

Porosity of Various Preparations of Acrylic Bone Cements

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The total porosity and mean pore sizes of various bone cement preparations were measured using image analysis. The porosity in different commercial bone cements varied from 5% to 16% when these cements were prepared in the usual fashion. Centrifugation for 30 seconds resulted in a substantial reduction in the overall porosity of Simplex P, AKZ, Zimmer Regular, and CMW bone cements by reducing both the mean pore size and the number of pores per unit area. In contrast, the porosity of LVC, Palacos R, and Palacos R with gentamicin bone cements was not significantly decreased by centrifugation. Chilling the monomer before mixing resulted in higher porosity of both the centrifuged and uncentrifuged Simplex P, Zimmer Regular, and CMW bone cements. Simplex P mixed with chilled monomer and centrifuged for 120 seconds has one of the lowest porosities of the various cements, while retaining good handling characteristics and excellent fatigue strength.

Nonseptic prosthetic loosening of cemented total joint replacements in the vast majority of cases can be attributed to disruption of the integrity of the cement mantle or its interfaces.^{14,15} Therefore, identification of the causes of the poor strength of bone cements and attempts to improve the fatigue

life of bone cements are of major importance in cemented arthroplasty.

The porosity present in cured acrylic bone cements is critically important in its poor mechanical properties.^{1,3,4,6-9,12,13} Plexiglas (DuPont, Wilmington, Delaware), the commercial preparation of basically the same acrylic material, exhibits considerably better fatigue strength. However, it is cured industrially under high temperature and pressure and is not porous. In contrast, surgical bone cement mixed in the operating room and cured cold under atmospheric pressure contains numerous voids, both large and small.^{3,5,8,12} The large voids may result from air entrapment during mixing³ and the small voids from evaporation of the volatile monomer during the curing process.¹⁶ These voids act as stress risers^{3,4,8,9} and make the cement susceptible to early fatigue failure. The desirability of decreasing the porosity in surgical bone cement has been emphasized repeatedly in the literature since Charnley first used acrylic cement in this fashion.⁵

Efforts to improve bone cement by attempting to improve the polymer have been unsuccessful.^{1,2,10,11,12,16} Bayne *et al.*¹ urged that efforts to improve bone cement be directed at eliminating porosity rather than attempting to attain higher degrees of polymerization. Lee *et al.*¹³ correlated the rapidity of cement mixing with porosity and recommended slower stirring rates. Centrifugation has recently been shown to improve the fatigue strength of Simplex P bone cement

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Supported in part by the William H. Harris Foundation, Massachusetts General Hospital, Boston, Massachusetts.

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Received: May 2, 1989.

markedly by reducing its porosity.³ Centrifugation of Simplex P for only 30 seconds after mixing increased the fatigue life by 136%. However, the amount of porosity that is present in various commercial bone cements and the effects of the various preparation techniques, such as different centrifugation times and chilling the monomer, on the porosity of the various bone cements are not known.

Therefore, the porosity and pore size distributions of various commercial bone cements that were prepared in the usual fashion were studied using high-speed computer-assisted image analysis. The effects of centrifugation after mixing and chilling the monomer before mixing were also systematically evaluated.

MATERIALS AND METHODS

Simplex P (Howmedica, Rutherford, New Jersey), AKZ (Howmedica), LVC (Zimmer, Warsaw, Indiana), Zimmer Regular (Zimmer), Palacos R (Merck, Hawthorn, New York), Palacos R with gentamicin (Merck), and CMW (CMW, Exeter, England) bone cements were investigated. The powder and liquid constituents were supplied by the manufacturers. Four different batches of cements were investigated for each preparation.

For each cement, a set of control specimens (the first set from four batches of cement) was mixed as recommended by the manufacturers at 21°, 50% humidity, and a 2-Hz mixing rate. After mixing, the cement was poured into cement syringes and allowed to cure.

A second set of specimens was similarly prepared with the liquid monomer chilled to 0° before mixing. This technique was studied because it is used clinically as a method of prolonging the period of low viscosity or reducing the viscosity, thereby improving intrusion of bone cement.

To assess the effect of centrifugation on porosity reduction, the various cements were mixed at 50% humidity and a 2-Hz mixing rate, with the monomer at 21° (second set). Immediately after mixing to a liquid state, they were poured into the syringes and spun in an IEC Model C1 centrifuge (Damon/IEC Division, Needham, Massachusetts) at 4000 rpm. To evaluate the effect of the duration of centrifugation on porosity, the third set of such specimens was spun for only 30 seconds, and the fourth set of such specimens was spun for two minutes. The specimens were removed from the centrifuge and, without further manipulation, allowed to cure in the syringes.

To evaluate the effect of both chilling and centrifugation on porosity, two additional sets of specimens were prepared by mixing with chilled monomer and centrifuging for 30 seconds (fifth set) and for two minutes (sixth set).

The cured cylindrical specimens were removed from the syringes and serially sectioned from top to bottom into discs 5 mm thick using a water-cooled diamond saw. Each face of each disc was ground flat on a Buehler grinding wheel (Lake Bluff, Illinois) with 600-grit silicon carbide paper and polished with 0.03- μ m alumina powder to a mirror finish. Residual grinding debris was removed by an ultrasound cleanser. The discs were then spray painted with a flat black paint to stain the pores. After drying, the paint was wiped off the polished surface, which left the pores stained black to contrast them from the surrounding white cement.

Porosity measurements were determined using a high-speed image analysis system consisting of a high-resolution television camera, analog-to-digital and digital-to-analog converters, a frame buffer with an internal memory of 400 kilobytes, and a Vax 11/750 minicomputer (Digital Equipment, Maynard, Massachusetts). The television camera was attached to a dissecting microscope, and the images were digitized at 30 Hz to 712 \times 512 pixel frames with eight bits of gray resolution. Digital images were accessed and processed by the computer, which determined the fractional porosity and the pore sizes based on the differences in the gray levels between the black-stained pores and the white cement.

Two-dimensional measurements of the pore area fraction were used to derive the three-dimensional volume porosity, since in isometric specimens the area fraction equals the volume fraction. The pore size measurements, however, represent only two-dimensional measurements and were not converted to three-dimensional quantities in this study.

RESULTS

The porosity values of the control bone cement preparations are shown in Figure 1. The mean (\pm standard deviation) porosity of control specimens prepared with the monomer at 21° measured 9.39% \pm 1.53% for Simplex P, 9.49% \pm 2.36% for AKZ, 9.7% \pm 1.83% for Palacos R, and 9.83% \pm 2.31% for Palacos R with gentamicin. None of these values was significantly different. The LVC control specimens, however, had a porosity of 5.06% \pm 0.52% when mixed with the

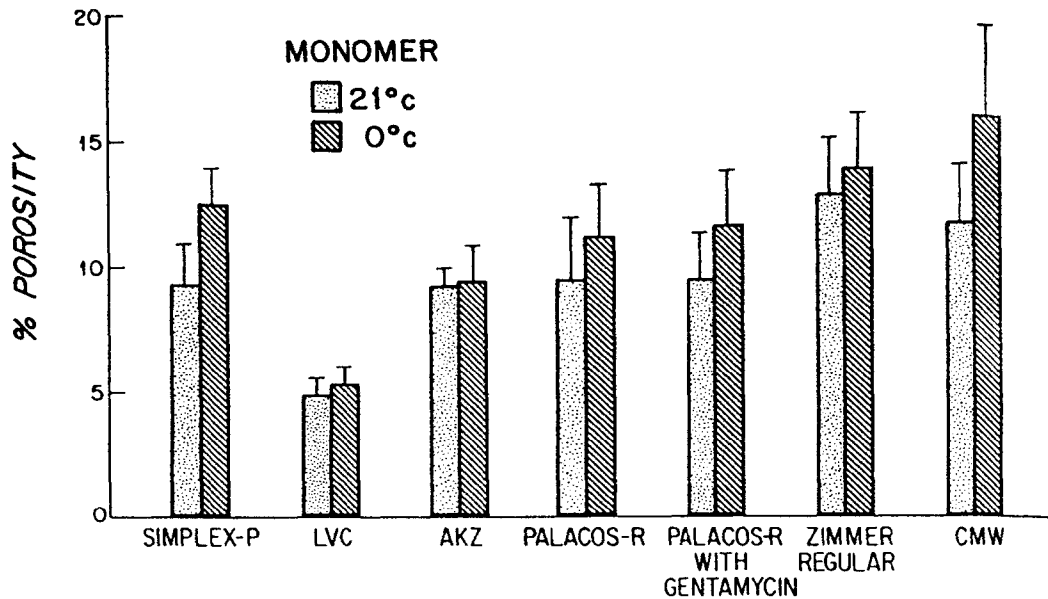


FIG. 1. Porosity of commercial bone cements mixed with chilled and room-temperature monomer.

monomer at room temperature, which was significantly lower than all of the other control specimens prepared in an identical manner ($p < 0.005$). The Zimmer Regular and CMW control specimens mixed with the monomer at 21° exhibited porosities of $12.38\% \pm 2.51\%$ and $11.99\% \pm 2.18\%$, respectively. These values were significantly higher than the Simplex control specimens prepared in identical fashion ($p < 0.005$).

The Simplex P and CMW control specimens prepared with the monomer chilled to 0° exhibited significantly higher porosities than the corresponding Simplex P and CMW control specimens prepared with the monomer at room temperature ($p < 0.0005$). In contrast, the porosities of AKZ and Zimmer Regular control specimens prepared with chilled monomer were not significantly different from the corresponding control specimens prepared with the monomer at room temperature. The Palacos R and Palacos R with gentamicin specimens prepared with chilled monomer exhibited slight but insignificant increases in porosities compared with the corresponding control specimens pre-

pared with the monomer at room temperature. The LVC control specimens prepared with chilled monomer showed slightly higher porosity compared with the LVC control specimens prepared with the monomer at room temperature ($p < 0.01$).

The effect of centrifugation on the porosity of different cements mixed with the monomer at 21° and at 0° is shown in Figures 2 and 3. Centrifugation of Simplex P bone cement mixed with the monomer at room temperature (21°) for 30 seconds substantially reduced its porosity to $4.25\% \pm 1.21\%$ (Fig. 2). Centrifuging Simplex P for two minutes lowered the porosity further to $2.89\% \pm 0.61\%$. The porosity values obtained with centrifugation of Simplex P for 30 seconds and for two minutes were significantly lower than uncentrifuged Simplex P control specimens ($p < 0.0005$). Centrifugation of Simplex P for two minutes resulted in significantly lower porosity than centrifugation for 30 seconds ($p < 0.005$).

When Simplex P was prepared using chilled monomer, centrifugation for 30 seconds and for two minutes also resulted in a

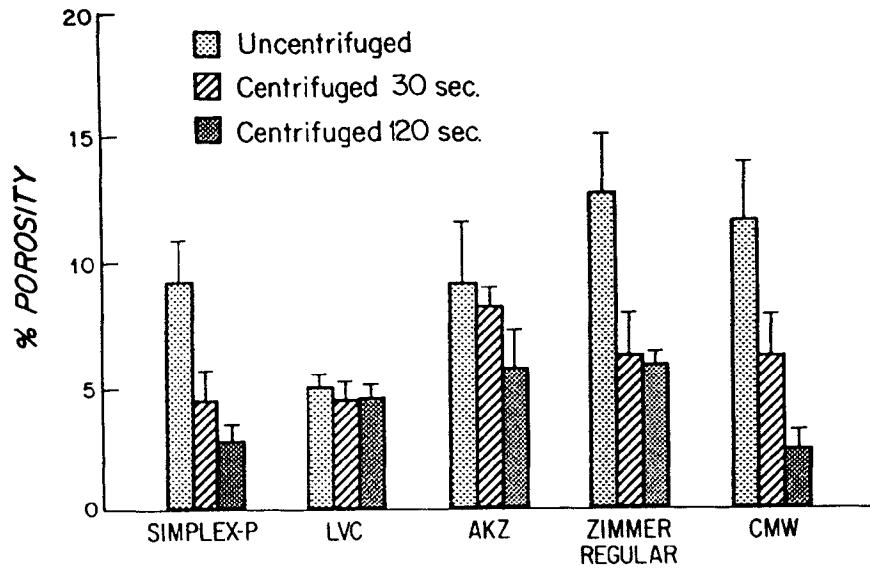


FIG. 2. Effect of centrifugation on porosity with the monomer at 21°.

significant decrease in its porosity compared with the uncentrifuged specimens prepared with chilled monomer. Both of these values were significantly different from the corresponding control specimens as well as from each other ($p < 0.0005$ and $p < 0.005$, respectively). However, the porosities of specimens

prepared with chilled monomer and centrifuged for 30 seconds or two minutes were significantly higher than the corresponding specimens prepared with the monomer at room temperature and centrifuged for 30 seconds ($p < 0.0005$) or two minutes ($p < 0.001$).

When AKZ bone cement was mixed with

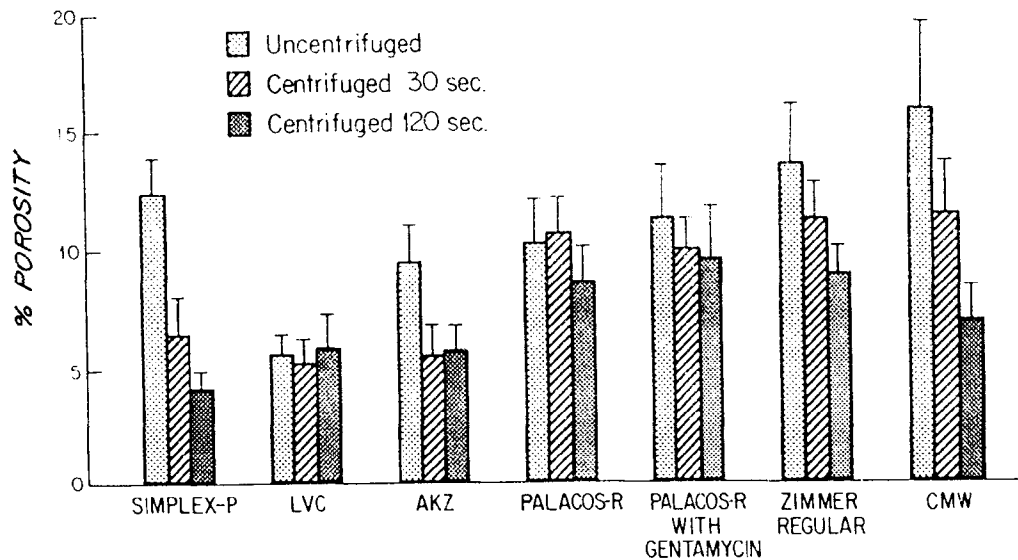


FIG. 3. Effect of centrifugation on porosity with the monomer at 0°.

chilled monomer, centrifugation for 30 seconds resulted in significant porosity reduction ($p < 0.005$) but not when it was mixed with the monomer at 21°. Centrifugation of AKZ for two minutes after mixing with either chilled or unchilled monomer produced a significant further porosity reduction. The reduction in porosity between the 30-second centrifuged unchilled monomer specimens and the two-minute centrifuged unchilled specimens was significant ($p < 0.0005$). Thus, centrifugation for 30 seconds significantly reduced the porosity of AKZ only when this cement was mixed with chilled monomer, but centrifugation for two minutes significantly reduced the porosity of both the chilled and unchilled monomer specimens.

Centrifugation of Palacos R and Palacos R with gentamicin bone cements for either 30 seconds or two minutes did not significantly decrease the porosities in these cements when they were prepared with chilled monomer. Centrifugation after mixing with the monomer at 21° proved difficult for the Palacos R and Palacos R with gentamicin cements because of their high viscosity. Therefore, the effect of centrifugation was not studied for these preparations.

The LVC bone cement, which had the least porosity when prepared in the usual recommended fashion, also failed to obtain significant porosity reduction with centrifugation either for 30 seconds or for two minutes. This was true whether the monomer preparation was 0° or 21°. Centrifugation of LVC, therefore, did not result in significant reduction in its porosity.

Centrifugation of Zimmer Regular bone cement for 30 seconds after mixing with the monomer at either 21° or 0° significantly reduced its porosity. However, the porosity of Zimmer Regular specimens mixed with chilled monomer and centrifuged for 30 seconds was significantly higher than the porosity of the specimens mixed with the monomer at 21° and centrifuged for 30 seconds. Centrifugation of Zimmer Regular bone cement for two minutes resulted in a significant

further decrease in its porosity when mixed with the monomer at 21° ($p < 0.05$). The specimens that were centrifuged for two minutes after mixing with chilled monomer obtained significantly lower porosity than those centrifuged for 30 seconds after mixing with chilled monomer but not those centrifuged for two minutes after mixing with unchilled monomer. Thus centrifugation was very effective in reducing the porosity of Zimmer Regular bone cement. A greater reduction in porosity was obtained when this cement was mixed with the monomer at 21° and centrifuged.

Centrifugation had similar effects on CMW and Zimmer Regular bone cements. Centrifugation for 30 seconds and two minutes resulted in significant decreases in porosity of CMW mixed with either chilled or unchilled monomer ($p < 0.005$), but a greater reduction in porosity was obtained by centrifuging this cement after mixing with the monomer at 21°.

The pore size distributions for the various specimens showed that centrifugation of Simplex P mixed with the monomer at 21° decreased both the mean pore size and the number of pores per unit area (Table 1). Centrifugation eliminated the large voids in all of the other cements, but in contrast to Simplex P, an increase in the number of small voids was observed in the other cements. This combination of reduction in the number of large voids and an increase in the total number of voids resulted in reduction of the overall porosity of AKZ, Zimmer Regular, and CMW specimens but did not result in reduction of the overall porosity of LVC, Palacos R, and Palacos R with gentamicin.

Mixing the cements with chilled monomer resulted in an increase in the number of pores per unit area. Centrifugation after mixing with chilled monomer was effective in reducing the porosity of Simplex P by decreasing the mean pore size but not the number of pores per unit area. Thus, chilling the monomer before mixing seemed to have the adverse effect of increasing the number of

TABLE 1. Pore Sizes of the Various Cement Preparations

<i>Monomer Temp.</i>	<i>Centrifuge Time (seconds)</i>	<i>Mean Pore Size (mm)</i>	<i>Voids per cm</i>	<i>Maximum Pore Size (mm)</i>
Simplex P				
21	0	0.48	93	3.32
0	0	0.44	165	3.20
21	30	0.36	62	1.68
0	30	0.36	198	1.48
21	120	0.20	63	1.56
0	120	0.28	197	0.88
AKZ				
21	0	0.44	151	4.48
0	0	0.36	190	2.88
21	30	0.28	254	2.16
0	30	0.24	267	1.52
21	120	0.24	257	1.48
0	120	0.24	253	1.56
LVC				
21	0	0.28	92	1.28
0	0	0.28	107	1.72
21	30	0.20	188	1.22
0	30	0.16	317	0.60
21	120	0.16	184	0.68
0	120	0.16	288	0.60
Palacos R				
21	0	0.32	164	6.56
0	30	0.40	232	1.52
0	120	0.40	188	1.72
Palacos R With Gentamicin				
21	0	0.32	223	5.69
0	30	0.40	250	1.76
0	120	0.40	213	1.52
Zimmer				
21	0	0.36	211	6.32
0	0	0.36	190	6.88
21	30	0.20	257	0.68
0	30	0.28	325	1.12
21	120	0.16	359	0.72
0	120	0.24	278	0.96
CMW				
21	0	0.34	202	5.98
0	0	0.38	218	6.49
21	30	0.26	272	1.96
0	30	0.28	316	2.32
21	120	0.14	220	0.91
0	120	0.22	215	0.86

voids. Centrifugation after mixing with chilled monomer was effective in reducing the overall porosity of some of the cements but not necessarily the number of pores.

DISCUSSION

Charnley's application of polymethylmethacrylate (PMMA) bone cement to artificial joint fixation in 1959 was a milestone achievement in the development of joint surgery. Almost 30 years later, despite its recognized shortcomings as a structural material, PMMA remains the standard material for anchoring total joint implants to the skeleton.

Computer-assisted image analysis was used in this study to measure the porosity of different commercial bone cements, prepared according to the manufacturers' recommendations, with chilled monomer and with centrifugation after mixing. When mixed according to the manufacturers' specifications, different commercial preparations of bone cement exhibited significantly different porosities. While Simplex P, AKZ, Palacos R, and Palacos R with gentamicin control specimens obtained similar porosity values, LVC control specimens exhibited significantly lower porosity, and Zimmer Regular and CMW bone cement control specimens exhibited significantly higher porosity. The porosity in some of the bone cements approached 10%–16% of the volume and therefore could be substantially deleterious to the bone cement.

Centrifugation after mixing resulted in a marked decrease in the porosity of several bone cement preparations. Centrifugation of Simplex P bone cement for 30 seconds after mixing reduced its mean porosity by about one-half by eliminating all of the large voids and many of the smaller voids. The mean porosity was further reduced by a factor of two when this cement was centrifuged for two minutes. However, after centrifugation of two minutes, the Simplex P mixed with room-temperature monomer was too viscous

to be practical for clinical use. Similar substantial reductions in porosity were obtained from centrifuging AKZ, Zimmer Regular, and CMW bone cements, but porosity values in these specimens remained higher than that obtained by centrifuging Simplex P.

In contrast, centrifugation of Palacos R and Palacos R with gentamicin for either 30 seconds or two minutes produced no significant reductions in their porosities. Similarly, porosity of LVC bone cement, which exhibited the lowest initial porosity of the control specimens, was not significantly reduced by centrifugation. The failure to obtain significant porosity reduction in either of the Palacos bone cements may be accounted for partly by the viscosity of these cement preparations. Palacos R and Palacos R with gentamicin had the thickest consistency during mixing, and they may not have been markedly affected by centrifugation. However, the porosity of LVC bone cement, which had the lowest viscosity of the cements tested, was also not reduced by centrifugation, the reasons for which are not entirely clear. Part of the explanation may lie in the fact that LVC prepared in the usual fashion contained only the smaller voids and had a low initial porosity, which represented these smaller voids. Although a small reduction in the mean pore size was obtained with centrifugation of this cement, the number of small voids per unit area was increased, which resulted in an insignificant reduction of the total porosity.

Chilling the monomer to 0° before mixing, often advocated as a means of reducing the viscosity or of prolonging the lower viscosity state of bone cements, resulted in a higher porosity for most of the cements mixed in the usual fashion. Cements prepared by chilling the monomer followed by centrifugation also had greater porosity than the corresponding specimens prepared by centrifuging after mixing with the monomer at room temperature. The mean pore size and the number of pores per unit area were increased by mixing the cement with chilled monomer. Thus the practice of chilling the monomer before mix-

ing to obtain lower viscosity and better intrusion properties may be detrimental to bone cements. When cements are mixed in this fashion, centrifugation is strongly recommended to offset the adverse effect of chilling the monomer on the porosity.

The fatigue strengths of the various cement preparations were not measured in this study. While porosity is clearly related inversely to fatigue life, within a given cement type, comparison of these porosity data to the fatigue strengths of cements reported previously⁷ shows that variables other than porosity may also affect the strengths of different commercial preparations of bone cements. Although LVC bone cement in this study had the lowest porosity, Davies *et al.*⁷ have shown that LVC bone cement had a substantially lower fatigue life than Simplex P when mixed in the usual fashion. Variables such as powder size, molecular weight, and addition of copolymers and radiopaque materials may also be important in determining the fatigue behavior of cements. More extensive fatigue testing and comparison with the porosity data may elucidate some of these differences.

Within each of the cement formulations, however, the changes in porosity obtained by the different preparation techniques correlated with previously reported fatigue strengths.^{6,7} The reduction in porosity afforded by the centrifugation of Simplex P and Zimmer Regular bone cements is most likely the cause of increased fatigue strengths of Simplex P reported previously with centrifugation. More extensive fatigue tests of the various cement preparations that obtained the lowest porosity may show the optimum formulations and preparation techniques.

Simplex P bone cement mixed with chilled monomer and centrifuged for 120 seconds had one of the lowest porosities of the various cement preparations tested in this study while retaining good handling characteristics suitable for its use in surgery. Simplex P mixed with the monomer at room temperature and centrifuged for 120 seconds had even lower porosity but was too viscous to be

of practical use at surgery. Unlike many of the other cements, Simplex P also has one of the highest fatigue strengths, and it is this preparation that is probably ideal for use in total arthroplasty.

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