MILWAUKEE SEWERAGE TUNNEL PROJECT

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The City of Milwaukee Sewerage Commission is at the present time engaged in constructing 70 miles of sewer tunnel under Milwaukee County, which ranges from 8 to 12 feet in finished diameter. Since much of the work is performed in wet porous soil, the pressures under which the men work have averaged from 20 to 38 psig.

When the author first arrived in Milwaukee, in 1969, to supervise the operation of two hyperbaric chambers at St. Luke's Hospital, he was familiar only with U.S. Navy decompression practices. It came as a surprise, therefore, to discover that the tunnel workers were using a split shift, with an hour's surface interval between shifts. The fact of repetitive exposure was not taken into account in the decompression following the second shift. Furthermore, these decompression schedules — a modification of the 1922 New York code incorporated into the Wisconsin statutes — provided only about a third of the decompression required following similar exposures in U.S. Navy practice.

Because of these discoveries, St. Luke's Hospital began routinely to X-ray the joints of any patient who presented himself for treatment of bends to see if he had contracted aseptic necrosis. It soon became evident that many men were afflicted with the disease, some of them already symptomatic. As a result of these preliminary investigations, a new state code committee was formed, of which the author became chairman. In August 1970 the Washington State decompression tables were adopted in Wisconsin by emergency order of its Department of Industry, Labor, and Human Relations; by September 1971 a completely new code had been devised. However, the decompression procedures followed until 1970 have produced an alarming incidence of bone disease.

Under the new code it is mandatory that each man be X-rayed before he enters compressed air. The author has therefore had the opportunity to examine all those men still working in tunnels who had had previous exposure to compressed air, in addition to some who have retired.

At this writing 188 men have been examined, of whom 169 had previous exposure to compressed air at pressures greater than 16 psig. Of the latter group, 59 (or 35%) were found to have lesions of aseptic necrosis. Forty-two (71%) of the men with the disease had potentially disabling juxta-articular lesions; of that number, 16 were already symptomatic. It is also of interest that an additional 26 of the 188 men examined were found to have classic "bone islands"; of those 26, only 3 had never worked in compressed air.

This extremely high incidence of aseptic necrosis is actually not surprising. Almost all compressed-air tunnel and caisson work done in the United States prior to 1963 was carried out with split-shift tables, usually modifications of the 1922 New York code — which provided inadequate decompression, as we are now well aware. Thus anyone who worked in compressed-air tunneling or caisson construction at pressures greater than 16 psig prior to 1963 is a likely candidate for aseptic necrosis.

Subsequent to their introduction in 1963, the Washington State decompression tables were adopted by California, Wisconsin, and Michigan. The Occupational Safety and Health Act of April 1971 has since designated them as the national standard for all compressed-air work done in the United States. To date not a single well-documented case of aseptic necrosis has evolved from use of the Washington State tables.

Washington and Wisconsin also have the first state codes requiring preemployment X-rays of tunnel workers. The new federal code unfortunately does not require such X-rays, despite strong recommendation from medical experts. For this reason, the true incidence of aseptic necrosis in areas where much pressurized tunnel construction has taken place is still unknown. For example, as far as is known the compressed-air workers of Illinois have not been X-rayed. Yet prior to the new federal code, Illinois had

even worse decompression schedules than Wisconsin did.

In establishing our own program, we were initially quite ignorant of the proper X-ray views to take to detect early necrosis. But, thanks to help from Albert Behnke of the San Francisco Transit Compressed Air Medical Center, and from John P. Jones, Jr. — and drawing, as well, from British experience — we have devised an X-ray protocol that we find quite suitable.

Regarding the shoulder, it is important to use the Grashey position so that overlap of the humeral head, glenoid, and acromion is eliminated or greatly reduced. Two views — one in internal and the other in external rotation — are obtained in the Grashey position, with the patient's shoulder tilted at a 45° angle to the table and with a 15° angle on the X-ray tube. To detect aseptic necrosis of the femur, it is not necessary to X-ray areas other than the hips and knees. The hips should be filmed in the A-P and frogleg lateral positions. For maximum trabecular detail, each side should be X-rayed separately.

In summary, a complete caisson worker's X-ray survey consists of two views of the shoulders, two views of the hips, and A-P and lateral views of each knee — a total of 12 films.

The U.S. Public Health Service is quite concerned about radiation from diagnostic X-ray, especially in large survey projects. In addition to gonadal shielding, therefore, pelvic shielding is also necessary, because of the bone-forming marrow present in the pelvis. Our present protocol has been approved by the U.S.P.H.S.

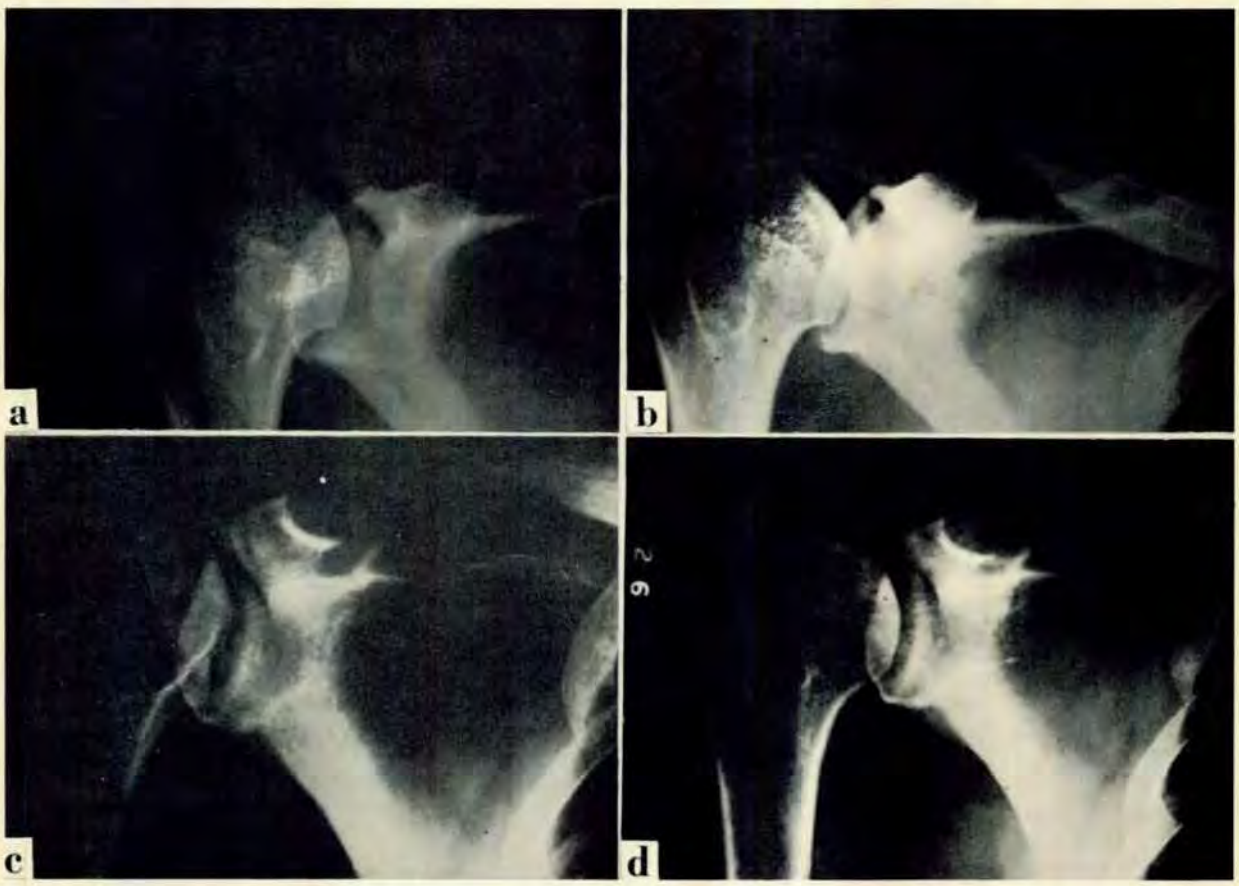

FIG. 1. (*a*) Shoulder of man who had suffered an attack of bends; (*b*) same shoulder one year later, during which time patient had worked in pressures up to 30 psig; (*c*), (*d*) X-rays of same shoulder with different rotation.

Figure 1 shows the shoulder of a man whom we first saw when he suffered an attack of bends. The film in 1*a* is poor, but after studying additional views we concluded that the shoulder was not diseased. The patient continued working a split shift at pressures up to 30 psig; a year later he was X-rayed again. Note the margin of sclerosis in 1*b*, which appeared in the juxta-articular view of the right shoulder after a period of one year. As stated, two views are now taken of the shoulder; the reason is well demonstrated in 1*c* and 1*d* — X-rays of the same shoulder, but with a different rotation. A large defect is visible in 1*d* on the superior aspect of the humeral head.

In Fig. 2*a* is a rather typical snowcap lesion, perhaps an early one. These snowcaps are quite common in aseptic osteonecrosis. In Fig. 2*b* is something we call a pseudosnowcap lesion. The superior medial aspect of the bone looks more dense than the area below it, but fades off with no line of demarcation. The trabeculae are visible on close examination; in our opinion, however, these changes may appear in normal people. The findings from this X-ray were not considered grounds for disqualifying the subject from further hyperbaric exposure.

A sizable sequestrum is seen in Fig. 3. This patient was symptomatic when he presented himself for examination. In Fig. 4 is a rather unusual phenomenon: a large sequestrum is visible in the hip. This man was absolutely asymptomatic when he came in for a routine X-ray before returning to work in compressed air. The articular space is normal and the articular cartilage is apparently intact, which probably accounts for his presently being pain-free. In all probability he will eventually have to have a prosthetic replacement.

Figure 5 shows the shoulders and hips of a patient who had maintained mining machinery under hyperbaric pressure. Figure 6 shows the same four joints of a man who actually had very little experience in compressed air, but did work at pressures greater than 16 psig. His hip joints have since collapsed completely. Figure 7 shows the shoulder of a man who worked as a miner with an air spade in his left hand. When he

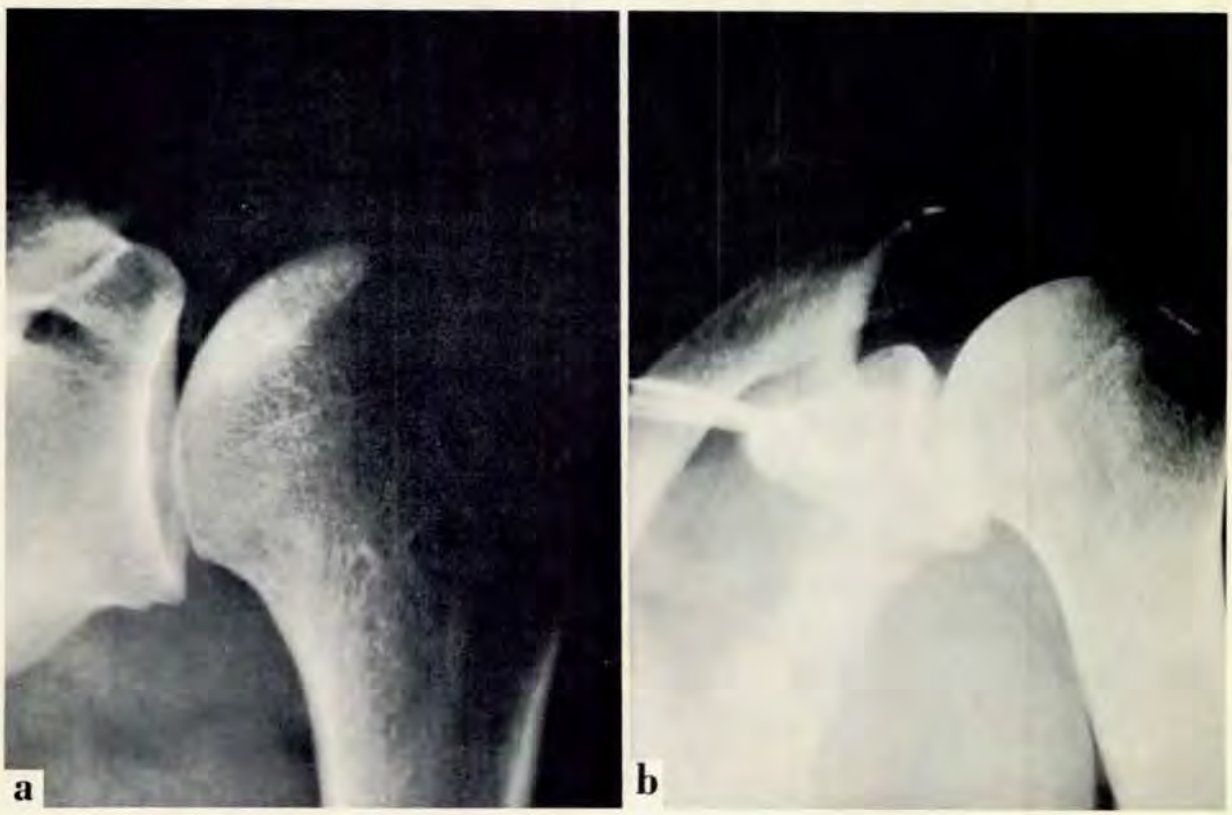

FIG. 2. (*a*) A typical snowcap lesion, common in aseptic osteonecrosis; (*b*) a pseudosnowcap lesion, which was not considered sufficient grounds to disqualify subject from further hyperbaric exposure.

FIG. 3. Sequestrum in cortex of humeral head.

could no longer lift the implement because of pain, he shifted it to his right hand and triggered it with his left. This offered a temporary solution to his problem and he kept working, despite his diseased left shoulder, for another three years. He felt that he merely had a severe case of arthritis.

FIG. 4. Sequestrum in hip of patient who was completely asymptomatic when he underwent routine X-ray.

Figure 8 is a very rare X-ray. Other than the series reported by El Ghawabi *et al.* (1971), only two or three lesions of the articular margin of the knee are cited in the world literature. Sclerosis in the distal shaft of the femur is commonplace. But sclerosis extending down all the way to the knee-joint margin, as seen here, is extremely rare. This man had symptoms of pain; in fact, the knee is that of the same man whose shoulder is shown in Fig. 7.

It is important to point out additional factors that possibly play a role in decompression sickness and aseptic necrosis. Comparisons of decompression tables are commonly made in terms of the length of *total decompression time*, which, although indeed important, is not the sole consideration. The entire *decompression profile* of any given table is of equal importance. The profiles of the Washington State tables are clearly inadequate in that they do not provide sufficient decompression time at intermediate pressures. The bends rate remains high. Those profiles call for the greatest decompression time (up to two hours) to be spent at pressures less than 4 psig, where bubble formation is quite likely to occur. In Milwaukee, we start decompressing directly from higher pressures by straight-line decompression from, say, 16 psig. Our men therefore spend significant decompression periods at the intermediate pressures. Once this protocol was introduced, the incidence of bends seemed to drop rather dramatically. Yet we have not shortened the tables in any way, for we wish to avoid further threat of aseptic bone necrosis.

Another possible contributory factor in bends or aseptic necrosis is the quality of the breathing atmosphere. The muck found in the Milwaukee tunnels produces large amounts of carbon dioxide when it comes into contact with compressed air. We find a definite correlation between a high CO_2 level in the tunnel and the incidence of bends among the workers. Thus it may be that decompression schedules alone cannot be depended upon to prevent the problems of bends and aseptic necrosis. Men using the new federal code, but working in contaminated air, could conceivably develop lesions of aseptic necrosis despite close adherence to adequate decompression schedules.

Regarding our management of these cases, we have borrowed freely from the experience of

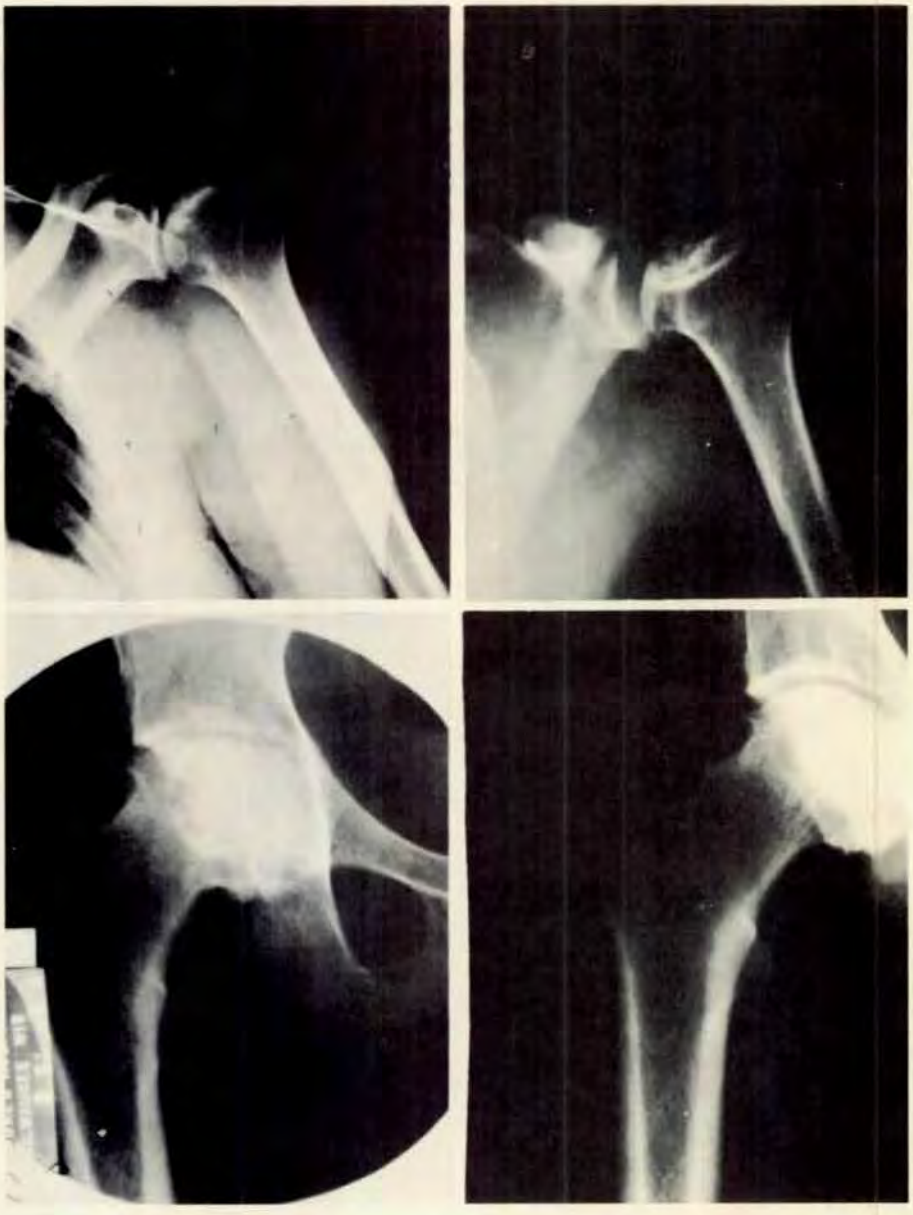

FIG. 5. Shoulders and hips of a mining machinist, who had been exposed to hyperbaric pressure, showing extensive osteonecrosis of all four joints.

others and claim no innovations. We might differ somewhat with the British MRC recommendations (see D. H. Walder's "Management and Treatment" chapter, this volume) regarding a juxta-articular lesion. We always consider it potentially disabling until it has proven to be otherwise. Our opinion is that we are probably not seeing the entire lesion. As opposed to British practice, therefore, we give the man no choice; he is simply disqualified. If a man has a juxta-articular lesion in the shoulder, for example, he is no longer permitted to work in compressed air. Nor is he permitted to lift more than 25 lb. from the floor, or raise more than 10 lb. above his head, until it is demonstrated that there has been no disease progression. These are Dr. Jones's recommendations.

The author consulted with Prof. Roland

FIG. 6. Shoulders and hips of man with little history of hyperbaric work, but with exposure to pressures greater than 16 psig.

Barnes of Glasgow about treatment of these men; he is becoming more permissive, as are we. In the past when we came across a patient with four joints involved, we thought of prescribing bed rest. However, this is impractical, as one cannot keep a man bedridden for two or three years if he is otherwise in excellent health. Since the majority of these men are young, we are hesitant about implanting prostheses immediately, even in severely damaged joints. But when a lesion becomes too painful and the disability can no longer be tolerated, operative intervention is offered.

Finally, we have found that rehabilitation or retraining is largely a failure, despite the efforts of Wisconsin's very active State Employment and Rehabilitation Service. These men find it difficult to cooperate, as they often lack the adaptive ability to learn a different trade.

FIG. 7. Collapse of L humeral head of miner who operated air spade with his L hand.

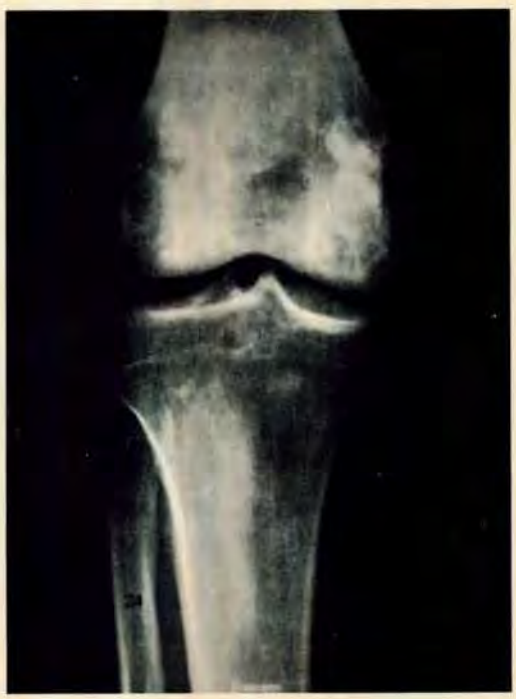

FIG. 8. Lesion of femoral condyles of knee, with sclerosis extending down to knee-joint margin. Patient is the same one whose shoulder is shown in Fig. 7.

REFERENCE

El Ghawabi, S. H., Mansour, M.B., Youssef, F. L., El Ghawabi, M. H., and Abd El Latif, M. M. (1971). Decompression sickness in caisson workers. Brit. J. Ind. Med. 28, 323-329.