Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 87 (2016) 93 – 98

Physics Procedia

44th Annual Symposium of the Ultrasonic Industry Association, UIA 44th Symposium, 20-22 April 2015, Washington, DC, USA and of the 45th Annual Symposium of the Ultrasonic Industry Association, UIA 45th Symposium, 4-6 April 2016 Seattle, Washington, USA

An ultrasonic caliper device for measuring acoustic nonlinearity

Christopher Hunter[a], Oleg A. Sapozhnikov[a,b], Adam D. Maxwell[a,c],
Vera A. Khokhlova[a,b], Yak-Nam Wang[a], Brian MacConaghy[a], Wayne Kreider[a,*]

[a] *CIMU, Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98105, USA*
[b] *Physics Faculty, Moscow State University, Leninskie Gory, Moscow 119991, Russia*
[c] *Department of Urology, University of Washington School of Medicine, 1959 NE Pacific Street, Seattle, WA 98195, USA*

Abstract

In medical and industrial ultrasound, it is often necessary to measure the acoustic properties of a material. A specific medical application requires measurements of sound speed, attenuation, and nonlinearity to characterize livers being evaluated for transplantation. For this application, a transmission-mode caliper device is proposed in which both transmit and receive transducers are directly coupled to a test sample, the propagation distance is measured with an indicator gage, and receive waveforms are recorded for analysis. In this configuration, accurate measurements of nonlinearity present particular challenges: diffraction effects can be considerable while nonlinear distortions over short distances typically remain small. To enable simple estimates of the nonlinearity coefficient from a quasi-linear approximation to the lossless Burgers' equation, the calipers utilize a large transmitter and plane waves are measured at distances of 15-50 mm. Waves at 667 kHz and pressures between 0.1 and 1 MPa were generated and measured in water at different distances; the nonlinearity coefficient of water was estimated from these measurements with a variability of approximately 10%. Ongoing efforts seek to test caliper performance in other media and improve accuracy via additional transducer calibrations.

Keywords: acoustic calipers, liver transplant, nonlinear acoustics, B/A

---

1. Introduction

In diagnostic and therapeutic applications of medical utrasound, there is a general need for knowing the acoustic properties of tissue. Although many measurements have been made (Duck, 1990), available data are not consistent

---

*Corresponding author
Email address: `wkreider@uw.edu` (Wayne Kreider)

doi:10.1016/j.phpro.2016.12.015

and were compiled from studies using different measurement techniques. Beyond a general interest in the acoustic properties of tissue, we are pursuing a specific project to use ultrasound for characterizing donor livers for transplantation. Despite efforts to expand the donor pool there is still a discrepancy between the availability of transplantable organs and the need for them (Orman et al., 2013; Wertheim et al., 2011). In particular, hepatic steatosis (fatty liver disease) is considered a primary risk factor in transplanted livers and can therefore result in organ nonuse (McCormack et al., 2011; Spitzer et al., 2010). Although there is interest in expanding the donor pool by using organs with a higher degree of steatosis, consistent measurements of steatosis are typically not available. The current gold standard for potential donor liver evaluation is histological biopsy, which is an inherently subjective and invasive process; moreover, because biopsies are often not performed, decisions are often based on visual inspection by the surgeon.

We seek to develop an ultrasonic caliper device capable of quantitatively characterizing liver tissue. The potential of such measurements was investigated by Sehgal et al. (1986), who used sound speed and nonlinearity measurements to infer the fatty and non-fatty composition of liver tissue. To build on this approach, we also aim to quantify the amount of fat that exists in small or large droplets. Small, sub-micron sized droplets (*i.e.*, microsteatosis) are metabolically different from large droplets and potentially much less problematic in transplants. Toward this end, dispersion calculations (Evans and Attenborough, 2002) for ultrasound propagation in a medium comprising fatty and non-fatty components suggest that micro-steatosis may be detectable from attenuation measurements at sub-megahertz frequencies. To measure ultrasonic sound speed, nonlinearity, and attenuation in transplant applications, we propose to develop a transmission-mode caliper device such as the one pictured in Fig. 1. Notably, this basic hardware design is comparable to that used for *in vivo* nonlinearity measurements by Zhang and Dunn (1987).

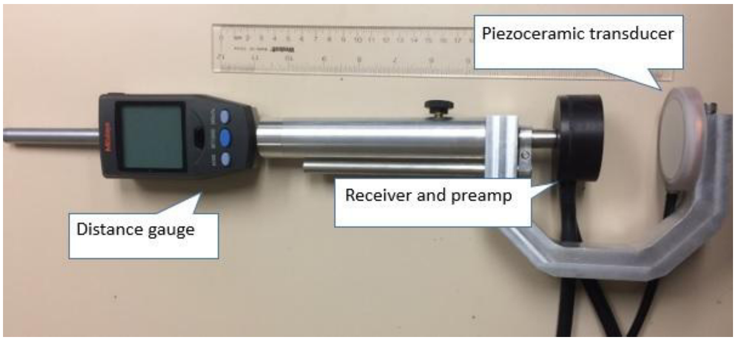

Fig. 1. Photo of the proposed hardware for an acousic calipers.

2. Methods

Nonlinear acoustic propagation is a well-known phenomenon characterized by distortion of the shape of an acoustic waveform as it propagates in a nonlinear medium. The nonlinearity comprises convective nonlinearity as well as the impact of higher-order terms in the medium's equation of state, which cause parts of the waveform at higher pressures to propagate faster than those at lower pressures (Hamilton and Blackstock, 1998). Previous work by Bjørnø (1986) suggests an estimation accuracy on the order of ±5% can be achieved for the coefficient of nonlinearity for biological fluids. There are two basic approaches for such measurements: the thermodynamic method and the finite-amplitude method. Though the thermodynamic method is considered to be more accurate, it is not viable for measuring tissues *in vivo*. Here we use the finite-amplitude method, which relies on a calibration of source output and direct measurement of waveform distortion over a known propagation distance. Typically, the finite-amplitude approach is implemented by using the amplitude of the second-harmonic component of the distorted waveform to quantify the nonlinearity of the medium.

For the present application, a key challenge is to accurately measure nonlinearity over a relatively short propagation distance (15–50 mm) using a transmitting transducer with a fundamental frequency below 1 MHz. Our basic approach is to use a large transmitting transducer such that measurements can be made in the plane-wave regime and diffraction effects can be ignored. However, for the geometry and frequency of interest, the plane-wave regime will be realized for only a few acoustic cycles, during which the real transducer output will be transient in nature.