Available online at www.sciencedirect.com

Journal of Sound and Vibration 280 (2005) 1143–1147

JOURNAL OF
SOUND AND
VIBRATION

www.elsevier.com/locate/jsvi

Short Communication

Mechanical vibration-induced particulate deposition and ionic mineralization at material boundaries in the fluid media

Paul C. Ho[a,*], Julius Melbin[b]

[a]Department of Bioengineering, The School of Applied Science and Engineering, University of Pennsylvania, Philadelphia, PA, USA
[b]Department of Animal Biology, School of Veterinary Medicine, University of Pennsylvania, Philadelphia, PA, USA

Received 12 January 2004; accepted 21 February 2004

1. Introduction

Boundaries and interfaces interrupt wave propagation [1]. At an interface, an antegrade propagating wave is fractionated into reflected and transmitted portions. In a system of multiple interfaces or layered media, the spatial patterns of wave magnitude result from summation of these "wavelets or wave fractions". A mathematical model [2], which considers such complex dynamical interaction of oscillating waves in a system of multiple interfaces, predicts the formation of sharp interfacial gradients. These induced interfacial gradients, which are distinct from and in addition to concentration gradients, are hypothesized to influence fluid and particle transport. Specifically, suspended particulate and ionic matters are predicted to aggregate at the softer, more compliant side of the interfaces [2], corresponding to the "troughs" of the gradients. In the following pilot experiments, pressure oscillations were chosen as stimuli to interfacial gradient formation demonstrating particulate and mineral deposits at the predicted interfacial sites.

2. Materials and methods

The experimental set-up consisted of mechanically generated pressure oscillations in a system of material interfacial boundaries. In two experiments, particulate and ionic markers were used to

---

*Corresponding author. Division of Cardiology, Kaiser Foundation Hospital, 3288 Moanalua Road, Honolulu, HI 96819, USA. Tel.: +1-808-432-8386; fax: +1-808-591-2689.
E-mail address: paul.c.ho@kp.org (P.C. Ho).

doi:10.1016/j.jsv.2004.02.053

illustrate transport and aggregation of suspended matter at expected interfacial sites. The first experiment comprised of vertically oriented chambers of distilled water each with an immersed open-cell urethane sponge (Fig. 1). The water–sponge boundaries served as the interfaces of interest. At time zero, the top portions of the chambers were introduced with the same concentrations (5%(v/v)) of black, 100 Å ink particles (“printer’s ink”). One set of study chambers was subjugated to pressure oscillations; the other served as controls (Fig. 1). After a period of time, the patterns of particulate distribution in these chambers were documented by light photograpy. Multiple frequencies and time durations were studied; representative results are shown in Fig. 1.

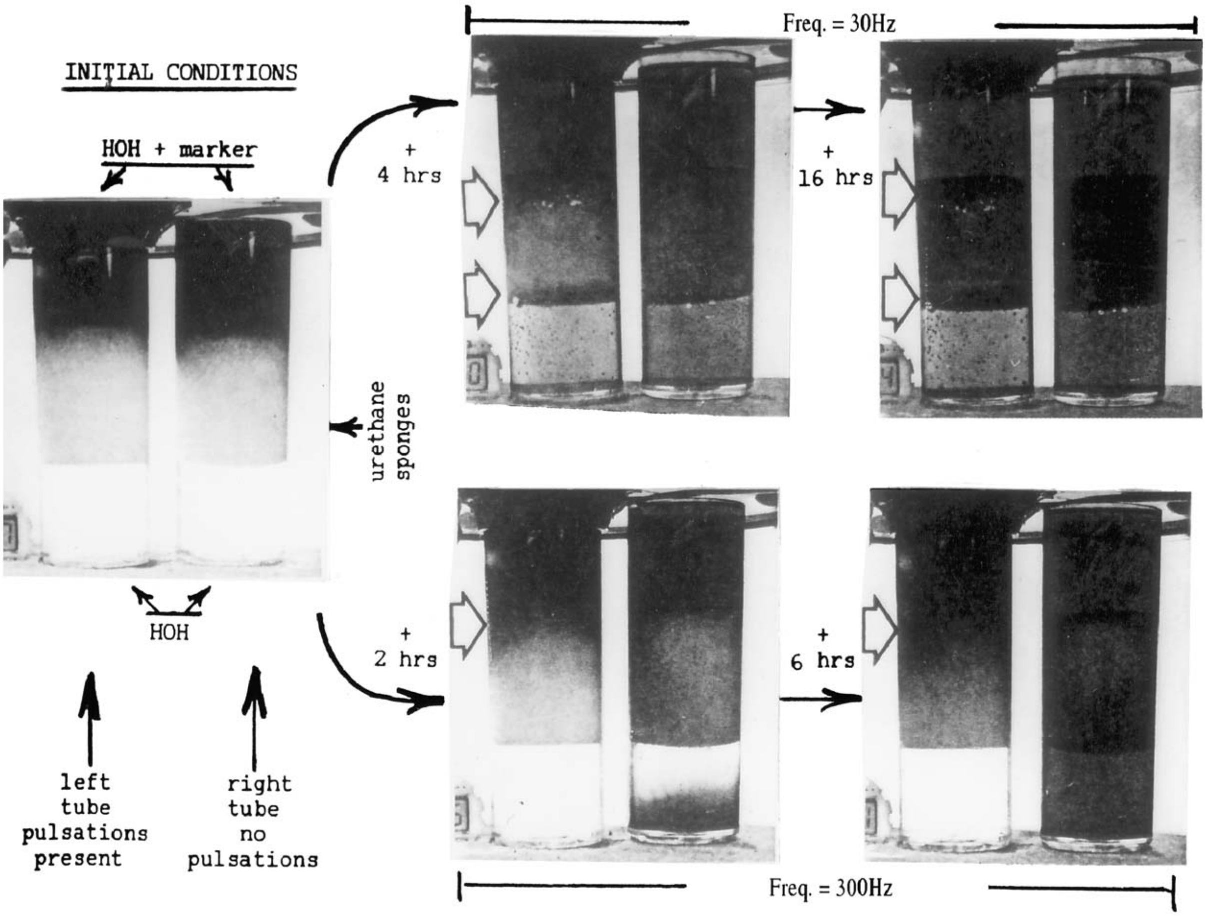

Fig. 1. Representative photograph of experiment #1. The left set of photographs of the experimental set-up was taken at time-zero when the same concentrations of ink particles were introduced at the top of the study chambers. In each subsequent set of photographs of the experiment, the left chamber was subjugated to pressure oscillations from the top; the right chamber was without oscillations. After periods of time, the chambers with pressure oscillations showed various amounts of demarcating bands of ink particulate aggregation at the sponge side of the interfaces; the control chambers demonstrated no interfacial deposits. At 300 Hz, intense deposition at the top interface prevented further downward distribution of the ink particles.

The second experiment was designed to study ionic transport and interfacial mineralization. Similar study chambers were used; one set was subjugated to pressure oscillations and the other served as controls. Random distribution of starch granules suspended in polyacrylamide gel provided interfaces of interest, hence the starch–polyacrylamide interfaces (Fig. 2). Calcium and phosphate ions, which were suspended in a supernatant of a supersaturated bath of tribasic calcium phosphate in distilled water at neutral pH, served as mineral markers. The composite polymer was immersed in the ionic supernatant in the study chambers. After preset time intervals, the chambers with pressure oscillations were compared with the control chambers for calcific deposits. The Von Kossa staining method was used to identify deposited calcific mineralization. The stained specimens from various time intervals were sectioned and the comparative results were documented by light microscropy and light photography; a representative result is shown (Fig. 3).

Oscillatory pressures were generated by a modified acoustic speaker–diaphragm system [3]. Frequencies of oscillations used were in the range of 30–300 Hz. Adjunctive electronics included a standard amplifier and a frequency generator were used.

3. Results and discussion

In both experiments, depositions occurred at predicted interfacial sites with pressure oscillations. The first experiment demonstrated well-demarcated bands of ink particles

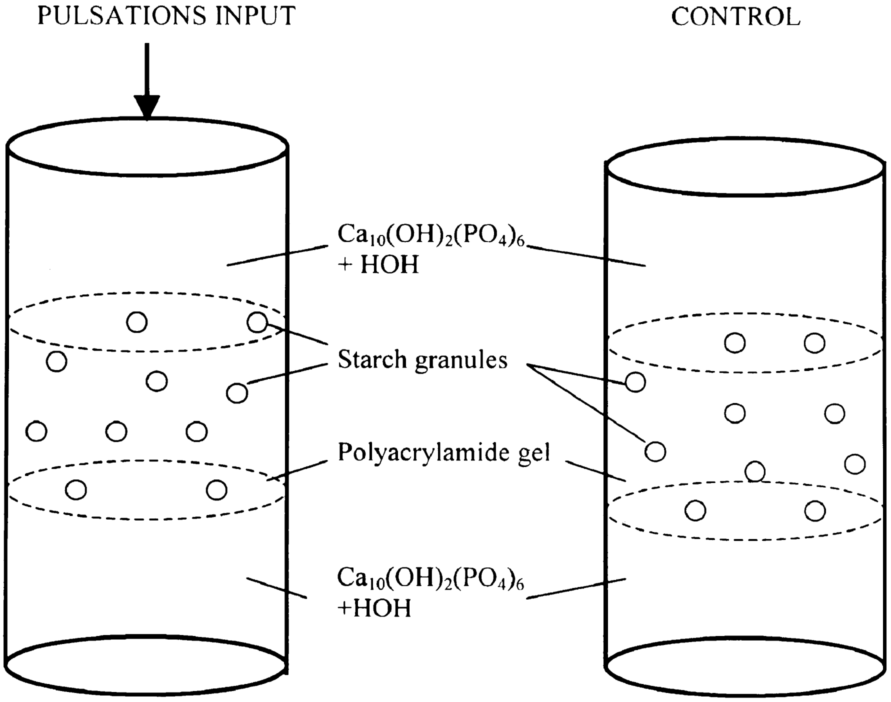

Fig. 2. Schematic illustration showing the set-up for experiment #2. The left chamber was under pressure oscillations; the right was without.

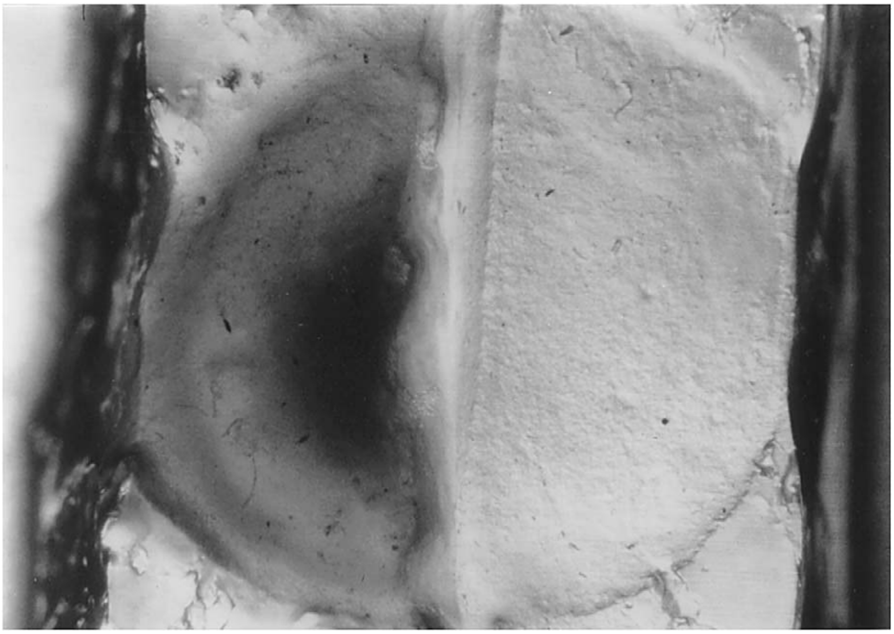

Fig. 3. Light microscropy of a side-by-side comparison of the study and control sections of the starch–polyacrylamide interfaces. The sample on the left was obtained from the chamber with pressure oscillations; the right was from the chamber without oscillations. The darkened shade within the left sample represented Von Kossa staining of calcific mineral; in colour, these calcific deposits stain dark brown. No such calcific mineralization is observed in the controls as seen on the right sample.

aggregating at the sponge side of the water–sponge interfaces (Fig. 1). In the second experiment, initial calcific deposits occurred at the starch side of the starch–polyacrylamide interfaces. In time, the calcific mineralization filled the entire starch granules (Fig. 3). In comparison, the control columns demonstrated no distinct particulate or ionic deposits at the respective interfaces; no depositions without the presence of pressure oscillations. From these early results, the interaction of pressure oscillations and material interfaces appeared to have produced additional driving gradients for interfacial aggregation of particle and ions. For the controls, the driving forces for transport consisted only of diffusion and Brownian motion.

The published mathematical model predicts transport gradients at interfaces that favours deposition at the mechanically softer or more compliant side [2]. In our experiments, the more compliant sides of interfaces were the sponge of the water–sponge interface and the starch granules of the starch–polyacrylamide interface. Depositions were indeed seen to occur at these predicted sites. In a separate in vivo observation with an experimental cardiac patch implant in sheep [4], the initial observed calcific mineralization within the implant also occurred at interfacial sites predicted by the mathematical model [2,4]. These observations supported the hypothesis that oscillation-induced interfacial gradients can cause interfacial deposition of particulate and ionic matter.

An interesting application may be found in the mammalian circulatory system. Examples of interactions of oscillatory waves and interfaces are commonly found in the arterial circulation [5]. At junctions between normal segments of arteries and pathologic processes such as atherosclerotic plaques or surgical anastomoses, disruption of wave propagation occurs. Connections between wave-boundary interactions and cardiovascular diseases have been explored [2,6], and further studies in this exciting area are needed.

Since the mammalian heart is a generator source of pressure as well as electromagnetic pulses [7], interactions of oscillating electromagnetic waves at cardiovascular junctions and boundaries should also be considered. Similar theoretical models of electromagnetic waves at interfaces can be derived based on fundamental expressions [8]. In vivo transport of charged matter at boundaries, e.g., charged ions and cellular debris, is likely to be affected by pressure as well as electromagnetic waves.

Most studies considered the important frequency range in the mammalian arterial circulation to be less than 20 Hz, and the higher harmonic frequencies tend to be attenuated as pulses propagate toward the peripheral circulation and capillaries [9]. In the left ventricle where the pulses originate, however, much higher harmonic frequencies can be appreciated [10]. Higher frequency, low amplitude oscillations in the arterial tree have traditionally been deemed unimportant, but may be relevant in the transport of very small particles, charged materials, and cellular debris in the setting of the described model. Choice of the initial experimental frequencies fulfills the goal of this pilot study.

In summary, wave oscillations and mechanical vibrations at interfaces induce local gradient formation, which may serve as additional driving factor for transport and interfacial deposition. These early experiments demonstrated the possibility of this connection. Specific applications, such as evaluations of specific cardiovascular disease processes, would require further specific and controlled studies.

References

[1] L.M. Brekhovskikh, *Waves in Layered Media*, Academic Press, New York, 1980 (Chapter 1).

[2] P.C. Ho, J. Melbin, A. Noordergraaf, Local contributions to pulse transmission through heterogeneous media, *IEEE Transactions on Biomedical Engineering* 35 (5) (1988) 346–351.

[3] P.C. Ho, Design and Construction of an Electromechanical Driver System in the Fluid Media, Senior Thesis, University of Pennsylvania, Philadelphia, PA, 1985.

[4] P. Frasca, J.W. Buchanan, R.Z. Soriano, J.M. Dunn, L. Marmon, J. Melbin, S.J. Buchanan, S.H. Chang, E.E. Golub, I.M. Shapiro, Mineralization of short-term pericardial cardiac patch grafts, *Scanning Electron Microscopy* 11 (1984) 973–977.

[5] W.W. Nichols, M.F. O'Rourke, *McDonald's Blood Flow in Arteries*, fourth ed., Arnold Press, New York, 1998 (Chapter 9).

[6] P.C. Ho, J. Melbin, R.W. Nesto, Nonphysiologic pulsewave reflections as physical stimuli for cardiovascular calcification, Council on Circulation, American Heart Association, February 22–25, 1998 (abstract).

[7] J.W. Hurst, *The Heart*, ninth ed., McGraw-Hill, New York, 1998 (Chapter 4).

[8] J.D. Jackson, *Electrodynamics*, second ed., Wiley, New York, 1975 (Chapter 8).

[9] A.G. Salotto, L.F. Muscarella, J. Melbin, J.K. Li, A. Noordergraaf, Pressure pulse transmission into vascular beds, *Microvascular Research* 32 (2) (1986) 152–163.

[10] F.L. Abel, Fourier analysis of left ventricular performance, *Circulation Research* 28 (1971) 119–135.