Cure State Sensing of Polymethylmethacrylate Using a Vibrating Axial Probe

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INTRODUCTION: In 1941, polymethylmethacrylate (PMMA) was first used in medicine as a dental prosthetic, and then subsequently as a substitute for bone in cranial surgery. It was in the late 1950s when its use widened into orthopedics for the fixation of total joint implants. Since that time, PMMA has become widely used and is the gold standard for the fixation of orthopedic implants in surgery. Due to PMMA's properties of being soft and pliable, it is used as grout to fill small interstitial spaces in the bone and implant to provide mechanical fixation. For that reason, knowing the viscosity of PMMA during surgery is important; if it is too thin, it will flow out of the interstices and if it is too thick, the PMMA will not enter the interstices. In either case, the result is the poor fixation of the implant. We present the development of a new type of bulk-scale axially vibrating sensor to monitor the in vitro state of cure in PMMA cement. The sensor probe uses a one-dimensional axially vibrating probe to act as a simple harmonic oscillator to sense viscosity changes. This ability would enhance the probability of secure fixation and potentially decrease the risk of revision surgery due to mechanical loosening.

METHODS: A probe shaft was mounted to a PZT transducer, which was connected to an audio voice coil transducer and USB Audio interface. The apparatus would monitor resonance frequency during acoustic resonance sweeping. Transducers were connected to an audio power amplifier, which was connected to computer using REW Acoustic Software. 5 g of Bosworth Duz-All® powder and 5 mL Jet™ Liquid curing acrylic resin were mixed in the sample holding container. Acoustic sweep trials using 20 to 20k Hz trials were accomplished using REW software. Resonance frequency was measured at 10-second intervals. The sensor was then used to measure the acoustic spectra for 19 identical PMMA mixtures undergoing the cure process. Viscosity, proportional to the resonance frequency (Hz) of the sample vial in its system, was recorded as a function of time. PMMA samples (4.00 g total) were all prepared in the same way by using a precision electronic scale (Weigh Gram, WG-220) to measure a 50:50 by weight mixture of the methyl methacrylate monomer (MMA) (Lang Dental Mfg. Co., Jet Liquid Ref 1404); the PMAA powder (Bosworth, 166264W Duz-All White Powder) was thoroughly mixed together in a disposable aluminum weigh boat using a disposable plastic spatula for a period of 45 s. MMA monomer liquid was dispensed with a disposable LDPE pipette directly onto the weigh boat sitting on the precision scale, and powder PMMA was dispensed using a stainless-steel spatula. The total mass of PMMA was measured to a precision of 0.01 g. Blended PMMA mixture was then poured into the HDPE sample container, fitted with an integral snap-top lid that had been predrilled with a 5 mm probe access hole. The sample container was then placed on the gauge blocks on top of a tacky 1 mm thick silicone adhesive pad to prevent the sample container from rattling and thus contributing to noise in the signal. A series of 22 separate tests were conducted to measure the resonance spectra of the sensor probe interacting with the sample of PMMA. The sensor probe was attached to a 15 mm cross-section aluminum T slot channel rail system to provide a frame for holding the sensor probe tip above the sample in a consistent manner. The sample of PMMA was placed on a stack of gauge blocks resting on the frame to maintain a fixed distance of 5 mm from the probe tip beneath the surface of the PMMA mixture. A series of acoustic excitation sweeps were taken at approximately 1 min intervals, and the raw time series data were collected and processed by software (REW) using an FFT with 8192 sample points using a Blackman–Harris window filter function to provide spectra of the signals from the PZT transducer.

RESULTS: The measurement of the vibrating axial sensor's acoustic spectra in PMMA undergoing curing can be described by a damped harmonic oscillator formalism and resonant frequency (ca. 180 Hz) shift can be used as an indicator of curing progress, with shifts to the blue by as much as 14 Hz. The resonant frequency peak was measured in 19 different 4.0 g PMMA samples to have a rate of shift of 0.0462 ± 0.00624 Hz·s−1 over a period of 400 s while the PMMA was in a dough state and before the PMMA transitioned to a hard-setting phase. This transition is unambiguously indicated by this sensor technology through the generation of a distinct circa 5 kHz high-Q under-damped ring-down response.

DISCUSSION: A one-dimensional axially vibrating probe acting as a simple harmonic oscillator can be used to sense viscosity changes. A data analysis revealed positive shifts in the sensor resonance frequency with increasing cure time. This frequency shift rate can be used as a parameter to determine the relative changes in viscosity and can also be used to unambiguously determine if the PMMA sample has reached the final cure state by observing clear ring-down behavior near 5 kHz. This technique has potential uses both with PMMA during other surgeries, as well as with other processes that require a precise knowledge of fluid viscosity. A new axially vibrating sensor based on an audio voice coil transducer and a lead zirconate titanate (PZT) piezoelectric disc microphone was developed as a probe for the measurement of in vitro rheological fluid properties, including curing progress for polymethylmethacrylate (PMMA) mixtures with important uses as bone cement in the field of orthopedics.

SIGNIFICANCE/CLINICAL RELEVANCE: The current standard of care is for the practitioner to palpate a small sample of the PMMA in their hand to determine the firmness or stickiness as a gauge of when the cement is of the right viscosity for use. This manner of testing is inherently inaccurate since the outside environment is significantly different from the in vivo cement environment. Even the warmth of the hand checking the cement changes its cure characteristics. Although studies have shown that there is an optimal viscosity to use the PMMA, the present state of the art amounts to a guess based on the experience of the surgeon. At this time, there is no method or instrument able to determine the viscosity of the PMMA during use in the operating room. The novelty of this sensor technology is that it will permit, for the first time, an interoperative instrument for use by an orthopedic surgeon to measure, in vivo or in vitro, the relative viscosity of a mixture of PMMA that has a ticking expiration clock measured in minutes. We propose a model and technology which now provides a sure way of knowing the PMMA cure state without ambiguity, which can facilitate greater implant accuracy during total joint arthroplasty, potentially mitigating the risk of secondary infections and decreasing the need for revision surgeries.

IMAGES AND TABLES:

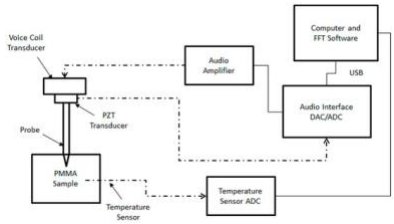

Figure 1: Simplified schematic diagram of the experimental setup. Note that the temperature sensor ADC was connected to the PC for means of power via USB.

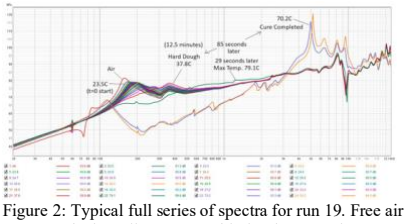

Figure 2: Typical full series of spectra for run 19. Free air spectrum is the yellow curve with the sharp notch at 70 Hz. The temperature starts at 22.7 °C and rises to 29.4 °C in a span of 17 min.

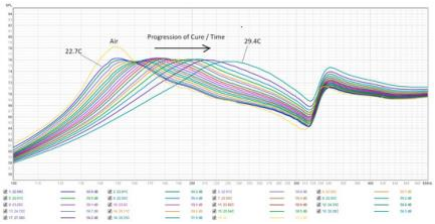

Figure 3: Closeup of spectra from test run 19 going through the curing stage. The corresponding temperatures for each curve are shown in the legend. The elapsed time is 17:02.