TECHNICAL NOTES

Technical Notes in BPR usually originate when a progress report goes beyond the usual form to present a wealth of detail about some single aspect of the subject under investigation. In other cases, a progress report may simply require a more generous physical format to do justice to its content, in the opinion of the Editor. BPR Technical Notes are carefully studied by the publication's staff, but are not formally refereed by reviewers from BPR's Editorial Board or ad hoc reviewers, as are the papers on the preceding pages.

In Vitro Evaluation of the Effect of Acetabular Prosthesis Implantation on Human Cadaver Pelves

WILLIAM PETTY, M.D
Associate Professor, Department of Orthopaedics
University of Florida College of Medicine
Co-Chief, Orthopaedic Surgery
Veterans Administration Hospital
Gainesville, Florida 32602

GARY J. MILLER, Ph. D.
Assistant Professor, Department of Orthopaedics
University of Florida College of Medicine
Gainesville, Florida 32610

GEORGE PIOTROWSKI, Ph. D.
Associate Professor
Department of Mechanical Engineering
University of Florida College of Engineering
Gainesville, Florida 32610

INTRODUCTION

During the past 15 years, total hip arthroplasty, as developed by Charnley, McKee, Watson-Farrar, and others, has revolutionized treatment of hip disease. The procedure is the most successful one ever developed for the treatment of the arthritic hip, and most patients achieve excellent results. However, a small percentage of patients are not so fortunate and develop a complication severe enough to cause failure of the total hip arthroplasty. Failure may occur due to several causes, and these can basically be broken down into three general groups, including (i) biological failures, the most prominent of which is infection, (ii) technical failure resulting from such problems as poor preparation of the bony beds, poor cementing technique, and poor placement of the prosthetic component, and (iii) mechanical failure of the prostheses, including loosening, migration, and breakage.

Early in the evolution of total hip arthroplasty, great attention was paid to the complications of infection and wear. Infection remains a major problem because of its severe consequences, but its incidence has been reduced by various measures, including improving the operative environment and the use of antibiotics. In some circumstances, wear of the components has been a problem; but, in general that problem has been a minor one, especially in the majority of total hip arthroplasties in which metal and polyethylene components are used.

The most common cause of failure in total hip arthroplasty is loosening. Loosening has received the greatest attention in the femur because of the relatively early recognition of this problem. There has been less concern about loosening of the acetabular component, but as duration of followup becomes longer, it is becoming apparent that failure of fixation on the socket side of total hip arthroplasty may become at least as common as, if not more common than, failure on the femoral side. For example,Müller and co-workers have reported that in 81 patients followed for 10 years or longer, 16 hips (20 percent) required re-operation, most commonly for a loose acetabular component. In Charnley's series, there has been a steady increase in the incidence of acetabular loosening as followup times have become longer. Review of 141 hips with an average followup of 10.1 years revealed that 70 percent had roentgenographic demarcation between the bone cement and bone on the socket side. Thirteen percent of the 70 percent of sockets had actually migrated, and 9 percent of the total groups of patients demonstrated migration of the acetabular component after 10 years. Most of these patients had symptoms.

The only factor that could be correlated with increased likelihood of acetabular failure was that it appeared to be more common in those patients with rheumatoid arthritis. Beckenbaugh and others reported in their series, after 4 to 7 years of followup, that 99 percent of their patients had roentgenographic demarcation between the cement and bone of the acetabulum.

Implantation of the prosthetic acetabulum involves reaming of the bony acetabulum, and socket fixation with bone cement. Several details of socket implantation technique (such as depth of reaming, use of a pilot hole, use of anchoring holes, and methods for reinforcing a weakened bony acetabulum) remain controversial.

The experiments reported here were performed to evaluate quantitatively the effects of these techniques on the stress and strain pattern of human cadaver pelves.

MATERIALS AND METHODS

Twelve pairs of cadaveric hemipelves were acquired by transsection of the sacroiliac joint and the pubic symphysis and cleaned of soft tissue. The mid-portion of the arcuate line of the ilium was degreased with Chlorothene-NU [a] and carefully sanded with 400 grit sandpaper. Three strain gage rosettes (EA-13-062RB-120) [a] were installed, using standard installation techniques, in positions as illustrated in Figure 1. Each of the three gages of a rosette measured strain in a different direction, and these three independent measurements were used to compute the largest tensile, compressive, and shear strains in the bony material at the site of the rosette, using the Mohr's circle transformation technique.

The loading of each hemipelvis was produced by a fixture (Figs. 2 and 3) designed to simulate conditions of single-leg stance phase in gait. The sacroiliac joint of each specimen was encased in a block of aluminum-filled epoxy [b] to

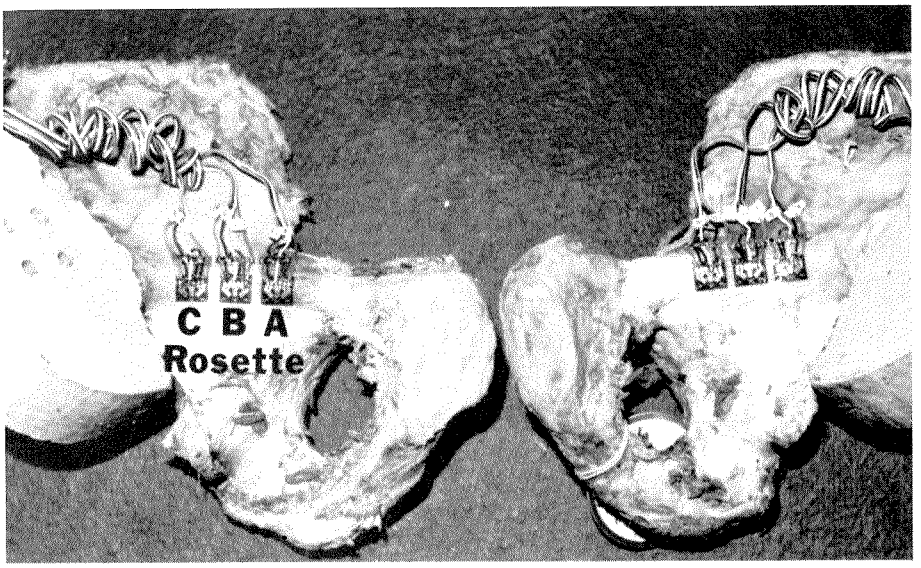

FIGURE 1.
Paired Hemipelves each instrumented with three strain gage rosettes, here labelled A, B, and C. The sacroiliac joints are encased in blocks of aluminum-filled epoxy.

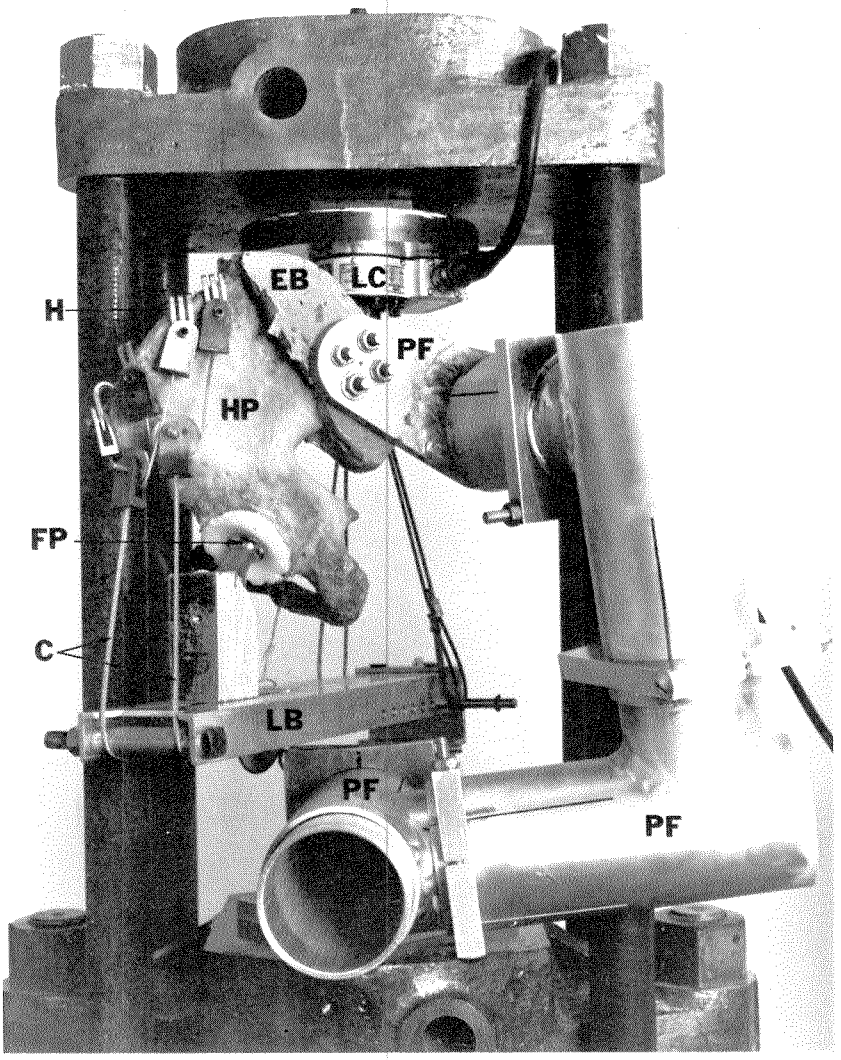

FIGURE 2
Lateral view of hemipelvis (HP) bolted, through the epoxy block (EB), to the positioning fixture (PF). A Charnley femoral head prosthesis (FP) is mounted on the loading bar (LB), along with cables (C) and hooks (H) which simulate the abductor muscle pull. The load cell (LC) monitors the simulated ground reaction, applied to the other end of the loading bar.

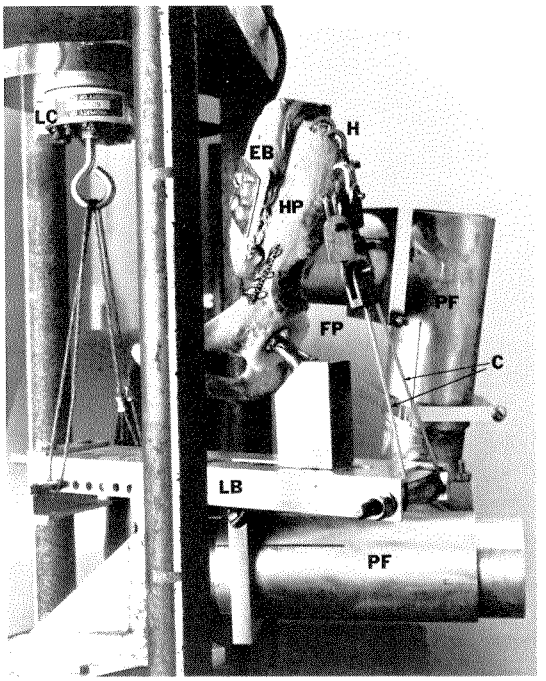

FIGURE 3.
Another view of the hemipelvis mounted in the loading fixture. (See caption of Figure 2 for identification of parts.)

provide a convenient means for attaching the bone to the positioning fixture. This fixture permitted the bone to be oriented in the position it assumes in erect standing, and rigidly held in that position. The loading bar connects to the hemipelvis through a femoral head prosthesis mounted on the loading bar, and by cables attached to the iliac crest by four small hooks. These hooks and cables simulate the pull of the abductor muscles of the hip. The opposite end of the loading bar is connected to a load cell which measures the upward force applied to the loading bar. This force simulates the ground reaction force on the standing leg.

The hemipelvis on the positioning fixture, the load cell, and the loading bar are mounted in a universal testing machine in such a way that the load cell pulls up on the loading bar, thereby producing the joint reaction force and the pull of the musculature simultaneously.

Each hemipelvis was mounted in the positioning fixture and carefully oriented. The positioning fixture was locked in place by tightening its clamps, and the loading bar installed. Two photographs of the test set-up, representing A-P and lateral views, were made and used to determine graphically the ratio between the applied load, as measured by the load cell, and the joint force.

The pubic symphysis was left unloaded by this loading fixture. This was deemed to be a reasonable approximation, since individuals with disrupted symphyses have been known to heal with a gap between the pubes which has not compromised their ability to walk normally.

The instrumentation (Fig.4) was designed to minimize the number of connections to be made in connecting each bone's nine strain gages. Only 10 conductors (one per gage plus power common), rather than 18, are required. Corresponding gages from paired bones are connected as half of a Wheatstone bridge; this insures automatic temperature compensation. The connections between the gage pairs are made within the calibration box which also contains the bridge completion resistors, trimming resistors which allow the output from each gage to be nulled at the start of each test run, and a calibration resistor. The calibration resistor electrically simulates a fixed value of strain to the amplifying and recording equipment; switch S1 can be used to select the sign of the calibration signal, and switch S2 allows the calibration signal to be generated for each gage in turn. The strains produced by each gage, as well as the force measured by the load cell, were recorded simultaneously on an oscillograph.

After each test, the photograph of the test set-up was used to determine graphically the ratio of joint force to applied load. At each of 15 positions along the oscillograph traces, values for the load cell and strain gage readings were read and input to a computer program which performed a linear regression of strain reading versus joint force for each gage reading. A typical graph of gage reading as a function of joint force for three gages from one bone is shown in Figure 5 and illustrates the linear relationship observed. Thus, all data are presented as strain per unit joint force.

The computer program further calculated the principal (maximum tensile and compressive) strains and their orientations for each rosette, as well as the maximum shear strain. These three strain values represent the largest deformations to which the material under the rosette was being subjected.

Two sets of data were obtained for each hemipelvis. The first was obtained with the acetabulum in its natural state (i.e., without an acetabular prosthesis), using a properly fitted Austin Moore prosthesis to apply the joint force. The second data set was obtained using an acetabular prosthesis and one of eight variations in the basic installation technique (Table 1).

[a] Micromeasurements Inc., Romulus, Michigan

[b] Devcon Corp., Danvers, Massachusetts

RESULTS

The "Normal" Pattern

A total of 24 hemipelves were tested with an Austin Moore prosthesis against an acetabulum without implant. The strain data are summarized in Figure 6, which includes the nine strain gage readings, the computed principal (maximum tensile and compressive) strains, and the maximum shear strain. Thus, Figure 6 represents the "normal" pattern of strain found along the arcuate line of the ilium in single leg stance. Each rosette yields a similar pattern of strain: the first and second

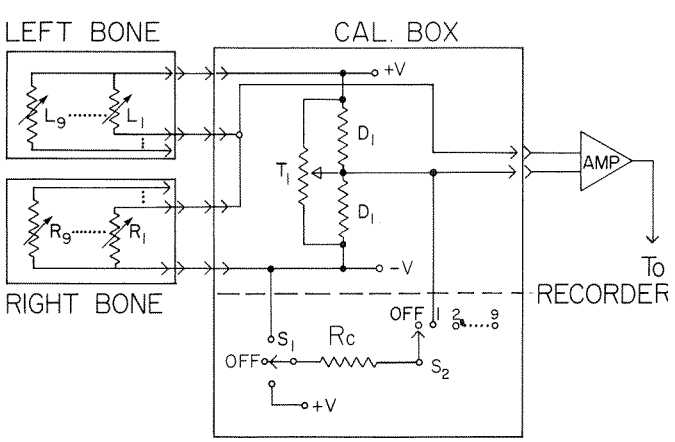

FIGURE 4.
Schematic diagram of the instrumentation used to balance and calibrate the strain gage outputs. The strain gages are represented by $L_1 - L_9$; D_1 and T_1 are bridge completion and trimming resistors, which are replicated for each of the nine strain gage pairs. The polarity of the calibration signal generated by R_c can be selected with switch S_1, while S_2 determines which strain gage is being calibrated.

TABLE 1.

Types of Implantations Performed

Set[a]	Side	Installation Technique
V	L	No center hole, removal of cartilage only
V	R	10 mm center hole, removal of cartilage only
VI	L	20 mm center hole, reamed to pelvic cortex : less than 1 mm of bone at hole edge
VI	R	Same as VI L, but with addition of protrusio ring
X	L	10 mm hole, reamed to 4 mm
X	R	Same as X L, but with three anchoring holes
XI	L	30-mm hole, reamed to pelvic cortex : less than 1 mm of bone at hole edge
XI	R	Same as XI L, but with protrusio ring

[a] Each set contains 3 pelves, with the left and right pelves treated differently.

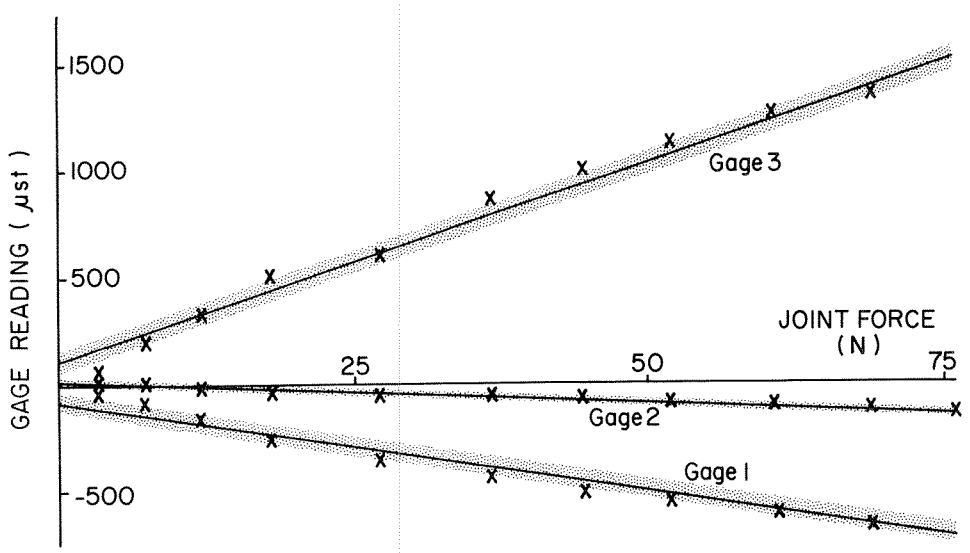

FIGURE 5.
A representative graph of gage readings as a function of joint force. Each line represents the best least-squares fit to the data points shown, with the bands representing ± one standard deviation indicated.

gages of each rosette exhibit moderate compressive strains, while the third gage (situated posteriorly but oriented almost vertically) shows a tensile strain. The two principal strains for each rosette are nearly equal in magnitude but of opposite sign, with the highest strain found at rosette C. The drawing (Fig. 7) illustrates the orientation of the principal strains, as well as their relative magnitudes. The difference between the principal strains equals the maximum shear strain experiencd by the material under a rosette; the "normal" values for maximum shear strain are also shown in Figure 6. Calculations indicate that the average normal strains at these locations are almost zero. This indicates that the bony material in the region is undergoing almost pure shear.

Side-to-side differences for all measured and computed strain variables were calculated, and are summarized on Figure 8. In all cases, the average value of the right-left differences was within two standard errors of zero, indicating no left-right bias in pelves without acetabular cups. It is also interesting to note that the scatter in the left-right differences is relatively uniform for all nine strain gages comprising rosettes A, B and C, as are their principal strains; but the scatter in the maximum shear strains is larger.

Effects of Various Installation Techniques[c]

1. NO CENTRAL HOLE

Three acetabular implants were installed with no central guide and with no bone removal. (i.e., curetting the cartilage only). Only the principal strains and maximum shear strains are presented here, since they are insensitive to gage orientation, while the individual gage readings are not. Figure 10a summarizes the principal and maximum shear strain data obtained for these three specimens along with the strains obtained prior to implantation. Also shown is the "normal" strain pattern for unimplanted pelves, from Figure 6. Figure 10b shows the difference in strain readings obtained before and after installation of the prosthesis (difference = value after — value before). All changes are very small compared to the individual gage readings, indicating that if the bone of the

pelvis is not disturbed while applying an acetabular cup, an essentially unchanged pattern of strain results after implantation of an acetabular prosthesis.

2. EFFECTS OF A CENTRAL HOLE AND REAMING

The effects of the presence of a central hole drilled during the installation of the prosthesis is depicted in Figures 11a and 11b through 14a and 14b. A 10 mm central hole with no accompanying reaming of the acetabulum (Group V R) causes only a slight increase in the tensile strains for rosettes A and B, with a modest increase in the shear strain at rosette A (Figs. 11a and 11b). Rosette C shows little change.

Drilling a 10-mm central hole and reaming the bone to a 4-mm thickness (Group X L) increases the strain experienced by the bone (Fig. 12a and 12b). While the strain data from this group conformed to the "normal" pattern before implantation, all principal strains undergo an approximately equal increase of about ½ μst/N (or ½ microstrain per Newton) in the magnitude of the strain post-implantation; consequently the maximum shear strain increases by roughly twice as much, on the average.

Enlarging the hole to 20 mm and reaming to the pelvic cortex (less than 1 mm of bone at hole edges, Group VI L) yields a similar increase in the tensile principal strains and maximum shear strain. Figures 13a and 13b illustrate that the post-implantation strain pattern clearly shows larger strains, with rosette A located more anteriorly, showing greater increases in maximum tensile strain than the posterior rosette C. The large increases for one of the specimens were not echoed by the other two specimens, especially posteriorly, and thus their significance is questionable. The data suggest a shift in the load distribution within the bone, with the antero-medial material (rosette A) experiencing increased strain.

Curiously, when there was more extensive removal (or loss) of acetabular bone, the above pattern of uniformly increased strain was reversed. This condition was simulated by drilling a 30-mm central hole and reaming the acetabulum to 1 mm of bone remaining at the hole edge (Group XI L). Figures 14a and 14b illustrate that rosette A is relatively unaffected, the effect on rosette B is inconsistent, while rosette C exhibits a decrease in the magnitude of the principal strains as well as the maximum shear strain. As with Group X L 10-mm central hole and reaming to 4-mm thickness (Fig. 12a and 12b), the strain under rosette A increased relative to the strain in rosette C, suggesting an antero-medial shift in the load distribution within the bone. This antero-medial shift was similar to that found in Group VI L (Figs. 13a and 13b).

3. REINFORCEMENT WITH A PROTRUSIO RING

The bones of one set (Group VI R) were first perforated with a 20-mm center hole, similar to the bones represented by Group VI L (Figs. 13a and 13b)—but with the acetabular cup installation reinforced with a protrusio ring. [d] As Figures 15a and 15b show, the maximum tensile strain for all rosettes increased equally from pre-installation values. As in the case without the reinforcement (Group VI L), the strains increase, but the use of the protrusio ring inhibits the anterior shift of strains seen in the previous preparation without reinforcement. The maximum compressive strain remained essentially unchanged for all three rosettes.

Bones of another group of specimens (Group XI R, Figs. 16a and 16b) were drilled with a 30 mm hole and reamed to simulate extensive bone loss (similar to the over-reamed but unreinforced bones represented by Group XI L, Figs. 14a and 14b) but with the additional installation of a protrusio ring for reinforcement. Tensile strains for rosettes A and B increased, concurrent with an increase in the maximum shear strain. Rosette C, on the other hand,experienced decreases in the maximum tensile strain and the maximum shear strain observed. This pattern is quite similar to that shown in the unreinforced case. (The data in both of these cases exhibit much scatter, making them difficult to interpret, however.)

4. EFFECT OF ANCHORING HOLES

In one group of three hemipelves (Group X R) each received three anchoring holes, which are intended to provide greater stability to the fixation of the acetabular prosthesis. As Figures 17a and 17b illustrate, the principal strains and the shear strains all increased in magnitude, with the most consistent effect being a substantial increase in the shear strain at rosette B. The results for this group are quite similar to the results for Group X L (Figs. 12a and 12b) which had similar preparation but without anchoring holes. (In the case of one bone, the shear strain at rosette A nearly doubled; this bone will be sectioned in order to study the spatial relationship between the anchoring holes and the strain gages.)

DISCUSSION

The strain pattern found in hemipelves without an acetabular prosthesis was quite consistent from specimen to specimen. All three rosettes are in almost pure shear, and there is a monotonic increase in strain values from rosette A to rosette C.

This strain pattern appears to remain unaltered by the installation of an acetabular prosthesis—if the acetabulum is not reamed or perforated by a central hole. Thus, the presence of the prosthesis appears to be less significant than the disruption of the bony structures during its installation. A 10-mm central hole has a relatively small effect on the strain pattern, but the increase in tensile and shear strain for rosette A strongly suggests a shift in the load distribution; the bone situated anteriorly (and medially) to the acetabulum is strained more. This shift is much more pronounced for bones with 20-mm central holes and further reaming (in 2 out of 3 cases).

---

[c] Figure 9 describes the key used in Figures 10-17.

[d] DePuy Inc., Warsaw, Indiana

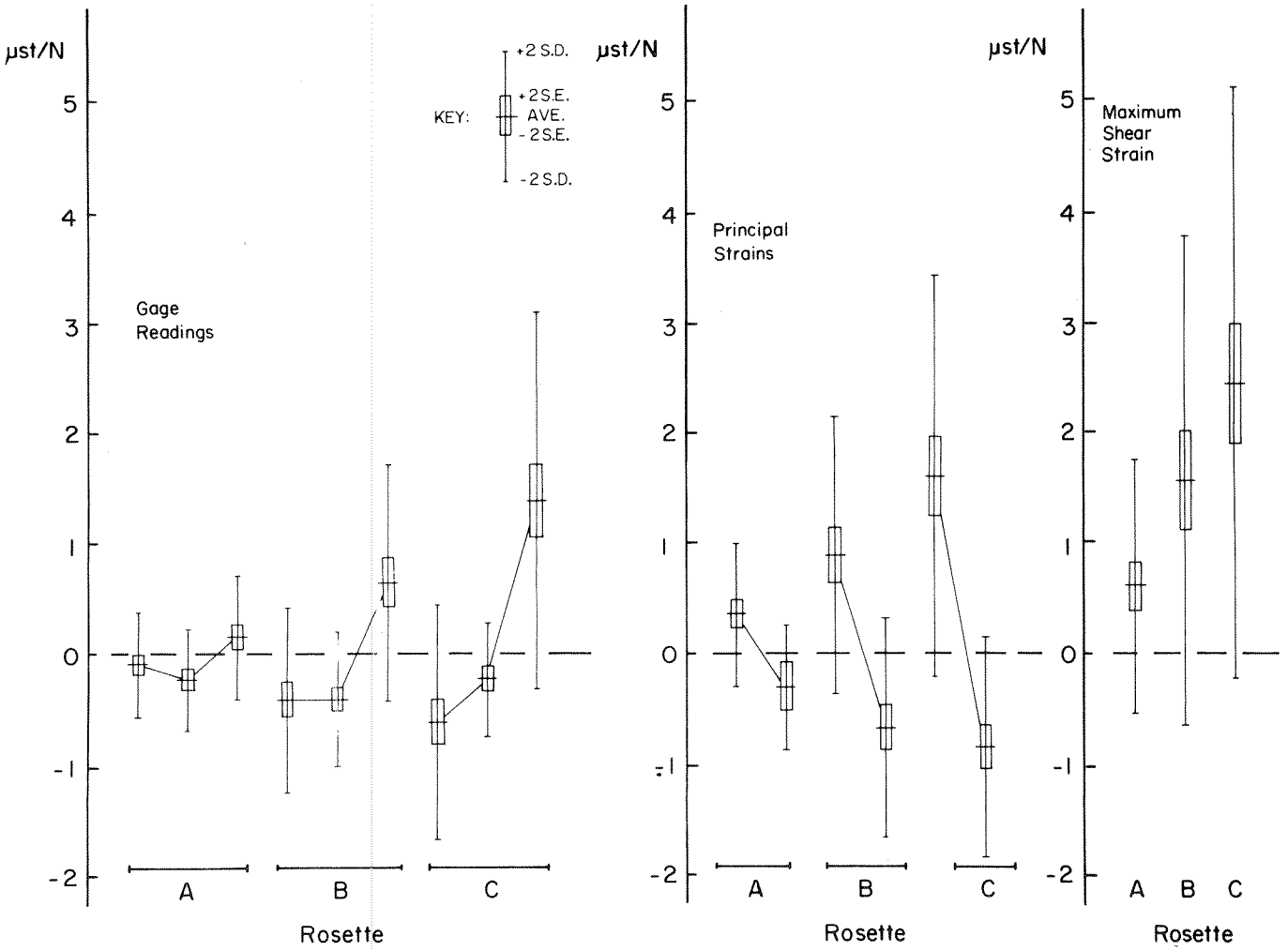

FIGURE 6.
Summary of strain data (strain per unit joint force) obtained from 24 hemipelves loaded through an Austin Moore prosthesis without acetabular implant.

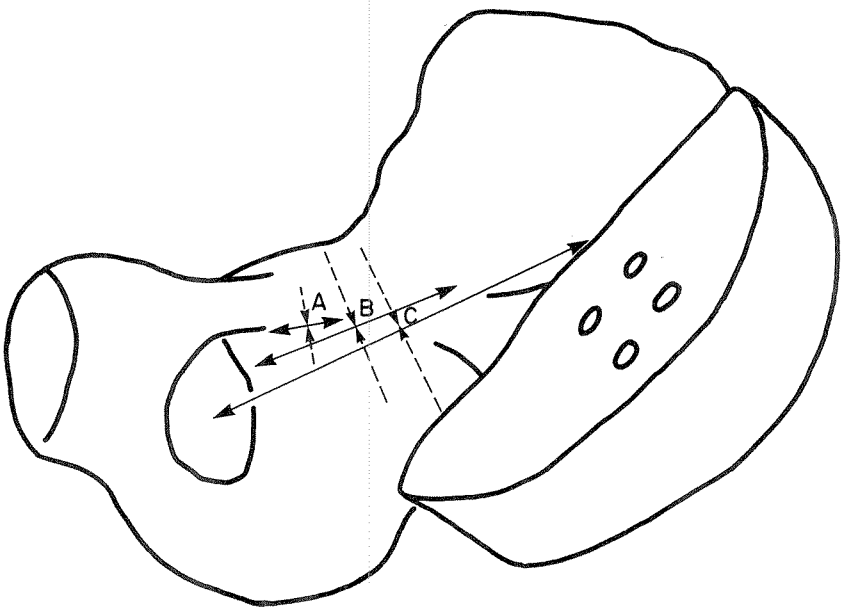

FIGURE 7.
A pictorial representation of the average orientation and magnitude of calculated principal strains for the hemipelves loaded through an Austin Moore prosthesis without acetabular implant. Solid arrows represent tensile strains, while dashed arrows represent compressive strains.

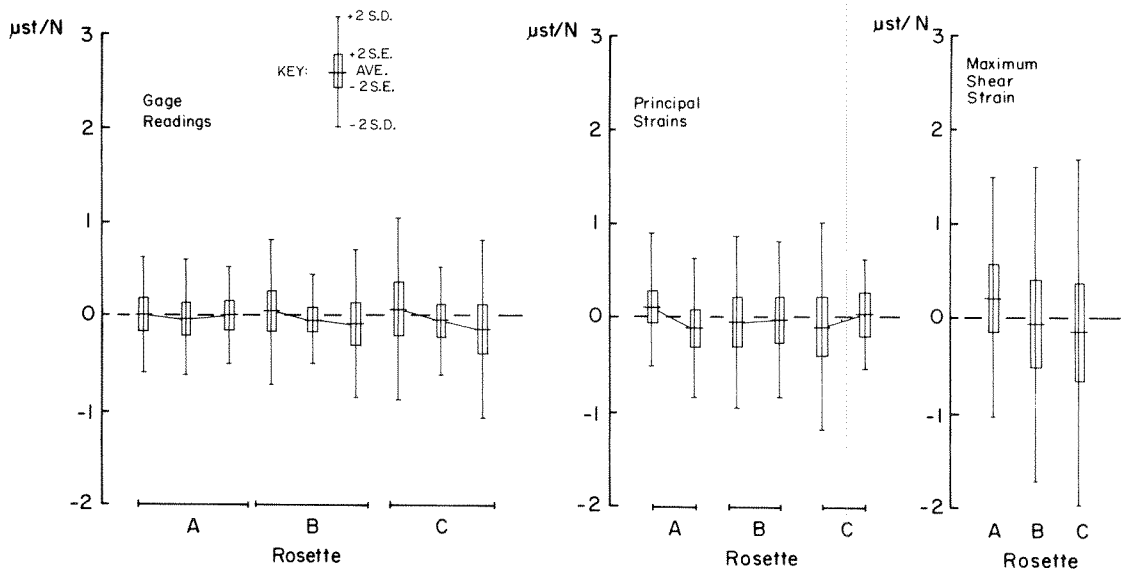

FIGURE 8.
Summary of side-to-side differences in strain data from the 12 pairs of hemipelves of Figure 6.

Further removal of bone by reaming elevates all strain levels more or less uniformly. If almost all cancellous bone is removed, the picture changes. The changes in strain, from pre-implantation to post-implantation, appear to be quite varied and arbitrary. Surprisingly, however, the maximum shear strains appear to have decreased, most dramatically at rosette C. (It should be noted that this set of bones appeared to deviate from the normal patterns of strain considerably, pre-implantation, and any conclusions drawn are very tentative.)

The use of a protrusio ring to reinforce the acetabular implantation after moderate bone removal eliminated the antero-medial shift in the strain pattern. Compressive strains are unaffected, but tensile and shear strains are almost uniformly increased by about ½ µst/N. When extensive bone removal (and/or destruction) has occurred, the protrusio ring does not have the same effect, as shown by the increases in tensile and shear strain antero-medially (rosettes A and B). (The large scatter in the data is probably due to variations in the amount of bone remaining and indicates the need to replicate this group of specimens to gain additional confidence in the data.)

Reinforcing holes do not appear to affect the strain patterns overall, but local effects anteriorly in the vicinity of rosette A were noted. This is undoubtedly related to the proximity of one of the anchoring holes to that rosette.

ACKNOWLEDGEMENT

The authors acknowledge the excellent technical assistance of Mina Robinson and the editorial assistance of Linda Hensdell.

SOURCES AND RELATED READING

1. Anderson, C.B.J.; M.A.R. Freeman; and S.A.V. Swanson: Loosening of the Cemented Acetabular Cup in Total Hip Replacement. J. Bone Joint Surg. 54B:590, 1972.
2. Beckenbaugh, R.D. and D.M. Ilstrup: Looking Back at Total Hip Arthroplasty, A Review of 333 Hips Four to Seven Years after Surgery, with Special Emphasis on Loosening and Wear. Presented at the American Academy of Orthopaedic Surgeons Meeting, Dallas, February 26, 1978.
3. Beckenbaugh, R.D. and D.M. Ilstrup: Total Hip Arthroplasty. A Review of 333 Cases with Long Follow-Up. J. Bone Joint Surg. 60A:306-313, 1978
4. Charnley, J.: The Long-Term Results of Low-Friction Arthroplasty of the Hip Performed as a Primary Intervention. J. Bone Joint Surg. 54B;61-76, 1972.
5. Charnley, J.: Total Hip Replacement by Low-Friction Arthroplasty. Clin. Orthop. 72:7-21, 1970.
6. Charnley, J. and Z. Cupic: The Nine and Ten Year Results of the Low-Friction Arthroplasty of the Hip. Clin. Orthop. 95:9-25, 1973.
7. DeLee, J.G. and J. Charnley: Radiological Demarcation of Cemented Sockets in Total Hip Replacement. Clin. Orthop. 121:20-32, 1976.
8. Eichler, J.: Ein Vorschlag Zur Operativen Behandlung der Protrusio Acetabuli. Arch. orthop. Unfall-Chir. 75:76, 1973.
9. Harris, W.H.: Loosening in The Hip. Proceedings of the Sixth Open Scientific Meeting of The Hip Society, pp. 162-175, 1978.
10. Harris, W.H. and W.N. Jones: The Use of Wire Mesh in Total Hip Replacement. Clin. Orthop. 106:117, 1975
11. McCollum, D.E. and J.A. Nunley: Bone Grafting in Acetabular Protrusio: A Biologic Buttress. In The Hip, Proceedings of the Sixth Open Scientific Meeting of the Hip Society, pp. 124-146, 1978.
12. Müller, M.: New Aspects in Total Hip Replacement. Presented at the Eastern Orthopaedic Association Meeting, Southhamptom, Bermuda, October 14, 1977.
13. Reckling, F.W.; M.A. Asher; and W.L. Dillon: A Longitudinal Study of the Radiolucent Line at the Bone-Cement Interface Following Total Joint Replacement Procedures. J.Bone Joint Surg. 59A:355-358, 1977.
14. Salvati, E.A.; P. Bullough; and P.D. Wilson: Intrapelvic Protrusio of the Acetabular Component Following Total Hip Replacement. Clin. Orthop. 111:212, 1975.
15. Wilson, P.D., Jr.: Frequency of Mechanical Failure of Total Joint Replacement. In Proccedings of the Workshop on Mechanical Failure of Total Joint Replacement, Atlanta, Georgia, May 31, 1978

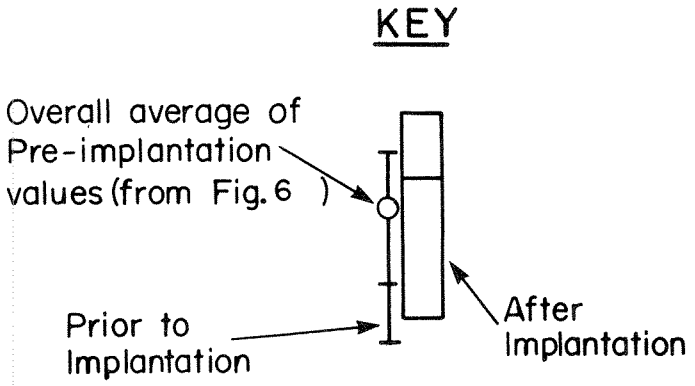

FIGURE 9.
Key for data presented in Figures 10 through 17. The three crossbars on the vertical line represent the three values of strain recorded or computed for each of the three hemipelves in groups tested prior to installation of the acetabular component with the circle indicating the average value for "normal" hemipelves, as shown in Figures 6 and 7. The three crossbars of the rectangle indicate values of strain obtained after component installation.

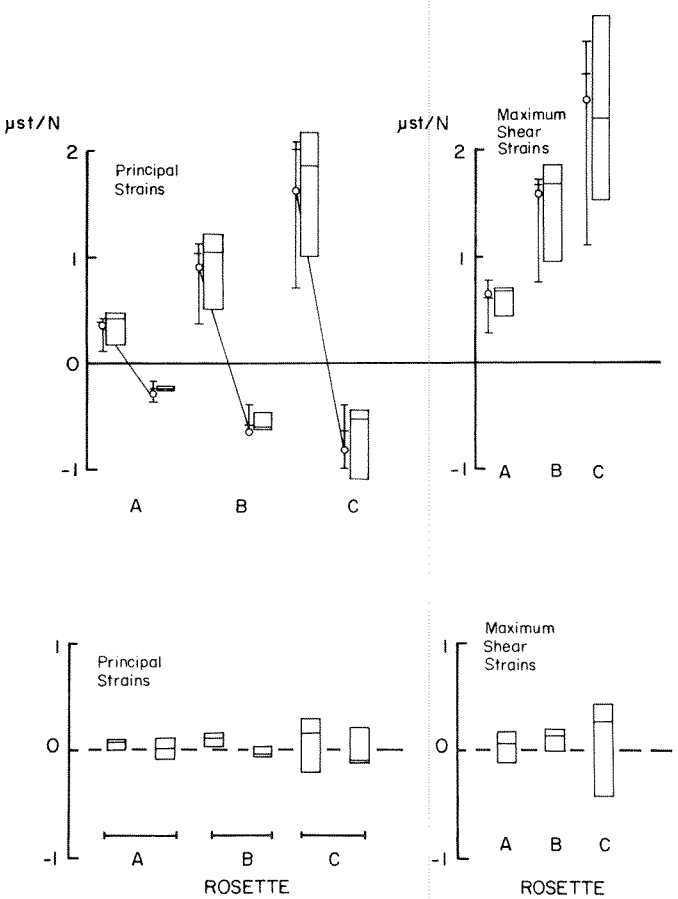

FIGURE 10a (top)
Summary of strain data for hemipelves in set V L (no center hole, removal of cartilage only).

FIGURE 10b (bottom)
Summary of difference in strain readings obtained before and after component installation for hemipelves in set V L.

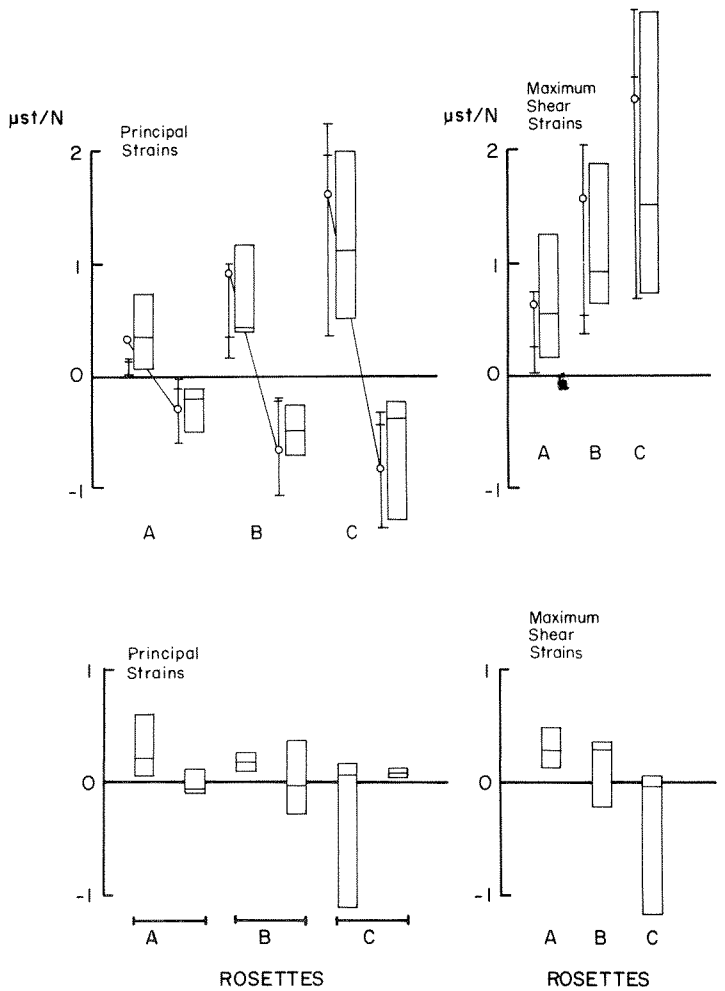

FIGURE 11a (top)
Summary of strain data for hemipelves in set V R (10-mm center hole, and removal of cartilage only).

FIGURE 11b (bottom)
Summary of difference in strain readings obtained before and after component installation for hemipelves in set V R.

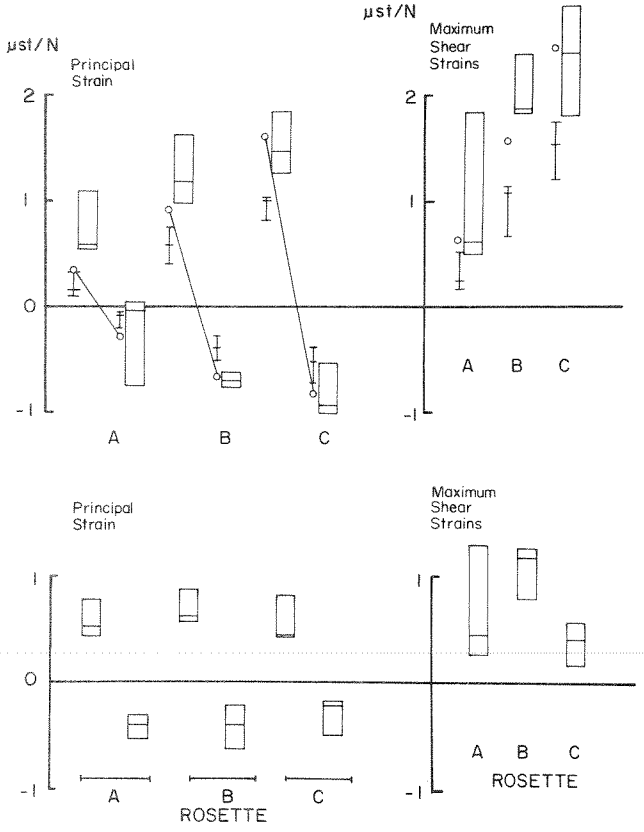

FIGURE 12a (top)
Summary of strain data for hemipelves in set X L (10 mm center hole, reamed to 4 mm).

FIGURE 12b (bottom)
Summary of difference in strain readings obtained before and after component installation for hemipelves in set X L.

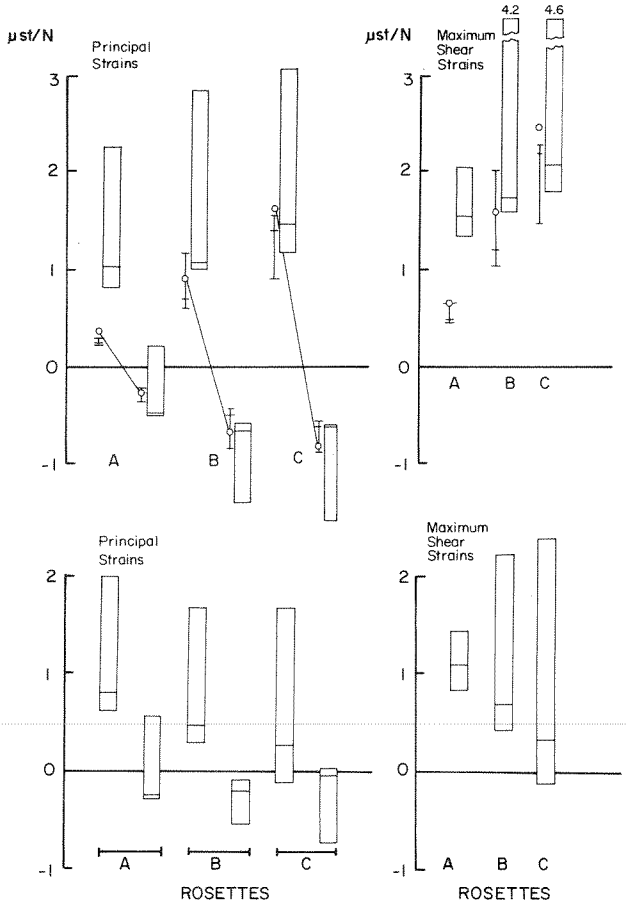

FIGURE 13a (top)
Summary of strain data for hemipelves in set VI L (20 mm center hole, reamed to pelvic cortex — less than 1 mm of bone at hole edge).

FIGURE 13b (bottom)
Summary of difference in strain readings obtained before and after component installation for hemipelves in set VI L.

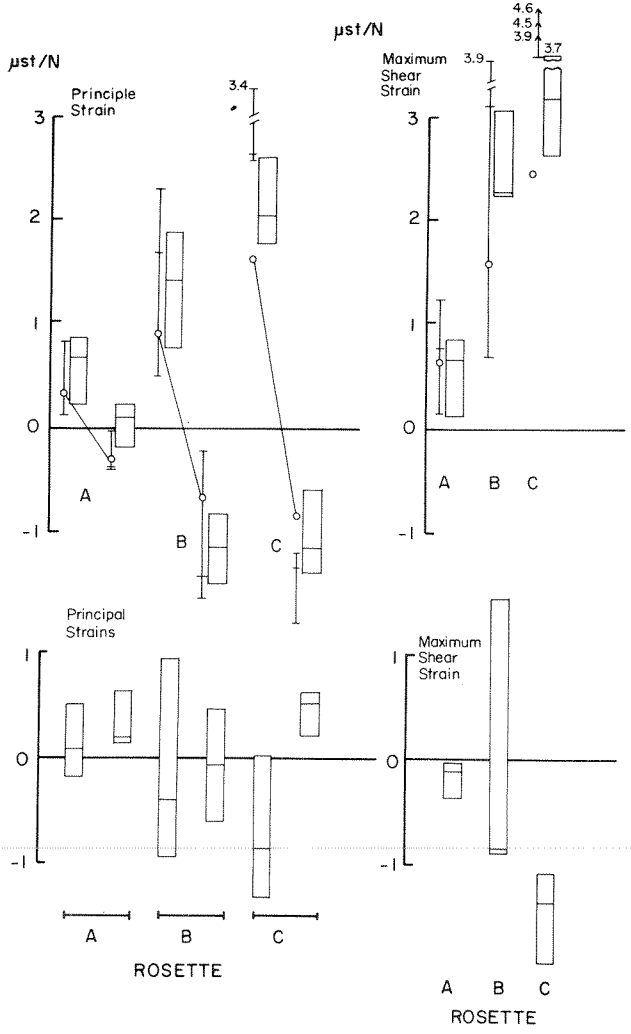

FIGURE 14a (top)
Summary of strain data for hemipelves in set XI L (30 mm center hole, reamed to pelvic cortex — less than 1 mm of bone at hole edge).

FIGURE 14b (bottom)
Summary of difference in strain readings obtained before and after component installation for hemipelves in set XI L.

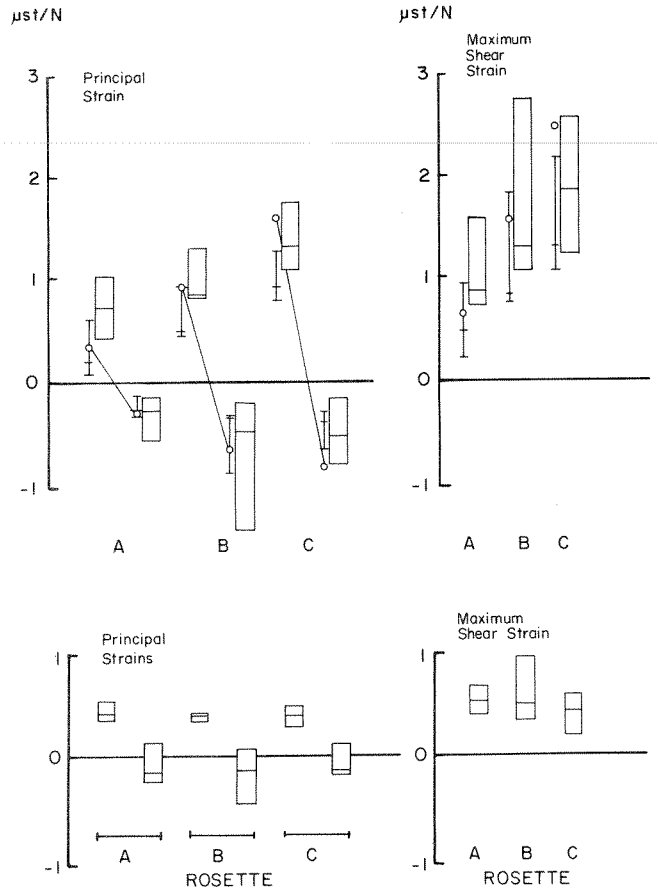

FIGURE 15a (top)
Summary of strain data for hemipelves in set VI R (20 mm center hole, reamed to pelvic cortex — less than 1 mm of bone at hole edge plus protrusio ring).

FIGURE 15b (bottom)
Summary of difference in strain readings obtained before and after component installation for hemipelves in set VI R.

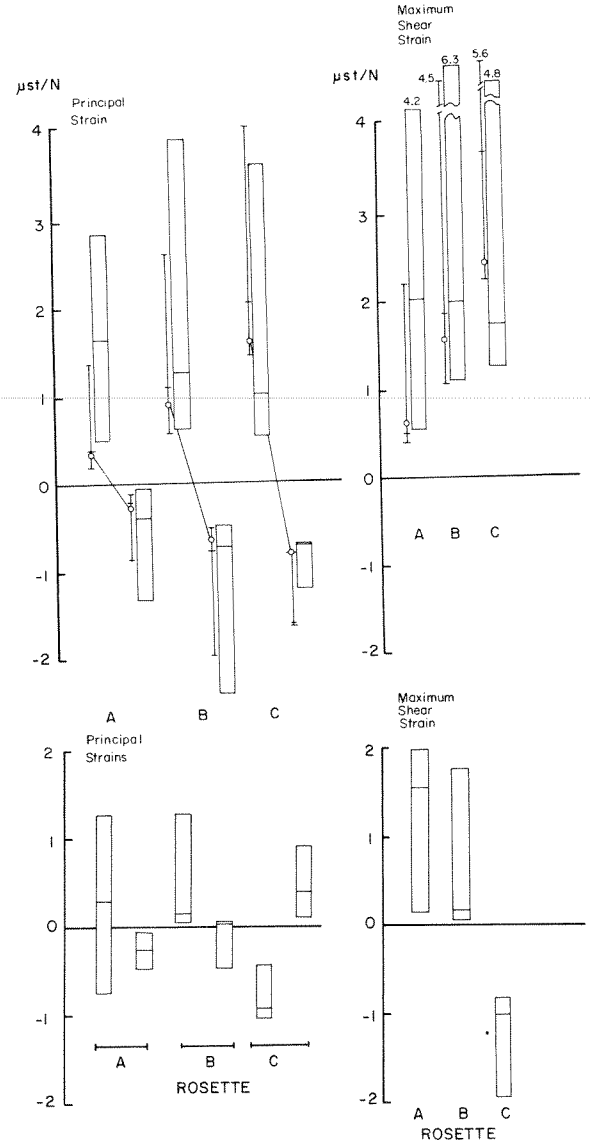

FIGURE 16a (top)
Summary of strain data for hemipelves in set XI R (30 mm center hole, reamed to pelvic cortex — less than 1 mm of bone at hole edge plus protrusio ring).

FIGURE 16b (bottom)
Summary of difference in strain readings obtained before and after component installation for hemipelves in set XI R.

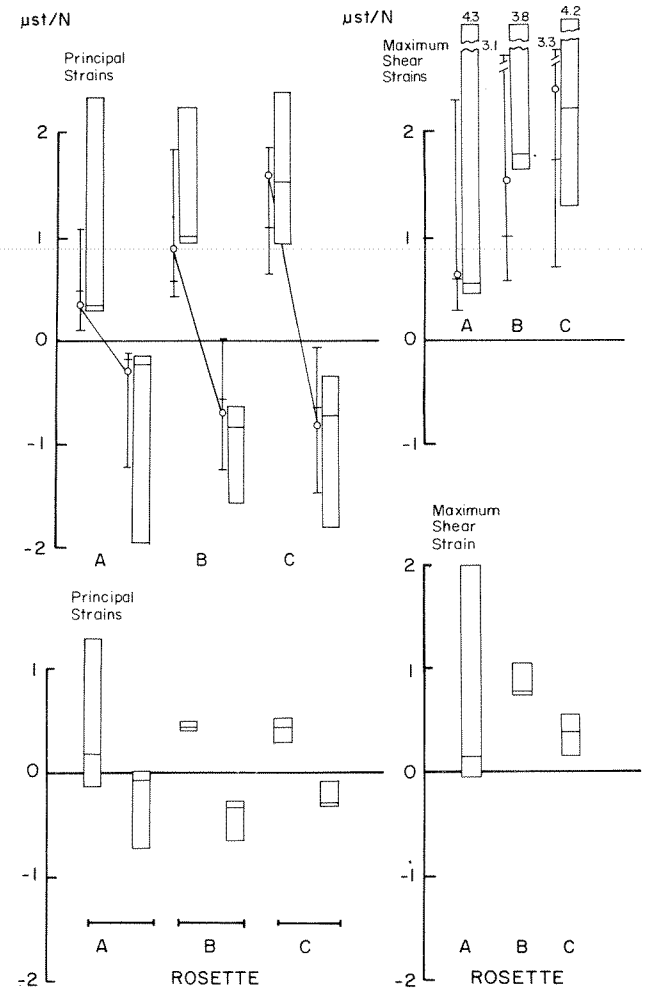

FIGURE 17a (top)
Summary of strain data for hemipelves in set X R (10 mm center hole, reamed to 4 mm but with addition of three anchoring holes).

FIGURE 17b (bottom)
Summary of difference in strain readings obtained before and after component installation for hemipelves in set X R.