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AN EXPERIMENTAL STUDY IN BIO-BALLISTICS

FEMORAL FRACTURES PRODUCED BY PROJECTILES*

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Abstract—Very few quantitative data are available on the response of human bones to projectile impacts. Steel spheres of various diameters were projected at embalmed human femurs. Electronic monitoring and high-speed photography were used to determine the amount of energy lost by the projectiles in fracturing the femurs. The extent of damage produced by the projectiles was studied quantitatively, and the effects of projectiles of different diameters were determined.

VERY FEW experimental studies on the effects of projectile impacts on biological tissues, especially bone, have appeared in the literature. The research on the response of bone to projectile impacts has consisted almost entirely of descriptions of gunshot wounds, Horsley (1894); LaGarde (1895); and Keith and Hall (1919), with very little experimental work having been reported wherein human bones were used, Huelke and Darling (1964); and Huelke, Buege and Harger (1967). Some quantitative investigations on the energy expended in penetrating and fracturing bones have been conducted, Grundfest (1945), but the test specimens were cow bones, which have physical properties markedly different from those of human bone, Evans (1957).

Recently, a quantitative study on the effects of projectile impacts on human bones were presented, Huelke, Buege and Harger (1967). This paper reported the effects of impacts at varying velocities by steel spheres of constant mass and diameter. Very little is presently known, however, about the effects of a change in projectile diameter on the response of bone to impact, or the effects of change in the projectile's mass on the bone's response to impact. The purpose of this paper is to report the effects of projectiles of varied diameter and mass in impacts to human bones.

MATERIALS AND METHODS

To avoid the problems of pitch, yaw, and deformation of the projectile, steel spheres were used in this study. The spheres were fired from a smooth-bore, helium-operated gun modified and built in our laboratory from a basic design provided by government ballisticians, Stewart (1956). Spheres as large as 0·500 in. in dia. can be shot by interchanging the 48 in. gun barrels. In the present study, spheres of 0·250 in. dia. (16·1 gr) and 0·406 in. dia. (69·1 gr) were used.

The gun was loaded by inserting the sphere into the barrel to a predetermined depth using a ramrod graduated in inches. Once loaded, the gun was fired by remotely opening a valve of our own design that allows helium, under pressures of 10 to 2200 psi, to enter the breech and propel the sphere. The velocity of the sphere is, therefore, controlled by both the depth of loading into the barrel and the regulated pressure of the helium in the breech. Muzzle velocities of 200 to 2200 ft/sec were used in the present study. When the depth of loading and helium pressure were held con-

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stant, the gun produced a very consistent muzzle velocity varying no more than 2 per cent.

Human femurs were used throughout this study. A total of 395 embalmed femurs were used, 222 bones in tests with 0·250 in. spheres and 173 in the series with 0·406 in. spheres. In addition, 50 fresh unembalmed femurs were impacted with 0·250 in. spheres. The femur was mounted 6 ft from the muzzle of the gun. The target area was the posterior surface of the femur in the popliteal fossa between and slightly proximal to the femoral condyles. In this region the femur consists mainly of cancellous bone enclosed by a thin shell of cortical bone.

The impact (entrance) velocity of the projectile was determined by measuring the time required for the sphere to pass through two electronic grids spaced on a very precise twelve-inch baseline. When the projectile passed through the first grid, it triggered a counter chronograph (Electronic Counters, Inc., Model 464T). As it pierced the second grid, the counter stopped, displaying the sphere's travel time between grids. The baseline was mounted one foot in front of the femur. Since the grids are made of thin paper, they have no significant retarding effect on the projectile.

The velocity of the projectile after exiting from the bone was determined using a Dynafax high speed camera (Beckman and Whitley Model 326) and two high intensity electronic flash units (Beckman and Whitley Model 358) as light sources. The camera has adjustable framing rates up to 26,000 frames/sec. The intensity and duration of the light pulse generated by the flash units are variable. As the framing rate of the camera was increased, the intensity of the light pulse was increased correspondingly while the duration was reduced to 10·8, 5·4, or 2·7 msec to avoid multiple exposures of the film.

This photographic equipment recorded the flight of the sphere past a scale standard consisting of two pointed metal rods spaced 6·00 in. apart. The exit velocity of the projectile was calculated from the information in the photographic record. From the impact and exit velocities and the known mass of the projectile, the kinetic energy of the sphere before and after impact was calculated. The difference between these two quantities represents the energy expended by the projectile in penetrating and fracturing the bone. These experimental methods yield an error no greater than 3 per cent.

There is great variation in the dimensions of human femurs and in their degree of calcification. In order to control for the variations in size, the anteroposterior thickness of each bone in the popliteal fossa was measured with a micrometer.

Anteroposterior and lateral X-rays of the distal end of each bone were taken to determine the degree of calcification. These X-rays were read by a radiologist and the bones were then classified as 'normal,' mildly osteoporotic, or osteoporotic specimens.

The nature of the mathematical relation between impact velocity and energy loss was determined through the use of a computer, programmed to find the straight line and the quadratic curve which would best fit each set of data. An f-test was then performed to decide which of the two curves most closely fitted the data.

RESULTS

For the 222 bones impacted by 0·250 in. spheres, the mathematical relation between impact velocity and the energy lost by the sphere in penetrating and fracturing the bone is given by a second-power equation, not by a linear one. The curve which best fits all 222 paired values is the parabola described by the equation $y = -16{\cdot}175 + 1{\cdot}312x + 0{\cdot}0094x^2$ (Fig. 1). The data from the 173 bones impacted by 0·406 in. spheres are best fitted by a different parabola described by the equation $y = -9{\cdot}283 + 3{\cdot}343x + 0{\cdot}0208x^2$. At any given impact velocity the amount of energy lost by a 0·406 in. sphere (Table 1) was markedly greater than that lost by a

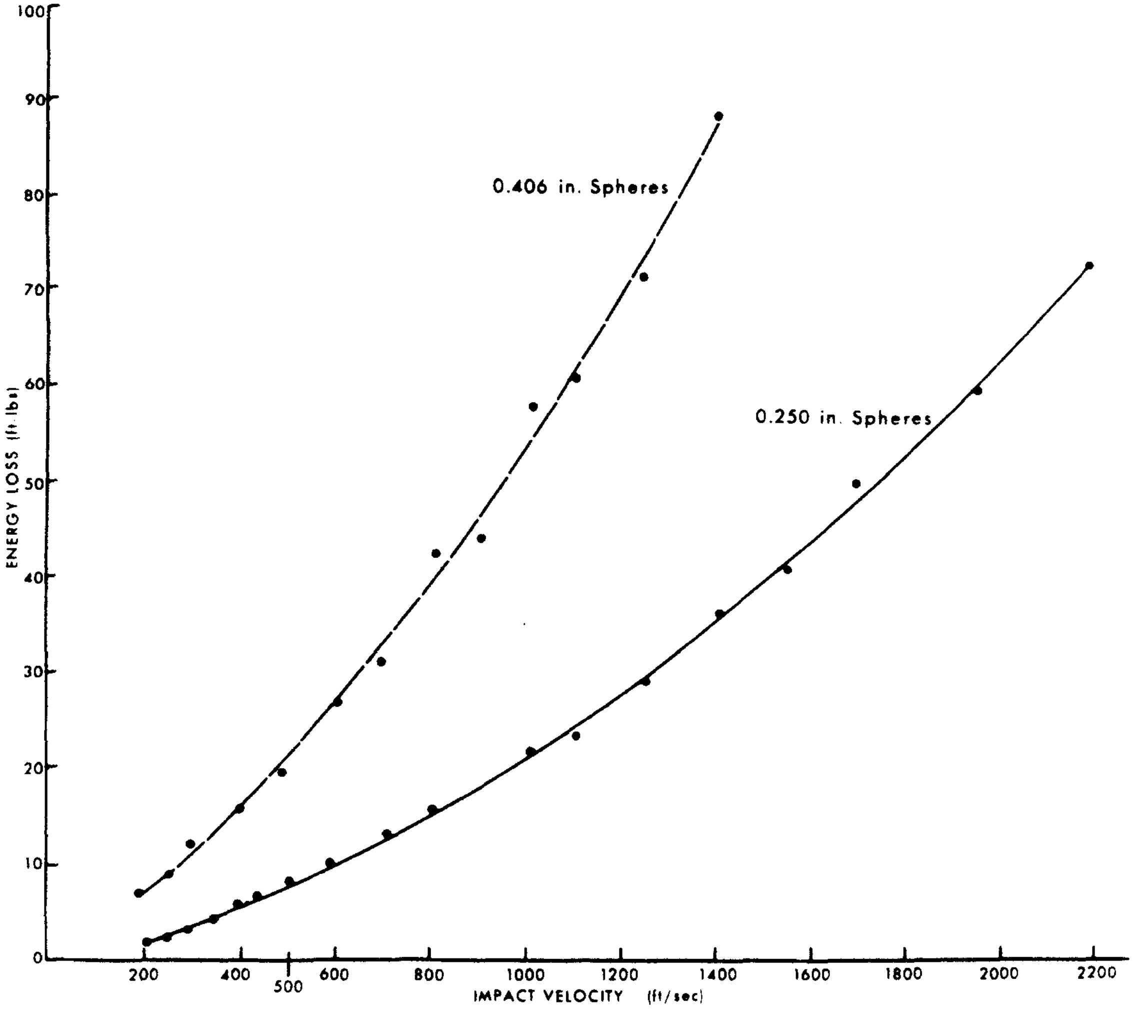

Fig. 1. The mathematical relation between impact velocity and energy loss in impacts by steel spheres on the distal end of human femurs. The points along each curve indicate the average energy loss at each impact velocity and suggest the closeness of fit of the curves. Both curves are parabolas.

0·250 in. sphere (Table 2), but the *percentage* of impact energy lost by the larger sphere was less than that lost by the smaller one at the same impact velocity (Table 3).

Within the range of variation found in the specimens, the anteroposterior thickness of the femurs through the popliteal fossa was not a significant determinant of energy loss.

The degree of calcification of the bones had a very marked influence on the amount of energy lost by a sphere in penetrating and fracturing the specimen. For both the larger and smaller spheres, more energy was required to penetrate and fracture 'normal' femurs than the mildly osteoporotic specimens; more energy was required to fracture mildly osteoporotic femurs than osteoporotic bones (Fig. 2). By the *f*-test, the fit obtained with a parabolic curve was significantly better than the fit with a straight line for data on impacts by 0·250 in. spheres on normal bones (p 0·01), mildly osteoporotic bones (p 0·001), and osteoporotic bones (p 0·001). The difference between the parabola for normal bones and

Table 1. Quantitative effects of impacts by 0·406 inch steel spheres on the distal end of embalmed human femurs

Number of specimens	Average impact velocity (ft/sec)	Average exit velocity (ft/sec)	Average impact energy (ft–lb)	Average exit energy (ft–lb)	Average energy loss (ft–lb)	Average percentage energy loss
11	203	0	6·3	0	6·3	100·0%
4	252	40	9·8	1·0	8·8	89·6%
14	297	72	13·5	1·7	11·8	87·3%
15	400	232	24·5	8·7	15·8	64·7%
12	493	338	37·2	17·7	19·5	52·7%
12	603	432	55·6	28·7	26·9	48·5%
14	699	534	74·8	43·9	30·9	41·4%
14	814	619	101·4	59·0	42·4	42·1%
12	906	729	125·5	81·7	43·9	35·0%
16	1011	801	156·4	98·7	57·7	36·8%
13	1101	903	185·5	124·9	60·6	32·6%
12	1247	1045	238·2	167·3	71·0	29·7%
12	1409	1186	303·5	215·2	88·4	29·1%
12	1548	1310	366·6	262·8	103·8	28·3%
173						

that for mildly osteoporotic bones was found to be not significant. Parabolas also best fitted the individual sets of data for impacts by 0·406 in. spheres on normal (p 0·01), mildly osteoporotic (p 0·001), and osteoporotic bones (p 0·01). Calculations showed that the difference between the curves for normal and mildly osteoporotic bones was statistically

Table 2. Quantitative effects of impacts by 0·250 in. steel spheres on the distal end of embalmed human femurs

Number of specimens	Average impact velocity (ft/sec)	Average exit velocity (ft/sec)	Average impact energy (ft–lb)	Average exit energy (ft–lb)	Average energy loss (ft–lb)	Average percentage energy loss
5	207	0	1·5	0	1·5	100·0%
4	255	29	2·3	0·1	2·2	94·6%
4	294	46	3·1	0·1	3·0	96·5%
8	350	81	4·4	0·6	3·8	88·5%
12	398	88	5·6	0·6	5·0	89·5%
12	434	95	6·6	0·7	6·0	89·8%
14	504	155	9·1	1·4	7·7	85·0%
17	591	263	12·3	2·7	9·7	78·3%
12	701	363	17·4	4·9	12·6	72·1%
13	806	456	23·0	7·7	15·3	66·7%
13	904	558	28·9	11·3	17·6	60·8%
13	1006	631	35·9	14·4	21·5	60·0%
15	1104	747	43·2	19·8	23·3	54·1%
12	1249	863	55·3	26·7	28·5	51·5%
15	1405	974	70·0	34·1	35·9	51·4%
13	1548	1115	84·8	44·3	40·5	47·8%
14	1697	1213	101·9	52·3	49·6	48·7%
13	1951	1453	134·8	74·8	59·8	44·5%
13	2198	1670	171·1	98·8	72·3	42·2%
222						

Table 3

	0·250 inch spheres		0·406 inch spheres	
Impact velocity	Energy loss (ft–lb)	% Loss	Energy loss (ft–lb)	% Loss
200	1·5	100·0%	6·3	100·0%
250	2·2	94·6%	8·8	89·6%
300	3·0	96·5%	11·8	87·3%
350	3·8	88·5%		
400	5·0	89·5%	15·8	64·7%
430	6·0	89·8%		
500	7·7	85·0%	19·5	52·7%
600	9·7	78·3%	26·9	48·5%
700	12·6	72·1%	30·9	41·4%
800	15·3	66·7%	42·4	42·1%
800	17·6	60·8%	43·9	35·0%
1000	21·5	60·0%	57·7	36·8%
1100	23·3	54·1%	60·6	32·6%
1250	28·5	51·5%	71·0	29·7%
1400	35·9	51·4%	88·4	29·1%
1550	40·5	47·8%	103·8	28·3%
1700	49·6	48·7%		
1950	59·8	44·5%		
2200	72·3	42·2%		

significant (p 0·01) but that the difference between the other two curves was not significant.

The damage done to the bones varied with the dia. and impact velocity of the projectiles. At an impact velocity of 200 ft/sec, none of the spheres completely penetrated the distal end of the femur; they were all imbedded in the cancellous bone (Fig. 3). When the impact velocity was 350 ft/sec, three of the four 0·250 in. spheres striking osteoporotic bones entirely penetrated the distal end, leaving a cylindrical permanent cavity slightly larger than 0·250 in. in dia. However, at the same impact velocity only one of the four spheres completely penetrated the mildly osteoporotic, and therefore stronger, bone. At 400 ft/sec all four spheres completely penetrated the osteoporotic bones, but only two of the four spheres penetrated the mildly osteoporotic bones. None of the four spheres at 400 ft/sec completely penetrated the normal bones.

At an impact velocity of 600 ft/sec, however, each of the seventeen 0·250 in. spheres passed through the specimens, whether the target bone was normal, mildly osteoporotic, or osteoporotic. Thus, the maximum damage done at impact velocities of 700 ft/sec or less consisted of cylindrical permanent cavity through the bone (Fig. 4).

At 800 and 900 ft/sec the 0·250 in. spheres caused a slightly enlarged cavity through the bone and chipping of the cortical bone surrounding the exit hole. With velocities of 1000 to 1550 ft/sec the spheres produced a very large permanent cavity within the cancellous bone of the distal end and an exit hole 0·5 to 2·0 in. in dia. (Fig. 5). At impact velocities of 1400 ft/sec and above, the femoral condyles were frequently broken away from the shaft. The majority (63 per cent) of impacts at velocities from 1700 to 2200 ft/sec separated the condyles from the diaphysis, and all these impacts pulverized the bone in the popliteal region (Fig. 6).

The damage produced by impacts of 0·406 in. spheres increased similarly with the increase in impact velocity, but at a given impact velocity these larger spheres caused much more severe damage than did the 0·250 in. spheres. At a velocity of 200 ft/sec, none of the eleven 0·406 in. spheres completely

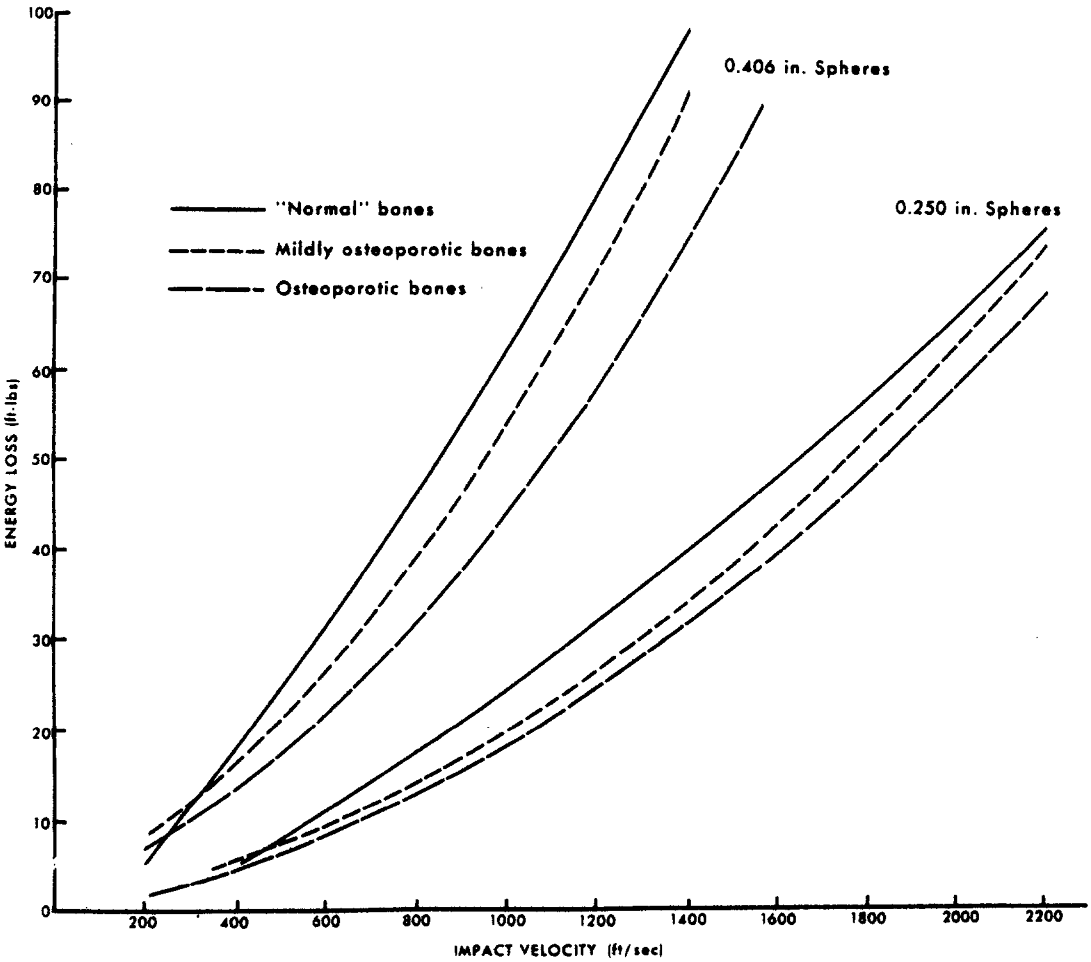

Fig. 2. The effect of bone condition on the mathematical relation between impact velocity and energy loss. All six curves are parabolas.

penetrated the femur, regardless of the bone's state of calcification. At 400 ft/sec, however, all of the larger spheres completely penetrated the distal end, leaving a cylindrical permanent cavity slightly larger than the dia. or the sphere itself. Impacts at 600 ft/sec produced marked enlargement of the exit hole and a conical permanent cavity within the bone (Fig. 7). At velocities of 1000 to 1550 ft/sec, 80 per cent of all impacts resulted in complete separation of the condyles from the diaphysis, and the region surrounding the impact point was consistently pulverized (Fig. 8).

The data obtained from impacts by 0·250 in. spheres on unembalmed femurs (Table 4) was best fitted by a parabola of slightly different shape from that fitting the data on 0·250 in. sphere impacts to embalmed femurs (Fig. 9). A polynomial regression analysis, to determine whether the difference between these two curves was statistically significant, showed that there was no statistically significant difference between them.

DISCUSSION

The lack of significant difference between the curves obtained from impacts by 0·250 in. spheres on embalmed femurs and on fresh,

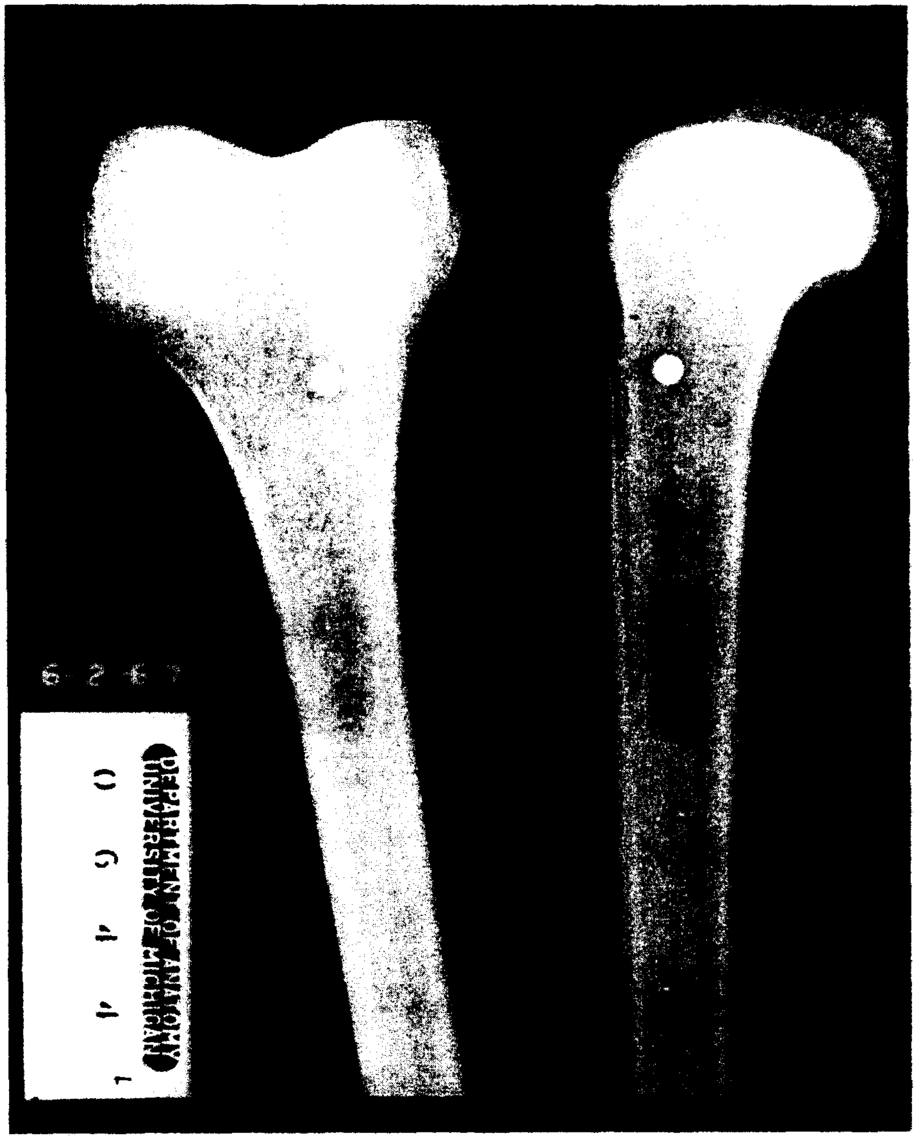

Fig. 3. Radiograph of a mildly osteoporotic femur impacted at a velocity of 508 ft/sec by a 0·250 in. sphere. The left-hand image is a posteroanterior view. The right-hand image is a right lateral view, and in this view the projectile entered the bone from the right.

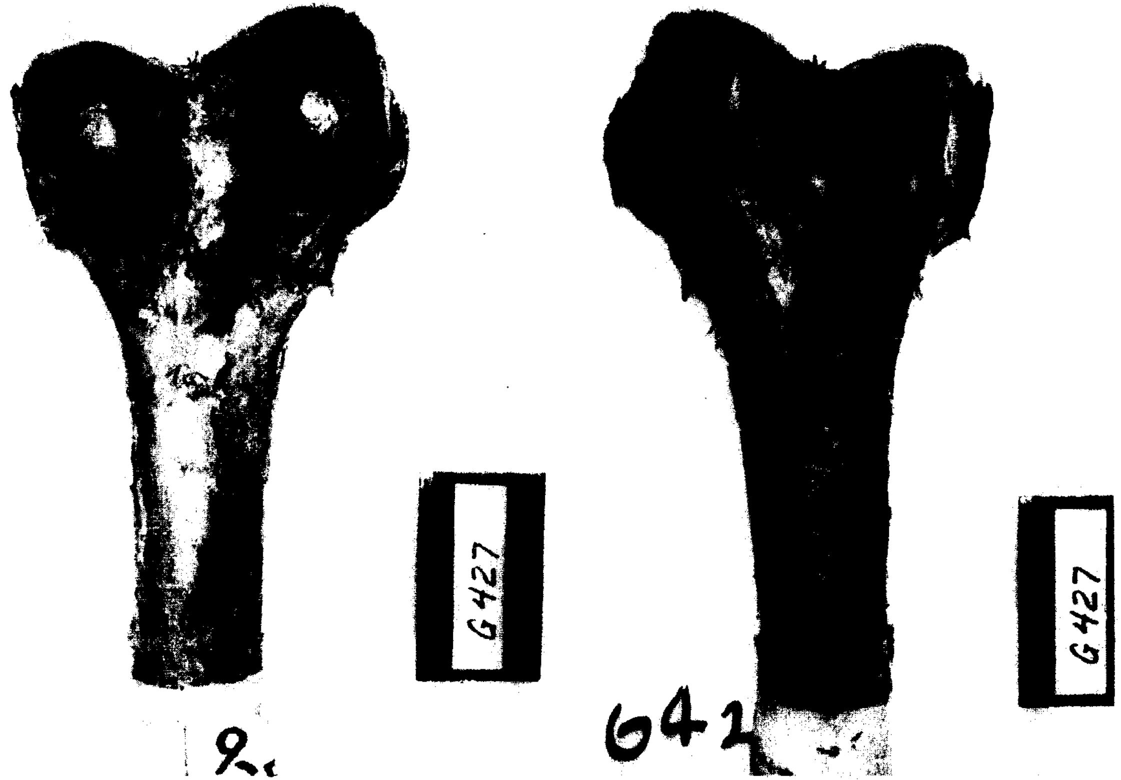

Fig. 4. Photograph of a normal femur impacted at a velocity of 600 ft/sec by a 0·250 in. sphere. The permanent cavity is an even cylinder through the bone. The entrance hole is shown on the left; the exit hole, on the right.

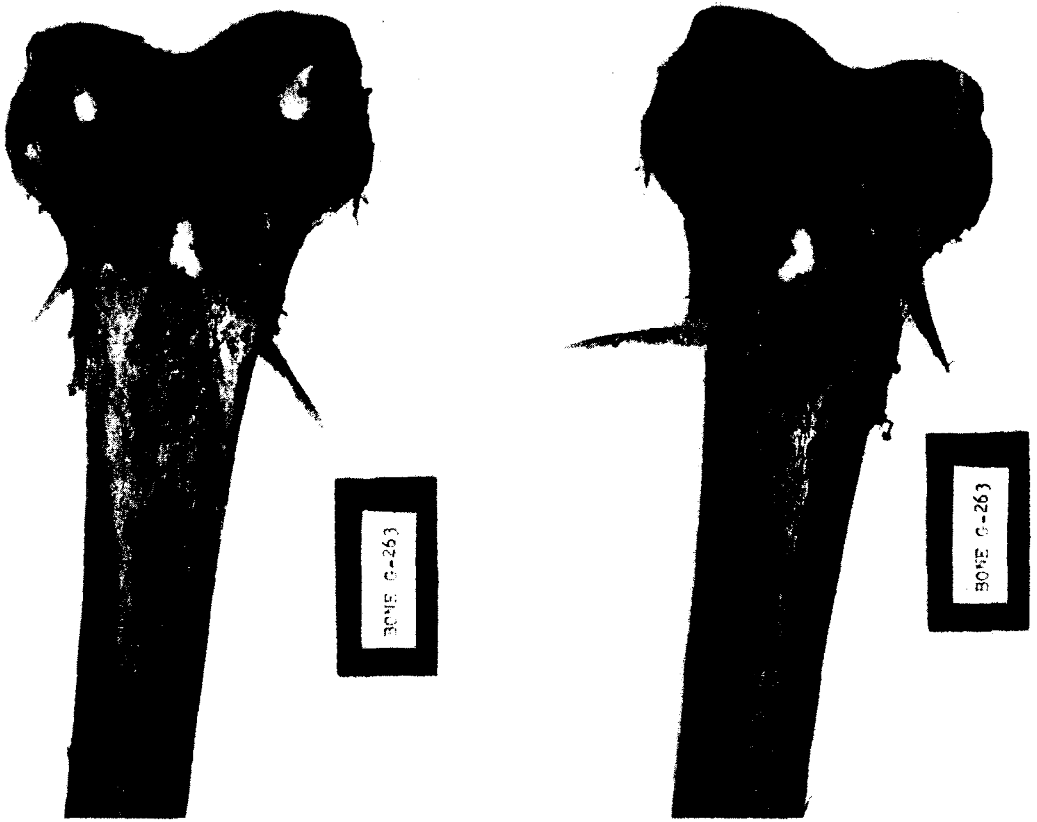

Fig. 5. **Photograph of an** osteoporotic femur impacted at 1240 ft/sec **by a 0·250 in.** sphere. The entrance hole, shown at the **left**, is small, but the exit hole on the right shows evidence of an explosive cavitation phenomenon.

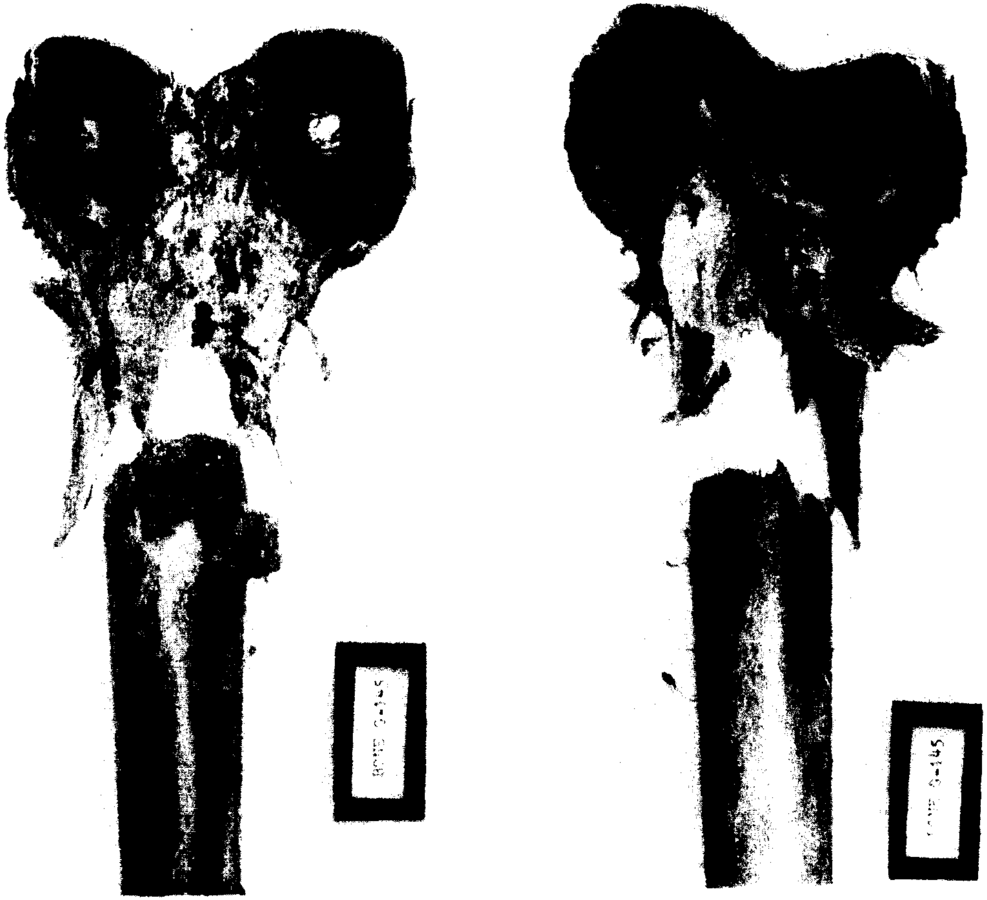

Fig. 6. Photograph of a normal femur impacted at 1710 ft/sec by a 0·250 in. sphere. The cavitation was so extensive that it pulverized the entire popliteal region, separating the condyles from the shaft.

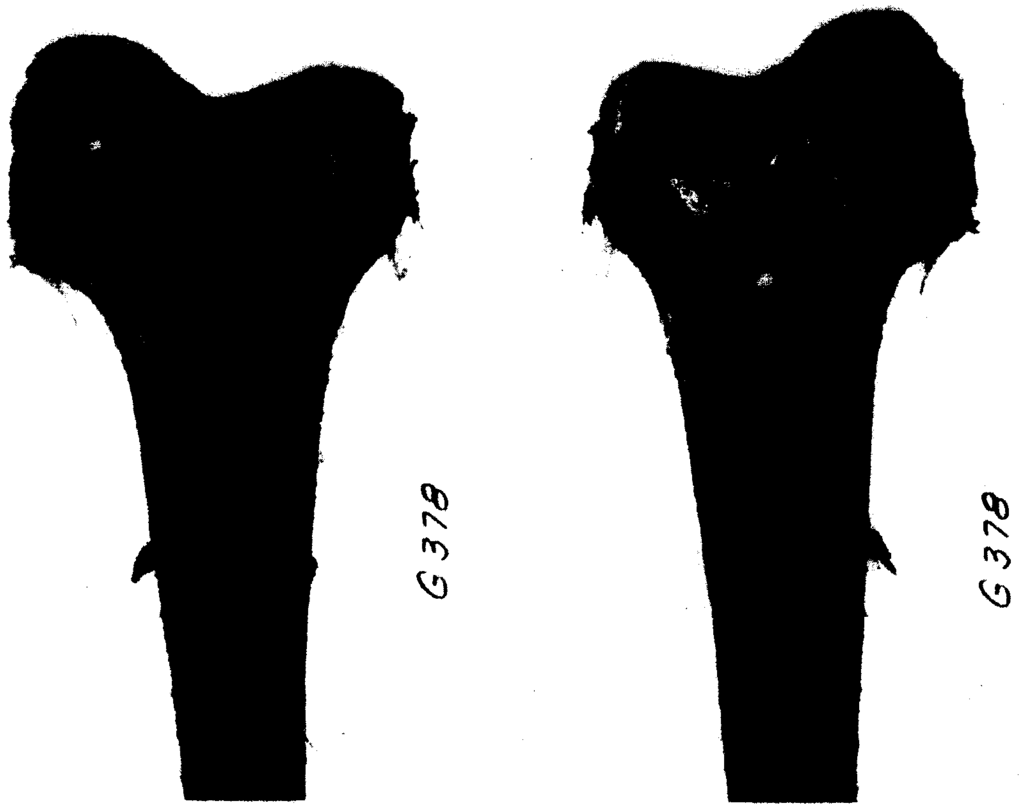

Fig. 7. Photograph of an osteoporotic femur impacted at 604 ft/sec by a 0·406 in. sphere. The entrance hole is shown on the left. The posterior view of the femur shows a conical permanent cavity, suggesting the presence of cavitation at this relatively low velocity.

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Fig. 8. Photograph of a normal femur impacted at 1110 ft/sec by a 0·406 in. sphere. The extensive cavitation appears at a much lower velocity than is needed to produce comparable damage with 0·250 in. spheres.

Table 4. Quantitative effects of impacts by 0·250 in. steel spheres on the distal end of unembalmed human femurs

Number of specimens	Average impact velocity (ft/sec)	Average exit velocity (ft/sec)	Average impact energy (ft–lb)	Average exit energy (ft–lb)	Average energy loss (ft–lb)	Average percentage energy loss
10	599	75	12·7	1·5	11·3	88·8%
7	797	439	22·5	7·2	15·3	68·1%
7	1008	620	35·9	13·6	22·3	62·1%
8	1250	865	55·3	26·7	28·7	51·8%
18	1402	962	69·5	33·1	36·4	52·4%
50						

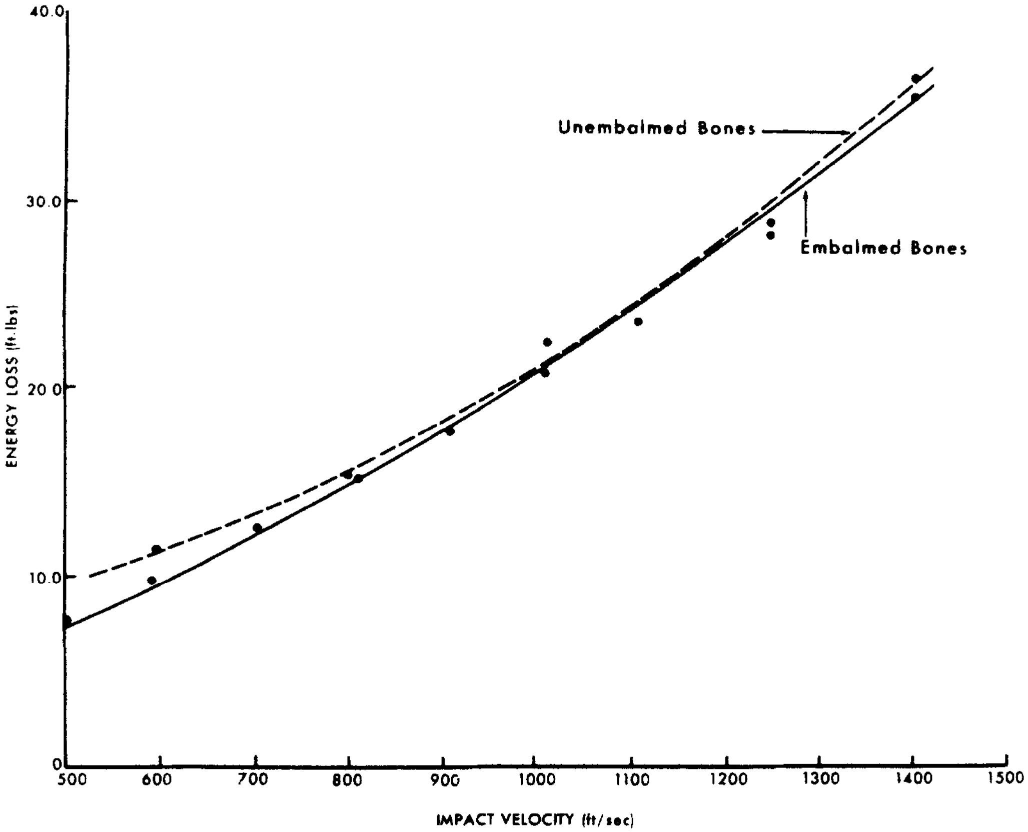

Fig. 9. A comparison of the relation between impact velocity and energy loss in impacts by 0·250 in. spheres on fresh, unembalmed femurs and on embalmed specimens. The points along the curves indicate the average energy loss at each impact velocity and suggest the closeness of fit of the curves. The similarity in responses strongly suggests that embalmed bones provide a valid experimental model for the response of human bones to projectile impacts *in vivo*.

unembalmed femurs indicates that it is valid to use embalmed bones to gain an accurate picture of the response of human bones to impacts at 200 ft/sec, and above.

A projectile passing through any tissue imparts radial velocity to the substance in its path. If that substance is liquid it may behave like a profusion of secondary missiles, moving away from the projectile's path and thereby producing a relatively large temporary cavity within the tissue. A temporary cavity in soft tissue collapses very rapidly to form the much smaller permanent cavity, but in cancellous bone the fast-moving secondary missiles pulverize the surrounding structure so that the permanent cavity is very nearly the same size as the temporary cavity.

That cavitation phenomena do occur in projectile impacts to bone as well as in soft tissues has been suggested previously, Huelke and Darling (1964); and Harvey, McMillen, Butler and Puckett (1962). Early in the present study we found strong evidence that cavitation does occur in projectile impacts to bone and that its magnitude, as determined by the size of the cavity produced, increases as impact velocity increases, Huelke, Buege and Harger (1967). Comparison of the damage produced by spheres of different diameters, however, suggests that the magnitude of cavitation is not a function of impact velocity alone. Cavitation phenomena appear at velocities as low as 600 ft/sec with 0·406 in. spheres, whereas cavitation is first observed at 800 ft/sec in impacts by 0·250 in. spheres. Further, cavitation produced by 0·406 in. sphere impacts at and above 1000 ft/sec is so extensive that the femoral condyles are almost separated from the diaphysis. Comparably severe cavitation damage, however, is not found in impacts by 0·250 in. spheres until a velocity of 1700 ft/sec is attained. The reason for this disparity of effects is that at any impact velocity the 0·406 in. sphere collides with more of the fluid within the cancellous bone than does the 0·250 in. sphere, thereby setting more fluid in motion to produce greater cavitation damage. The leading surface of the larger sphere presents a total area of 0·259 in^2. to the bone while the smaller sphere only presents an area of 0·098 in^2. Thus, certain degrees of cavitation damage appear at lower velocities in impacts by 0·406 in. spheres than in impacts by 0·250 in. spheres. The severity of damage due to cavitation primarily depends, then, on *two* variables—impact velocity and projectile size.

Most of the variation observed in the data was accounted for by the differences in structural strength between bones, which was largely a reflection of their state of calcification. As Fig. 2 indicates, the normally calcified bones caused a greater energy loss by the sphere because of greater bone strength, whereas the osteoporotic bones were weaker and thus significantly lower amounts of energy were lost by the projectile.

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