Ultrasound in Med. & Biol., Vol. 37, No. 8, pp. 1340–1349, 2011
Published by Elsevier Inc. on behalf of World Federation for Ultrasound in Medicine & Biology

0301-5629/$ - see front matter

doi:10.1016/j.ultrasmedbio.2011.05.009

● *Original Contribution*

NEWTONIAN VISCOUS EFFECTS IN ULTRASONIC EMBOLI REMOVAL FROM BLOOD

CARA A. C. LECKEY* and MARK K. HINDERS†
*NASA Langley Research Center, Hampton, VA, USA; and †Department of Applied Science, College of William and Mary, Williamsburg, VA, USA

(*Received* 6 *December* 2010; *revised* 4 *May* 2011; *in final form* 9 *May* 2011)

Abstract—We have modeled the removal of emboli from cardiopulmonary bypass circuits *via* acoustic radiation force. Unless removed, emboli can result in cognitive deficit for those undergoing heart surgery with the use of extracorporeal circuits. There are a variety of mathematical formulations in the literature describing acoustic radiation force, but a lingering question that remains is how important viscosity of the blood and/or embolus is to the process. We implemented both inviscid and viscous models for acoustic radiation force on a sphere immersed in a fluid. We found that for this specific application, the inviscid model seems to be sufficient for predicting acoustic force upon emboli when compared with the chosen viscous model. Thus, the much simpler inviscid model could be used to optimize experimental techniques for ultrasonic emboli removal. (E-mail: cara.ac.leckey@nasa.gov) Published by Elsevier Inc. on behalf of World Federation for Ultrasound in Medicine & Biology.

Key Words: **Microemboli, Cardiopulmonary bypass, Acoustic radiation force.**

INTRODUCTION

Emboli in the form of air bubbles and artery wall plaque can enter the blood stream during cardiac surgery. The relationships between increased embolic load to the brain and postoperative neurocognitive decline have been a concern for the past few decades (Shann et al. 2006). During the past 15 years, numerous studies have been published linking neurocognitive decline to emboli (Pugsley et al. 1994; Clark et al. 1995). Reports have shown long-term postoperative neurocognitive impairment as high as 30% in coronary artery bypass graft surgery (CABG) patients (Gunaydin 2008). Although recent reports clearly show that the direct relation between embolic load and cognitive impairment is still unresolved, removal of emboli from cardiopulmonary bypass (CPB) circuits appears at the present to be a valid precaution (Shann et al. 2006; van Dijk et al. 2007). Arterial line filters are currently used to stop emboli in CPB circuits from passing back into the body during surgery. However, the pores of arterial line filters are only 25 to 40 μm in diameter (Barak and Katz 2005; Shann et al. 2006). Emboli smaller than the pore diameter can pass through the filters and make their way toward the brain. In addition, if the embolic load is high, larger emboli can pass through the filters (Barak and Katz 2005). It is important to monitor emboli load pre-filter because a warning of increased load allows the medical team to eliminate emboli sources. Previous work in the field has shown that broadband ultrasound pulses can be used to detect, size and track emboli using backscatter echoes (Lynch et al. 2007; Lynch and Riley 2008).

Via acoustic radiation force, ultrasound may also be used for thorough, real-time removal of gas and lipid emboli from extracorporeal circuits, including emboli smaller than 30 μm. Gas bubble removal from CPB circuits using acoustic radiation force was proposed as early as two decades ago but has yet to be implemented (Schwarz et al. 1992). A lipid embolus is a good approximation of artery plaque composition which generally has a high-lipid content unless extreme calcification has occurred (Romer et al. 1998). The acoustic force could push emboli out of the blood flow path. Removing emboli from the bloodstream would decrease the risk of micro-emboli traveling to the brain. Development of this technique would require precise knowledge of the behavior of radiation force as a function of ultrasound frequency to optimize the removal process. We have implemented

Address correspondence to: Cara A. C. Leckey, NASA Langley Research Center, MS 231, Hampton, VA 23681 USA. E-mail: cara.ac.leckey@nasa.gov

viscous and inviscid models to predict the acoustic radiation force exerted by incident plane progressive waves upon freely suspended air and plaque emboli in blood.

Acoustic force

Acoustic radiation force is the force exerted upon an object by an incident sound wave. Over the past century, numerous authors have modeled acoustic radiation force. In the literature, there are two primary formulations for the acoustic radiation force upon spheres. One is an inviscid model that appeared in the literature as early as the 1930s in a paper written by King (1934). King's work is focused on calculating the force of plane progressive and plane stationary waves upon a rigid sphere immersed in an inviscid fluid. Yosioka and Kawasima expanded King's derivation to include the effects of plane progressive or standing waves incident upon a compressible sphere in an inviscid fluid Yosioka and Kawasima (1955). The inviscid model for incident plane progressive waves has been studied extensively and matches well with experimental results (Hasegawa and Yosioka 1969, 1975). The second model includes the effects of viscosity and was derived in the 1990s by A.A. Doinikov (1994a, 1994b). Doinikov derived equations for the force of plane progressive and standing waves upon a compressible sphere immersed in a viscous fluid. In this work we implement the both the inviscid and viscous acoustic force equations. To our knowledge, Doinikov's viscous force model has not been implemented until now. The lack of published plots using the viscous model is likely due to the large computational power required by the complicated equations. When the compressible-inviscid case is extended to include viscosity, the complexity of the derivation increases in a number of ways: (1) a shear wavenumber must be included both outside and inside the sphere, (2) compressional and shear wavenumbers are now complex and depend on density, speed of sound, frequency, and viscosity and (3) viscous terms must be included in the stress tensor. The equations for radiation force in a viscous and inviscid fluids are shown below. We will not outline the derivations as they are rather lengthy and can be found in (Hasegawa and Yosioka 1969; Doinikov 1994a).

Theory

The general equation for the time average acoustic radiation force of a sound wave upon on an object in a fluid is

$$\vec{F} = \oint \langle \underline{\boldsymbol{\sigma}} \cdot \hat{n} \; dS \rangle, \tag{1}$$

where $\langle\rangle$ denotes the time average of the quantity enclosed over one cycle, $\underline{\boldsymbol{\sigma}}$ is the stress tensor, $\hat{n}$ is an outward pointing unit vector normal to the surface and the integral is taken over the surface area of the sphere. In its general form, the stress tensor can be written as Varadan et al.(1991)

$$\begin{aligned}\underline{\boldsymbol{\sigma}} = -p\,\underline{I} + \eta\left(\nabla\vec{v} + \vec{v}\nabla - \frac{2}{3}\underline{I}\,\nabla\cdot\vec{v}\right)\\ +\xi\,\underline{I}\,\nabla\cdot\vec{v},\end{aligned} \tag{2}$$

where p is pressure, $\vec{v}$ is fluid velocity, η is shear viscosity, ξ is bulk viscosity and I is the identity matrix.

For an inviscid fluid the viscosity and bulk viscosity go to zero in eqn (2). Following Hasegawa's notation, the equation for radiation force upon a sphere due to an incident plane wave in an inviscid fluid is (Hasegawa 1977):

$$F = -2\pi\rho_1^{(0)} \sum_{n=0}^{\infty} (n+1)(\zeta_n + \zeta_{n+1} + 2\zeta_n\zeta_{n+1} + 2\chi_n\chi_{n+1}), \tag{3}$$

where we have assumed unit amplitude, force is in the direction of propagation, $\rho_1^{(0)}$ is equilibrium density, and

$$\zeta_n = \frac{-G_n^2}{G_n^2 + H_n^2}, \quad \chi_n = \frac{-G_n H_n}{G_n^2 + H_n^2}, \tag{4}$$

$$Gn = (L_n - n)j_n(k_1 a) + (\mathrm{k_1 a})\mathrm{j_{n+1}}(\mathrm{k_1 a}), \tag{5}$$

$$H_n = (L_n - n)y_n(k_1 a) + (\mathrm{k_1 a})\mathrm{y_{n+1}}(\mathrm{k_1 a}). \tag{6}$$

In these equations the compressional wavenumber in the inviscid surrounding fluid is simply $k_1 = \omega/c_1$, a is the sphere radius, and $j_n(z)$ and $y_n(z)$ are spherical Bessel functions of the first and second kind. L_n for a fluid sphere is

$$L_n = \frac{\rho_1^{(0)}(k_2 a)}{\rho_2^{(0)} j_n(k_2 a)}[n j_n(k_2 a) - (k_2 a) j_{n+1}(k_2 a)], \tag{7}$$

where $\rho_2^{(0)}$ is the equilibrium density of the sphere material and the compressional wavenumber, k_2, is defined as $k_2 = \omega/c_2$, where c_2 is the compressional wave speed in the sphere. Our numerical implementation of the inviscid equations was checked by direct comparison with the validated published plots from (Hasegawa and Yosioka 1969, 1971; Hasegawa, 1977). We found that our plots of the radiation pressure function, Yp, match Hasegawa's plots exactly (Leckey 2011). We were, therefore, able to establish confidence in our implementation of the inviscid model.

The inviscid model is nearly always used in the literature to calculate acoustic force for various applications, however, since blood is a viscous fluid the simple inviscid