the contact areas which were visible.

None of the three prostheses or specimens embodying a polyethylene cup produced any visible change in the fluid.
### Table II

**Concentrations of Metallic Ions in Solution and Masses of Metals in Sediment**

<table>
<thead>
<tr>
<th>Prosthesis</th>
<th>Fluid</th>
<th>Bone</th>
<th>Load</th>
<th>Number of cycles before removal of fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shiers knee</td>
<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
<td>0–1,080,100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,080,100–1,236,400</td>
</tr>
<tr>
<td>Walldius knee</td>
<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
<td>0–110,200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>110,200–301,400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>301,400–1,275,100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,275,100–1,836,100</td>
</tr>
<tr>
<td>McKee hip (1)</td>
<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
<td>0–280,700</td>
</tr>
<tr>
<td>McKee hip refitted (1)</td>
<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
<td>0–319,800</td>
</tr>
<tr>
<td></td>
<td>Ringer's</td>
<td>Present</td>
<td>Varying</td>
<td>0–260,300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>260,300–361,600</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>361,600–471,100</td>
</tr>
<tr>
<td>McKee hip (2)</td>
<td>Ringer's</td>
<td>Absent</td>
<td>Varying</td>
<td>0–222,700</td>
</tr>
<tr>
<td></td>
<td>Ringer's+synovial fluid</td>
<td>Absent</td>
<td>Varying</td>
<td>0–141,600</td>
</tr>
<tr>
<td></td>
<td>Ringer's+synovial fluid</td>
<td>Absent</td>
<td>Constant</td>
<td>0–97,500</td>
</tr>
<tr>
<td></td>
<td>Ringer's+synovial fluid</td>
<td>Absent</td>
<td>Constant</td>
<td>0–160,000</td>
</tr>
<tr>
<td></td>
<td>Ringer's+synovial fluid</td>
<td>Absent</td>
<td>Varying</td>
<td>0–223,300</td>
</tr>
<tr>
<td></td>
<td>Ringer's+bone fat</td>
<td>Absent</td>
<td>Constant</td>
<td>0–269,700</td>
</tr>
<tr>
<td></td>
<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
<td>0–183,100</td>
</tr>
<tr>
<td></td>
<td>Ringer's</td>
<td>Absent</td>
<td>Varying</td>
<td>0–275,600</td>
</tr>
<tr>
<td>McKee hip refitted (1)</td>
<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
<td>0–26,800</td>
</tr>
</tbody>
</table>

**Notes:**
1) The smallest detectable concentrations were: cobalt, chromium or molybdenum 0.1 part per million. manganese 0.02 part per million.
2) "nd" means "not detected".
3) None of the four metals listed was detected in Ringer's solution as obtained from stock, or removed after surrounding an unloaded stationary prosthesis at 37 degrees Celsius for seventy-two hours.
4) The various tests performed on the McKee hip joints are listed above in chronological order.
5) A horizontal line in the table, followed by a new zero for the number of cycles, means that the prosthesis and the bath were thoroughly cleaned; but of course the bearing surfaces of any one prosthesis were subjected to all the cycles cumulatively.
6) Constant Load was 890 Newtons (200 pounds-force); varying load was 0–890 Newtons.

Table II shows the concentrations of metallic ions found in solution, and the masses of metals in the sediment, for each of the cobalt-chromium-molybdenum prostheses tested under various conditions as listed in the table.

No metal was detected in any of the solutions taken from the bath during tests on the prostheses or specimens embodying polyethylene cups.

A sample of the solution removed during the test on the Charnley hip prosthesis was examined by Imperial Chemical Industries (Plastics Division) for the presence of polyethylene particles. No particles were found.

On examination after testing, all the cobalt-chromium-molybdenum prostheses showed severe scoring over their bearing areas. The Charnley hip prosthesis showed no marks on the stainless steel ball, and slight burnishing (leaving some of the manufacturer's machining marks still visible) of the bearing surface of the cup. The IMI 318 titanium alloy ball showed some scoring and black discoloration, as did the polyethylene cup in which it had worked.
## TABLE II—continued

CONCENTRATIONS OF METALLIC IONS IN SOLUTION AND MASSES OF METALS IN SEDIMENT

<table>
<thead>
<tr>
<th>Concentrations of metals in fluid (parts per million)</th>
<th>Masses of metals in sediment (milligrams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>Chromium</td>
</tr>
<tr>
<td>7-2</td>
<td>0.17</td>
</tr>
<tr>
<td>166</td>
<td>0.3</td>
</tr>
<tr>
<td>3-4</td>
<td>nd</td>
</tr>
<tr>
<td>6-1</td>
<td>nd</td>
</tr>
<tr>
<td>5-4</td>
<td>nd</td>
</tr>
<tr>
<td>4-4</td>
<td>nd</td>
</tr>
<tr>
<td>11-4</td>
<td>nd</td>
</tr>
<tr>
<td>6-0</td>
<td>0.61</td>
</tr>
<tr>
<td>2-2</td>
<td>0.32</td>
</tr>
<tr>
<td>1-4</td>
<td>0.41</td>
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<tr>
<td>3-3</td>
<td>0.71</td>
</tr>
<tr>
<td>5-8</td>
<td>nd</td>
</tr>
<tr>
<td>20-0</td>
<td>nd</td>
</tr>
<tr>
<td>19-4</td>
<td>nd</td>
</tr>
<tr>
<td>9-0</td>
<td>nd</td>
</tr>
<tr>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>2-7</td>
<td>0.32</td>
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<tr>
<td>8-4</td>
<td>0.25</td>
</tr>
<tr>
<td>4-8</td>
<td>nd</td>
</tr>
<tr>
<td>5-6</td>
<td>nd</td>
</tr>
</tbody>
</table>

Notes: 1) The smallest detectable concentrations were: cobalt, chromium or molybdenum 0.1 part per million, manganese 0.02 part per million.
2) "nd" means "not detected".
3) None of the four metals listed was detected in Ringer's solution as obtained from stock, or removed after surrounding an unloaded stationary prosthesis at 37 degrees Celsius for seventy-two hours.
4) The various tests performed on the McKee hip joints are listed above in chronological order.
5) A horizontal line in the table, followed by a new zero for the number of cycles, means that the prosthesis and the bath were thoroughly cleaned; but of course the bearing surfaces of any one prosthesis were subjected to all the cycles cumulatively.
6) Constant Load was 890 Newtons (200 pounds force); varying load was 0–890 Newtons.

A mishap in the apparatus damaged the IMI 680 titanium alloy specimen so that nothing could be concluded from its appearance.

Figure 1 shows a transmission electron micrograph of particles obtained during the test on the Shiers knee prosthesis running in Ringer’s solution, and Figure 2 shows particles from the second McKee hip prosthesis tested while implanted in bone, with synovial fluid and Ringer’s solution present.

Frictional moments—Table III shows the frictional moments calculated from measurements made during tests in the simulator under the various conditions which are listed in the table. Table IV shows the frictional moments derived from tests on two prostheses in the Stanton pendulum. These tests were intended merely to confirm the results obtained in the simulator, preferably without damaging the bearing surfaces, and were therefore fewer in number and of much more restricted scope.

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<table>
<thead>
<tr>
<th>Prosthesis</th>
<th>Fluid</th>
<th>Bone</th>
<th>Load</th>
<th>Number of cycles</th>
<th>Frictional moment (Newton metres)</th>
<th>Frictional moment (poundforce inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flexion</td>
<td>Extension</td>
</tr>
<tr>
<td>Walldius knee . .</td>
<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
<td>0</td>
<td>5.0 (44)</td>
<td>4.5 (40)</td>
</tr>
<tr>
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<td></td>
<td>2,600</td>
<td>8.9 (79)</td>
<td>11.6 (103)</td>
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<td>9,700</td>
<td>9.9 (88)</td>
<td>9.9 (88)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,836,000</td>
<td>17.6 (156)</td>
<td>17.6 (156)</td>
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<tr>
<td>McKee hip (1) . .</td>
<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
<td>400</td>
<td>6.2 (55)</td>
<td>5.4 (48)</td>
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<td>1,000</td>
<td>16.0 (141)</td>
<td>9.9 (88)</td>
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<td></td>
<td></td>
<td></td>
<td>16.2 (143)</td>
<td>9.9 (88)</td>
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<td>McKee hip refitted (1)</td>
<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
<td>400</td>
<td>6.0 (53)</td>
<td>4.5 (40)</td>
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<tr>
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<td></td>
<td></td>
<td>1,300</td>
<td>7.0 (62)</td>
<td>6.0 (53)</td>
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<td></td>
<td></td>
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<td>9.9 (88)</td>
<td>7.0 (62)</td>
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<td>167,000</td>
<td>10.2 (90)</td>
<td>7.4 (66)</td>
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<td></td>
<td>14.0 (124)</td>
<td>6.9 (61)</td>
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<tr>
<td>McKee hip (2) . .</td>
<td>Ringer's</td>
<td>Present</td>
<td>Varying</td>
<td>0</td>
<td>4.5 (40)</td>
<td>2.9 (26)</td>
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<td>260,900</td>
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<td>2.1 (19)</td>
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<td>265,400</td>
<td>7.1 (55)</td>
<td>2.1 (19)</td>
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<td></td>
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<td></td>
<td>2.9 (26)</td>
<td>2.6 (23)</td>
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<tr>
<td>Ringer's + synovial fluid</td>
<td>Present</td>
<td>Varying</td>
<td>542,200</td>
<td>1.0 (9)</td>
<td>2.0 (18)</td>
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</tr>
<tr>
<td>Ringer's + synovial fluid</td>
<td>Absent</td>
<td>Constant</td>
<td>50,000</td>
<td>3.7 (33)</td>
<td>6.7 (59)</td>
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</tr>
<tr>
<td>Ringer's + synovial fluid</td>
<td>Absent</td>
<td>Constant</td>
<td>2,000</td>
<td>5.0 (44)</td>
<td>2.5 (22)</td>
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<td></td>
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<td>29,400</td>
<td>8.9 (79)</td>
<td>3.7 (33)</td>
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<td></td>
<td>152,600</td>
<td>9.9 (88)</td>
<td>2.7 (24)</td>
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<tr>
<td>Ringer's + synovial fluid</td>
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<td>Varying</td>
<td>223,300</td>
<td>7.9 (70)</td>
<td>3.7 (33)</td>
<td></td>
</tr>
<tr>
<td>Ringer's + bone fat</td>
<td>Absent</td>
<td>Varying</td>
<td>1,300</td>
<td>1.7 (15)</td>
<td>0.8 (7)</td>
<td></td>
</tr>
<tr>
<td>Ringer's + bone fat</td>
<td>Absent</td>
<td>Constant</td>
<td>103,600</td>
<td>1.7 (15)</td>
<td>1.2 (11)</td>
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</tr>
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<td>Ringer's + bone fat</td>
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<td>1.5 (13)</td>
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<td>1.0 (9)</td>
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<td></td>
<td></td>
<td>2.3 (20)</td>
<td>1.2 (11)</td>
</tr>
<tr>
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<td>Absent</td>
<td>Constant</td>
<td></td>
<td>2,000</td>
<td>4.5 (40)</td>
<td>1.7 (15)</td>
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<td>4.5 (40)</td>
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<td></td>
<td></td>
<td>12.0 (106)</td>
<td>4.7 (42)</td>
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<tr>
<td>Ringer's</td>
<td>Absent</td>
<td>Varying</td>
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<td>Ringer's</td>
<td>Absent</td>
<td>Constant</td>
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<td>1.2 (11)</td>
<td>0.8 (7)</td>
</tr>
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<td>Constant</td>
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<td>1,629,553</td>
<td>1.0 (9)</td>
<td>1.2 (11)</td>
</tr>
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TABLE IV
FrICTIONAL MOMENTS MEASURED USING A STANTON PENDULUM UNDER A CONSTANT LOAD OF 956 NEWTONS (215 POUNDFORCE)

<table>
<thead>
<tr>
<th>Prosthesis</th>
<th>Fluid</th>
<th>Time after application of load</th>
<th>Frictional moment (Newton metres)</th>
<th>Frictional moment (poundforce inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McKee hip (3)</td>
<td>Synovial fluid</td>
<td>5 seconds</td>
<td>2.7 (24)</td>
<td>0.49 (4.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 seconds</td>
<td>2.7 (24)</td>
<td>0.32 (2.8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16 seconds</td>
<td>2.7 (24)</td>
<td>0.36 (3.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28 seconds</td>
<td>3.3 (29)</td>
<td>0.47 (4.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 seconds</td>
<td>3.7 (33)</td>
<td>0.58 (5.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 seconds</td>
<td>4.2 (37)</td>
<td>0.58 (5.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9 seconds</td>
<td>4.4 (39)</td>
<td>0.58 (5.3)</td>
</tr>
<tr>
<td></td>
<td>Motor oil</td>
<td>10 seconds</td>
<td>0.49 (4.3)</td>
<td>0.32 (2.8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28 seconds</td>
<td>0.32 (2.8)</td>
<td>0.36 (3.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 minutes</td>
<td>0.36 (3.2)</td>
<td>0.36 (3.2)</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>5 seconds</td>
<td>1.02 (9.9)</td>
<td>0.88 (7.7)</td>
</tr>
<tr>
<td>Charnley hip (2)</td>
<td>Ringer's</td>
<td>10 seconds</td>
<td>0.88 (7.7)</td>
<td>0.88 (7.7)</td>
</tr>
<tr>
<td></td>
<td>Synovial fluid</td>
<td>10 seconds</td>
<td>0.47 (4.2)</td>
<td>0.47 (4.2)</td>
</tr>
</tbody>
</table>

Note: A horizontal line followed by a new series of times means that the load was removed and the fluid allowed to redistribute itself over the bearing surfaces.

Figure 1—Transmission electron micrograph of particles obtained at 1,080,100 cycles from Shiers knee, tested in Ringer's solution at constant load. Figure 2—Transmission electron micrograph of particles obtained at 361,600 cycles from second McKee hip, tested mounted in bone, with Ringer's solution and synovial fluid present, under varying load.
MATERIALS AND METHODS: BIOLOGICAL TESTS

Preliminary results of early tests in this series were given by Heath, Freeman and Swanson (1971).

Particles—Particles obtained during tests on cobalt-chromium-molybdenum prostheses in the simulator were filtered and washed as described above. Three samples were used, as follows. C: Walldius knee prostheses, tested in Ringer's solution under constant load, produced between 301,400 and 1,275,100 cycles. D: as C, but produced between 1,275,100 and 1,836,100 cycles. ME: first McKee hip prosthesis, tested in Ringer's solution under constant load, produced between 1,046,600 and 1,642,600 cycles.

After being washed, the filter paper and deposit were dried at room temperature in a desiccator, and then the deposit was gently scraped off. The preparation to be injected was obtained by sterilising 280 milligrams of the deposit by dry heat at 150 degrees Celsius for one hour and then suspending it in 4 millilitres of sterile horse serum.

Animals and injections—Rats were used, of the hooded strain of the Strangeways Research Laboratory. Their ages at the time of injection were within the range seven to nine weeks. Each rat was injected in the thigh muscle, from the medial aspect of the leg, with 0-4 millilitre of the suspension. In all other respects, the methods followed those used by Heath (1956) in investigating carcinogenesis by pure powdered metals.

Solubility of particles—The solubility of these particles in sterile horse serum was tested, following the methods used by Heath, Webb and Caffrey (1969) with pure powdered metals. Eighteen milligrams of the sample ME were sterilised by dry heat at 150 degrees Celsius for one hour, and then incubated aerobically under sterile conditions with 50 millilitres of sterile horse serum at 37 degrees Celsius, with occasional gentle shaking. After thirty-eight days, 10-millilitre samples of the serum were centrifuged to remove any particulate matter, and the cobalt content of the fluid was determined by atomic absorption spectrophotometry.

RESULTS OF BIOLOGICAL TESTS

Carcinogenic effects—Five rats injected with sample C were killed by cervical dislocation at monthly intervals after injection, and one rat injected with sample D was killed one month after injection. The tissues at the injection site, and the inguinal, axillary and prevertebral lumbar lymph nodes were removed and fixed in Carnoy's fluid (60 millilitres of absolute alcohol, 30 millilitres of chloroform and 10 millilitres of glacial acetic acid), and thereafter embedded in paraffin wax and cut into sections 8 microns thick. The sections were then stained in methyl green and pyronin, and also in azan.

Muscle at the injection site in these rats showed deposits of metallic debris and areas of necrosis and regeneration consequent upon the initial mechanical and chemical injury caused by the particles. The appearance of this necrosis and regeneration was very like that observed in earlier experiments in which particles of pure cobalt had been the cause of the damage (Heath 1960) and abnormal fibroblasts and myoblasts were seen at an early stage.

The remaining rats in each group were kept alive for possible tumour formation. To date twenty-two tumours have arisen and all have been examined in detail. Table V shows the total incidence of tumours to April 1972, and Table VI shows the histological findings recorded for the twenty-two tumours.

Solubility of particles—The concentration of cobalt measured in each of two samples of serum treated as described above was 31 micrograms per millilitre. Therefore the total Co⁺⁺ dissolved in the original 50 millilitres of serum was 50 x 31 micrograms, i.e., 1,555 milligrams. The particles used for this experiment would have contained 63–65 per cent of cobalt according to the analyses in Table I, or about 60 per cent of cobalt according to the analysis given in Table II of a sample of debris from a McKee hip prosthesis. The exact analysis of the particles used in the solubility experiment is unknown, but, assuming the cobalt content to have been between 60 and 65 per cent, the mass of Co⁺⁺ in the 18 milligrams of debris used was between 10.8 and
TABLE V
INCIDENCE OF TUMOURS

<table>
<thead>
<tr>
<th>Debris batch</th>
<th>Rat number</th>
<th>Result</th>
<th>Debris batch</th>
<th>Rat number</th>
<th>Result</th>
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<td>KNT</td>
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<td>L</td>
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<td>DNT(LS)</td>
</tr>
<tr>
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<td>11,747</td>
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<td>11,755</td>
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<td>11,167</td>
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<td>DNT</td>
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<td>T 15</td>
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</tr>
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<td>DNT</td>
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<td>11,758</td>
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<td>DNT</td>
<td></td>
<td>11,763</td>
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<td>11,770</td>
<td>L</td>
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<td>T 4</td>
</tr>
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<td>11,183</td>
<td>T 13</td>
<td></td>
<td>11,772</td>
<td>T 44</td>
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<td>DNT</td>
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<td>11,775</td>
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<td>11,776</td>
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<td>DNT</td>
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<td></td>
<td>11,196</td>
<td>L</td>
<td></td>
<td>11,785</td>
<td>L</td>
</tr>
</tbody>
</table>

* Since Table V was prepared, the following changes have occurred. Rat number 11,768, treated with debris of batch ME, developed at twenty-four months a tumour which has not yet been examined histologically. All other rats in this series either died at the end of their normal life span of about thirty-one months (twenty-nine months after injection) or were killed before this time because of intercurrent illness. No further rats, other than the one mentioned above, had tumours.

KNT: killed for histological examination; no tumour found.
DNT: died; no tumour found at injection site.
DNT(LS): died; no tumour at injection site but widely disseminated lymphosarcoma.
T+: number: tumour formed at injection site after the stated number of months.
L: living at twenty-five months of age—that is, twenty-three months after injection.

11.8 milligrams. Thus, during thirty-eight days at 37 degrees Celsius, about one-seventh of the Co²⁺ in the debris had dissolved in the serum.

DISCUSSION

Production of particulate debris by cobalt-chromium-molybdenum prostheses—Perhaps the most prominent feature of the present results is the significant quantities of particulate debris produced during tests on cobalt-chromium-molybdenum prostheses, contrasted with the absence
TABLE VI
DETAILED DIAGNOSIS OF THE LESION IN THE TWENTY-TWO RATS WITH TUMOURS AT THE INJECTION SITE

<table>
<thead>
<tr>
<th>Rat number</th>
<th>Primary tumour</th>
<th>Metastasis in</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,602</td>
<td>Osteofibrosarcoma</td>
<td>Lymph node in fat of thigh</td>
</tr>
<tr>
<td>11,167</td>
<td>Cellular fibrosarcoma with giant cells</td>
<td>Prevertebral lumbar lymph node</td>
</tr>
<tr>
<td>11,168</td>
<td>Cellular fibrosarcoma</td>
<td>Prevertebral lumbar lymph node</td>
</tr>
<tr>
<td>11,177</td>
<td>Cellular fibrosarcoma with giant cells</td>
<td>—</td>
</tr>
<tr>
<td>11,182</td>
<td>Cellular fibrosarcoma with giant cells</td>
<td>—</td>
</tr>
<tr>
<td>11,183</td>
<td>Anaplastic rhabdomyofibrosarcoma</td>
<td>Lumbar prevertebral region</td>
</tr>
<tr>
<td>11,184</td>
<td>Osteofibrosarcoma</td>
<td>—</td>
</tr>
<tr>
<td>11,736</td>
<td>Fibrosarcoma with giant cells</td>
<td>—</td>
</tr>
<tr>
<td>11,741</td>
<td>Poorly differentiated rhabdomyosarcoma with some areas of fibrosarcoma and giant cells</td>
<td>Prevertebral lumbar lymph node</td>
</tr>
<tr>
<td>11,747</td>
<td>Cellular fibrosarcoma with some areas of rhabdomyosarcoma and osteosarcoma, also giant cells</td>
<td>—</td>
</tr>
<tr>
<td>11,748</td>
<td>Rhabdomyosarcoma</td>
<td>—</td>
</tr>
<tr>
<td>11,751</td>
<td>Cellular sarcoma with some areas of rhabdomyo- and osteosarcoma; some giant cells</td>
<td>—</td>
</tr>
<tr>
<td>11,757</td>
<td>Anaplastic rhabdomyosarcoma with some areas of fibrosarcoma and some giant cells</td>
<td>—</td>
</tr>
<tr>
<td>11,758</td>
<td>Fibrosarcoma with some areas of rhabdomyosarcoma</td>
<td>—</td>
</tr>
<tr>
<td>11,761</td>
<td>Anaplastic rhabdomyosarcoma with some areas of fibrosarcoma</td>
<td>—</td>
</tr>
<tr>
<td>11,763</td>
<td>Cellular sarcoma with some areas of rhabdomyosarcoma and osteosarcoma and a few giant cells</td>
<td>Prevertebral lumbar lymph node</td>
</tr>
<tr>
<td>11,764</td>
<td>Fibrosarcoma with giant cells</td>
<td>Prevertebral lumbar lymph node</td>
</tr>
<tr>
<td>11,766</td>
<td>Well differentiated fibrosarcoma with some giant cells</td>
<td>Prevertebral lumbar lymph node</td>
</tr>
<tr>
<td>11,767</td>
<td>Rhabdomyosarcoma with area of fibrosarcoma and some giant cells</td>
<td>—</td>
</tr>
<tr>
<td>11,771</td>
<td>Cellular sarcoma with giant cells</td>
<td>—</td>
</tr>
<tr>
<td>11,772</td>
<td>Rhabdomyosarcoma of varying degrees of differentiation with some areas of fibrosarcoma and some giant cells</td>
<td>—</td>
</tr>
<tr>
<td>11,776</td>
<td>Rhabdomyosarcoma of varying degrees of differentiation with some areas of fibrosarcoma and some giant cells</td>
<td>Prevertebral lumbar lymph node</td>
</tr>
</tbody>
</table>

of such particles during tests on a stainless steel and polyethylene prosthesis. It is therefore important to establish whether this finding is relevant to the clinical situation.

There is no doubt that the tests in the simulator were more severe than the conditions to which such prostheses are subjected in life. In most tests the lubricant was Ringer's solution, and, even when synovial fluid was applied to the bearing surfaces before a test, it must be assumed that this fluid would become diluted or degraded, or both, during the test. Although the exact nature of the fluid surrounding a prosthetic joint in life is unknown, it seems reasonable to infer, from visual and tactile observations made on re-exploration of
such joints, that it is closer to synovial fluid than to Ringer's solution, and that it may therefore be a better lubricant than Ringer's solution. Care must be exercised here, however, because 1) a small number of experiments (Ropes, Robertson, Rossmeisl, Peabody and Bauer 1947; Tanner and Edwards 1959) have shown that, in rigid impermeable bearing surfaces, synovial fluid only gives significantly lower friction than saline solutions up to bearing stresses lower than those of the present tests; and 2) the friction-reducing ability of a lubricant is not necessarily proportional to its wear-reducing ability. If the conditions in the simulator are more severe than in life, the difference must be expected to become greater as any one test proceeds, because the destruction of the bearing surfaces is likely to be a self-accelerating process.

On the other hand, the presence of metallic particles in soft tissues adjacent to cobalt-chromium-molybdenum joint implants has been reported (Girzadas and colleagues 1968).

The few observations so far published on the appearance of the bearing surfaces of cobalt-chromium-molybdenum joint prostheses removed from patients (Walker and Gold 1971, Hessert 1971) have related to hip prostheses with lapped bearing surfaces, and show wear tracks much less severe than those seen on the surfaces of the two such hips tested in the simulator. Figure 3, however, shows two hinge pins from Shiers knee implants: one is from the implant included in the present tests. The other was taken from one removed, because of loosening, from a fifty-nine-year-old man whose body mass was 70 kilograms (155 pounds) and who was a moderately active walker for the four years during which the prosthesis was in place.

The work of analysing the tissues adjacent to this prosthesis and other similar tissues is still in progress, but preliminary results show cobalt and chromium contents several orders of magnitude higher than in corresponding tissues from a knee in which no prosthesis had been present. It is clear that, at least in this one patient, the severity of the wear was comparable to that in the same design of prosthesis tested in the simulator.

It is concluded that the rate of production of particles in the simulator, though almost certainly higher than in life, is not so much higher as to make the results meaningless. It may well be that the difference between the conditions in the simulator and those in life is greater for joints with lapped bearing surfaces (in these tests, the McKee hip) than for joints with less accurately-finished bearing surfaces (in these tests, the Walldius and Shiers knees). Production of particulate debris by polyethylene-containing prostheses or specimens—In the test on the Charnley hip prosthesis, the absence of dissolved metals and of both metallic and polyethylene particles is consistent with the absence of large changes in the appearance of the bearing surfaces at the end of the test. The length of the test (about 4,000,000 cycles) is equivalent to very roughly four years' walking by an average person, and therefore presumably to rather more than four years' walking by a typical patient having had a total hip replacement. This result is at first sight better than the results of measurements made

FIG. 3
Hinge pins from Shiers knee prostheses: (top) the prosthesis used in the present tests, after a total of 1,236,400 cycles; (bottom) removed from a patient after four years' moderately active walking. The wear took place in the central section of the top pin but in one end section of the bottom pin. The approximately longitudinal scratches on the bottom pin were made during dismantling of the prosthesis.
on Charnley hip prostheses in life, reported by Charnley (1970). Allowing for the errors inherent in making such measurements from radiographs, and for the possibility that some of the displacement, so measured, of the prosthetic femoral head relative to the prosthetic acetabulum could be due to creep of the polyethylene rather than to wear, it is difficult to say more than that the one test in the present series gave a result at one end of the range given by radiographic measurements. Recent reports (Charosky, Bullough and Wilson 1973) of the presence of birefringent particulate matter in soft tissues surrounding polyethylene-containing prostheses seem to confirm that, in at least some such prostheses, wear of the polyethylene component does occur.

Frictional moments—The tests in the simulator showed that, when lubricated with Ringer’s solution, all the cobalt-chromium-molybdenum prostheses gave frictional moments which increased as the tests progressed, usually tending towards a constant value. This increase was presumably accompanied by the progressive destruction of the bearing surfaces. The lowest frictional moments were obtained when bone fat had been added to the bath, even with prostheses of which the bearing surfaces had already been damaged, as indicated by the raised frictional moments, by being worked in Ringer’s solution alone. These tests with bone fat deliberately added were performed to explain the low frictional moments measured when the second McKee hip prosthesis was initially tested implanted in bone (Table III). It was assumed that these low values were due to lubrication of the joint by fat which could be seen to have floated to the top of the liquid in the bath despite attempts made to seal the bones, and the general similarity of the two sets of results seems to confirm this assumption.

Synovial fluid gave a smaller reduction than did bone fat, but, as mentioned above, a test in these circumstances cannot be regarded as a full test of the lubricating ability of synovial fluid.

Table III shows a considerable difference between the frictional moments in cobalt-chromium-molybdenum prostheses and those in polyethylene-containing prostheses. The only reasonably direct comparison is between the latter and the McKee hips. To extend this comparison, the tests in the Stanton pendulum, the results of which are given in Table IV, were performed. For the Charnley hip lubricated with Ringer’s solution, the frictional moment measured in the pendulum was within the range of the moments measured in the simulator; synovial fluid gave a frictional moment in the pendulum a little less than two-thirds of that given by Ringer’s solution. In the pendulum, the McKee hip was not tested with Ringer’s solution because it was desired not to risk damaging the bearing surfaces. Tested with synovial fluid, this hip gave frictional moments between five and nine times greater than did the Charnley hip tested in exactly the same conditions. It should be noted that, in the pendulum tests, the synovial fluid was neither diluted nor exposed for more than a few minutes to the atmosphere.

For incidental interest, the test using a standard automobile engine oil, giving frictional moments about one-tenth the magnitude of those obtained with synovial fluid, supports the view, quoted above, that synovial fluid on rigid impermeable surfaces at moderate stresses is a noticeably poorer lubricant than mineral oil.

The McKee hip tested in the pendulum should have given frictional moments lower than those tested in the simulator, because 1) it had a head 34.9 millimetres in diameter instead of 41.2 millimetres, and 2) it was of the later design in which the components are so finished as to give contact closer to the “polar” region than in the earlier designs in which contact took place over most of the hemispherical surface, including the “equatorial” region. This being so, the results of these tests in the pendulum are taken as corroborating the results obtained in the simulator.

Biological effects of wear particles—Previous work with pure powdered metals in which the particle size was heterogeneous had established that when cobalt of particle size 3·5 to 17 microns (Heath 1956), cadmium of particle size 3·5 to 85 microns (Heath and Daniel 1964a)
and nickel of particle size 0·5 to 117 microns (Heath and Daniel 1964b) were injected into rat muscle in the same manner as the cobalt-chromium-molybdenum alloy debris described above, they were carcinogenic. On the other hand powdered metallic zinc, tungsten (Heath 1956), iron, tantalum, chromium, beryllium, manganese, copper and molybdenum (Heath, unpublished material) were not carcinogenic.

Unpublished experiments by Heath and colleagues had earlier shown that of a 15-milligram sample of pure powdered cobalt metal incubated at 37 degrees Celsius aerobically under sterile conditions in 50 millilitres of horse serum for about thirty days, approximately 7 milligrams would dissolve. In the present experiments the cobalt component of the alloy debris is not so soluble, but nevertheless tissue cells in the presence of deposits of cobalt-chromium-molybdenum alloy debris are subject to the toxic and carcinogenic effects of cobalt in solution. Further, the very small size of the cobalt-chromium-molybdenum alloy particles means that they are readily phagocytosed and the cobalt can then dissolve out of particles actually within the cell. Furthermore, these metal-bearing macrophages can soon be found in abundance in the regional lymph nodes.

It was mentioned above that pure powdered metallic chromium does not produce tumours under the conditions described, although chromates are known to be carcinogenic. Therefore the evidence presented here points to the cobalt component of the cobalt-chromium-molybdenum alloy as the responsible factor in the initiation of the tumours observed. It would nevertheless be unwise to disregard completely the chromium component of the alloy which is presumably liberated when the cobalt-chromium-molybdenum alloy is degraded by the solution of the cobalt component in tissue fluids.

The dose given to each rat was many orders of magnitude greater, in relation to body mass, than any conceivable rate of liberation of particles in patients. The routes by which, and rates at which, such metallic particles are eliminated from the body are not known with precision. These considerations suggest that tumours, if they are to be expected at all in the clinical situation, are unlikely to be induced until after a considerable time, probably tens of years, of continuous wear of the prosthesis.

**Practical relevance of the results**—The results of these tests are relevant to two factors that might limit the useful life of a joint-replacing implant: loosening and the biological effects of wear or corrosion products.

*Loosening*—These tests have shown that stainless steel or either of two titanium alloys against high density polyethylene gives a significantly lower frictional moment than cobalt-chromium-molybdenum against itself. It is tempting to correlate this observation with the higher clinical incidence of loosening found with McKee-Farrar hip replacements than with Charnley hip replacements in the several series summarised by Andersson, Freeman and Swanson (1972). It must, however, be remembered that many other factors are involved in the comparison of such clinical findings. It must also be noted that the precise contribution of the frictional moment in a prosthesis to the stresses at the bone-cement junction is not yet established, and Paul, Radin and Rose (1973) have calculated that the maximum stress at the bone-cement junction associated with the femoral component of a hip prosthesis depends on factors other than the frictional moment. Nevertheless, the greater variability of the friction in all-metal prostheses, its closer dependence on the supply and nature of fluid, and the limited value of synovial fluid as a lubricant for all-metal bearings, all point to metal against polyethylene as the better of the two combinations. (Even if a prosthesis is made to have contact near the "polar" region, as the surfaces wear the area of contact must, in principle, expand towards the "equator" and thereby increase the frictional moment.) While the difference in friction may not be significant in all circumstances, it can only lie in one direction, and it can hardly be maintained that higher friction would in itself be better than low friction.

*Biological effects of wear or corrosion products*—The present results suggest that there may be a risk of carcinogenesis by cobalt-chromium-molybdenum alloy particles in patients, but that
this risk is probably very small and certainly not at present calculable. The probable induction period is longer than the life expectation of many of the patients who are likely to benefit from this type of operation.

Such information as is available about carcinogenesis by polyethylene refers to particles larger than those likely to be produced by wear in prostheses. According to the literature surveyed by Carter and Roe (1969), carcinogenic activity in animals found in large implants of plastics is either lost or greatly reduced if the same amount is implanted as a powder, while in Carter and Roe’s own experiments polyethylene particles up to a few milligrams in mass were carcinogenic in rats.

More must be known about both the biological effects of very small polyethylene particles, and about the rate of production of such particles clinically, before a clear choice can be made on this ground between prostheses in which both components are of cobalt-chromium-molybdenum alloy and those in which one component is polyethylene, but such information as is available and discussed above suggests a tentative preference for the latter.

SUMMARY
1. Currently available total replacement hip and knee prostheses were tested in a machine enabling flexion-extension movements to be applied whilst the prostheses were surrounded with Ringer’s solution or other liquid and loaded within the physiological range.
2. Prostheses of both components were made in cobalt-chromium-molybdenum alloy produced visible quantities of alloy particles, whose sizes ranged down to about 0.1 microns, and cobalt and molybdenum ions in solution.
3. No metallic or plastic particles were detected during tests on a hip prosthesis made of stainless steel and high density polyethylene.
4. The frictional moments in cobalt-chromium-molybdenum hip prostheses were higher than in stainless steel-polyethylene hip prostheses, by a factor of at least 2 to 1.
5. It is accepted that the conditions of these tests were probably more severe than in life, but the difference is held to be one of degree and not one of kind.
6. The particulate alloy debris, when injected in massive doses into the muscles of rats, gave an incidence of malignant tumours which was comparable to that already established for pure cobalt powder, whereas particles of several other metals, tested in the same way, gave no tumours.
7. It is argued that the particles which are known to be produced in at least some patients using cobalt-chromium-molybdenum total replacement joint prostheses constitute a risk of tumour formation which is certainly small, possibly negligible, but not accurately calculable at present.
8. The results of these tests, particularly the differences in frictional moment and in the production of particulate debris, suggest a preference for high density polyethylene as one component of a total joint replacement prosthesis.

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REFERENCES
LABORATORY TESTS ON TOTAL JOINT REPLACEMENT PROSTHESES


