# **Comment on “The role of interstitial fluid pressurization in articular cartilage lubrication.” (Ateshian, 2009)**

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I thank Ateshian for describing some of my work on joint lubrication. May I mention more of it, and argue two of his points?

As noted by Ateshian (2009), the lubricating consequences of the compressible, fluid-filled, micropored sponge, or “poroelastic*,” nature of cartilage -- called “biphasic” by Mow *et al.*, (1980) -- were deduced in McCutchen (1959), and the availability of the fluid for lubrication was demonstrated by Lewis and McCutchen (1959).

In McCutchen (1962) the permeability and stiffness of cartilage were measured, and the stiffening effect of Donnan osmotic pressure was demonstrated. Lubrication was measured by rubbing cartilage against smooth glass, and also treated mathematically, showing that the time constant when a cartilage bearing loses fluid under load is proportional to the square of its radius, and that resoaking through its rubbing surface follows a diffusion equation. A non-fatal error in the latter was corrected in McCutchen (1974, also 1975).

That the loaded region of cartilage must either separate from its mate or move as the joint works in a living animal so the cartilage can recharge itself with fluid was touched on in Lewis and McCutchen (1959) and treated more fully in McCutchen (1962).

Also in McCutchen (1962) it was shown that synovial fluid lubricated better than water (or saline) and that its lubricating advantage faded as the cartilage lost fluid under load. Wringing out of the fluid could be accelerated by using cartilage as a thin layer supported on porous glass. With fully wrung out cartilage rubbed against glass synovial fluid lubricated at a loading of 1.5 atm. but not at 4.5 atm. (McCutchen 1967). Treating the synovial fluid with hyaluronidase did not affect its lubricating ability.

The confounding effect of self-pressurization of cartilage fluid on lubrication measurements was later eliminated by testing lubricants in a latex *vs.* glass bearing (McCutchen, 1966; McCutchen and Wilkins, 1969).

That collagen fibers render cartilage much more easily compressed than stretched, and the consequences thereof, were described in McCutchen (1965 and 1969).

Ateshian suggests that which way fluid flows through the surface of cartilage is still uncertain. I disagree. Maroudas (1967) is right that it flows into the cartilage in the squeeze-film interval when separated cartilages are pushed toward each other. Though the fluid mostly escapes from the loaded region by flowing between the cartilages, a little enters the cartilages and escapes by flowing through them parallel to their surfaces.

But when the high spots on opposing cartilages touch (Lewis, and McCutchen, 1960) they start to carry some of the load, and because the escape of the fluid between the surfaces continues, the pressure in this fluid drops and is soon below that in the cartilages. Fluid then flows from within the cartilages to the space between the rubbing surfaces, and largely makes up for the escape of the fluid from this space, thus greatly slowing the transfer of load from the fluid to the friction-causing high spots. This is weeping lubrication.

In Fig. 3(a) of Ateshian (2009) the traces of pore pressure and friction coefficient look like mirror images of each other. Thus the friction coefficient is fairly accurately proportional to skeleton stress (i. e., gross stress, which is constant, minus pore pressure), leaving little room for the term $\phi(W^p/W)$ in Ateshian's Equation 9. Here W is the gross load, $W^p$ the load supported by hydrostatic pressure and $\phi$ = 2% the fractional area of real contact. Krishnan *et al.,* (2004) gave $\phi = .017 \pm .063$.

Ateshian's Equation 9, which is the same as the equation on page 119 of McCutchen 1969, starts with the fact, noted in McCutchen (1962), that opposing surfaces in the area of real contact will be forced together by the pore pressure as well as by the force from matrix stiffness. Multiply the pore pressure force by the solid-solid friction coefficient and one has a pore pressure contribution to friction.

But later I found that raising the hydrostatic pressure up to 100 atm. in water-lubricated bearings of neoprene and cartilage against glass caused no noticeable change in their friction. Further, Briscoe *et al.* (1974) found that the friction coefficient of seven plastics rubbed against steel in air fell by a few perecent as the air pressure was raised through 100 atm. Ergo, hydrostatic clamping adds little or nothing to the friction. The formula for friction with no contribution from hydrostatic clamping is given on page 471 of McCutchen (1978), which noted that it is independent of the area of real contact, as did Ateshian *et al.* (1998) indirectly. With n = 1 to satisfy Amontons's law my equation is the same as Equation 12 of Ateshian (1997).

It is also the same as Equation 9 in Ateshian (2009) with $\phi$ set equal to zero, a value not far from Ateshian's $\phi = .02$, or $\phi = .017 \pm .063$ in Krishnan *et al.* (2004). If it is true that hydrostatic pressure has negligible effect on friction, then rather than showing that $\phi$ is very small the data were saying that Ateshian's equation should not have had the $\phi$ term. In that case Ateshian's procedure for determining the area of real contact will not work.

*** l do not know who coined the term "poroelastic." I first used it in McCutchen (1974), which commented on a paper in which it was used.**

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Be warned that the equations on page 459 of the above reference use non-standard definitions of the permeability of bulk cartilage and of the flow conductance of the crack between the rubbing surfaces. (I had evidently forgotten the standard definitions when I wrote page 459.) The definitions on page 459 are for fluids of unit viscosity, and must be divided by the viscosity of the actual fluids to yield the conventional definitions.

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