Revealing the glass transition in shape memory polymers using Brillouin spectroscopy

Zachary A. Steelman,^{a)} Andrew C. Weems, Andrew J. Traverso, Jason M. Szafron, Duncan J. Maitland, and Vladislav V. Yakovlev
 Texas A&M University, 101 Bizzell St., College Station, Texas 77840, USA

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Emerging medical devices which employ shape memory polymers (SMPs) require precise measurements of the glass transition temperature (T_g) to ensure highly controlled shape recovery kinetics. Conventional techniques like differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) have limitations that prevent utilization for certain devices, including limited accuracy and the need for sacrificial samples. In this report, we employ an approach based on Brillouin spectroscopy to probe the glass transition of SMPs rapidly, remotely, and nondestructively. Further, we compare the T_g obtained from Brillouin scattering with DMA- and DSC-measured T_g to demonstrate the accuracy of Brillouin scattering for this application. We conclude that Brillouin spectroscopy is an accurate technique for obtaining the glass transition temperature of SMPs, aligning closely with the most common laboratory standards while providing a rapid, remote, and nondestructive method for the analysis of unique polymeric medical devices.

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Cardiovascular disease (CVD) is the most common cause of mortality worldwide, with ischemic heart disease and stroke alone accounting for more than a quarter of all deaths.¹ Perhaps the most urgent of CVD conditions is stroke, which affects roughly 800 000 Americans each year and exhibits a 1-year mortality rate of 33%, even with treatment.² To combat this problem, cardiovascular medical devices employing shape memory polymers (SMPs) have shown remarkable potential in benchtop and animal trials, with an eye towards clinical application.^{3,4} Shape memory polymers are useful because they exhibit strain recovery, which allows them to transition between predetermined shapes when actuated by a change in temperature above the glass transition (T_g) temperature of the polymer. This unique property allows for controlled filling of aneurysms to prevent hemorrhagic stroke,⁵ as well as penetration and extraction of clots for the prevention of ischemic stroke.³ While some of these devices are activated by body temperature, many are heated optically using infrared sources delivered via an optical fiber.^{6–8} A precise knowledge of the thermal properties of the specific polymer formulation is then essential to control the actuation of the device in treatment of an ischemic stroke or cerebrovascular aneurysm. Failure to properly characterize the transition temperature of the polymer can alter recovery time or result in premature actuation, which could be lethal in these circumstances.

Though a vital parameter in the theory of soft matter, there is currently no consensus as to the origin of the glass transition.⁹ Several models have been proposed, including entropy theory,¹⁰ the idea of heterogeneity,¹¹ the Dyre shoving model,¹² mode-coupling theory,¹³ and free volume theory,¹⁴ though none provide a complete explanation. Furthermore, few theories even attempt to address the laboratory glass transition, and there exists no complete theoretical basis for

specifying its value. Accordingly, many laboratory methods are used to measure the T_g , each interrogating related but disparate physical processes affected by the glass transition.

The most common method is differential scanning calorimetry (DSC) which measures the amount of energy flux necessary to maintain a certain temperature of a sample. DSC detects free volume changes by noting variances in the flux which correspond to the rearrangement of molecules during a phase change.¹⁵ While arguably the most accepted method, the T_g determined by DSC is dependent on the heating rate, is a destructive technique, and can be highly dependent on and limited by solvent-polymer interactions.^{16–18} As a destructive method, completed devices must be sacrificed to determine the T_g , and a single device cannot be simultaneously tested and employed clinically. Additionally, polymers may yield multiple T_g values depending on their solvent interactions and the polymer architecture, which may not directly correspond to the temperature at which shape recovery is known to occur.^{19–21} Dynamic mechanical analysis (DMA), another common technique, applies a stress or strain as a function of frequency or temperature to determine the elastic and viscoelastic behaviors of polymers.²² This method allows for analysis of the relaxation behaviors of materials over a temperature range. In polymers, the loss tangent ($\tan \delta$) is the ratio of elastic and viscoelastic relaxations, with the maximum value occurring at the T_g and corresponding to the onset temperature of shape recovery in SMPs. A thermo-mechanical rather than solely a thermal method, DMA requires inducing strain in the material, and simple geometries are necessary for the best results.^{23–25} In the literature, there is also a lack of consensus on appropriate parameters which define the glass transition. The maximum loss tangent, maximum loss modulus, and decaying storage modulus, for example, have each been used to characterize the T_g and subsequently the onset temperature of shape recovery.²⁶ Clearly, a different approach which is rapid, nondestructive, enables

^{a)} Author to whom correspondence should be addressed: zachary.steelman@duke.edu

arbitrary sample geometries and volumes, and can accurately assess the glass transition *in situ* is sorely needed.

Optical methods for T_g determination have been proposed previously, though each has practical limitations. Diffusing-wave spectroscopy (DWS) uses correlations in the speckle created by elastic scattering to predict rheologic behavior.²⁷ While effective, DWS is limited to strongly multiple scattering (opaque) media, requires high optical power on the order of 400 mW, and produces very large (10^5 to 10^7 CCD frames) datasets which may be impractical to analyze quickly. DWS also possesses fundamental limits in acquisition time, since the experiment must be conducted over a time scale much longer than the relaxation time in the material, excluding characterization of certain polymer networks, colloidal gels, and glassy materials.²⁸ Confocal microscopy has also been proposed as an alternative method, though this requires the addition and monitoring of well-characterized particles to the sample.²⁹ Furthermore, the need for accurate tracking of particle motion at length scales very near the diffraction limit (~ 200 nm) suggests that this will not be useful *in vivo*. In this work, we propose and validate Brillouin spectroscopy as an alternative method of evaluating the T_g of SMPs intended for medical devices. By probing a photon-phonon interaction, Brillouin scattering gives a rapid assessment of the longitudinal elastic modulus of samples.^{30–36} While Brillouin scattering has been previously suggested for T_g determination of some polymers,^{37,38} earlier studies used a scanning Fabry-Perot interferometric spectrometer which required lengthy acquisition times, often on the order of 10 min for a single spectrum,³⁹ dozens of which are needed to determine the T_g point. In addition, low tolerance for elastic light scattering required that the polymer be polished to an optical quality finish, removing from consideration polymers fashioned into embolic coils or compressed foams for ischemic stroke or aneurism treatment, respectively. Using a virtually imaged phase array (VIPA) spectrometer⁴⁰ and a molecular notch filter to remove the Rayleigh line,⁴¹ Brillouin measurements can now be accomplished with sub-second integration times^{42,43} and unprecedented accuracy.⁴⁴ This allows for high temporal sampling of the Brillouin shift while sweeping the temperature of the sample in time. A sudden change in the slope of this curve is indicative of the temperature of the glass transition,⁴⁵ which can be easily calculated from temperature-dependent measurements of the Brillouin shift. Thus, while early studies have shown that such methods are technically feasible, improved instrumentation which is both robust and simple may lead to widespread adoption of Brillouin scattering as a glass transition metric.

A sample of an aliphatic, crosslinked polyurethane polymer used in these devices was synthesized for use in thermal, mechanical, and scattering analysis. To synthesize the polymer, N,N,N',N'-tetrakis(2-hydroxypropyl)ethylenediamine (HPED, 99%) and triethanolamine (TEA, 98%, Alfa Aesar) were used as the starting tetra-functional alcohol and triol, respectively. 2,2,4-trimethyl hexamethylene diisocyanate (TMHDI, TCI America, a mixture of 2,2,4 and 2,4,4 monomers) and isophorone diisocyanate (IPDI, Sigma Aldrich, 99%) were used as monomers. Proper stoichiometric ratios of the tetra-functional alcohols and triols with diisocyanates were used for synthesis (1:1 ratio of NCO:OH) using

solution polyaddition. Tetrahydrofuran (THF) was added at 10% (wt) to aid in the dissolving of reactants. Solutions were mixed until all components were dissolved and then cast onto silicone trays, de-gassed for 120 s, and placed in a pressure chamber overnight (60 psi), followed by a cure at 60 °C under vacuum for an additional 24 h.

Polymer samples were tested using pre-established protocols for differential scanning calorimetry (DSC, Q200 TA DSC with TA Refrigerated Cooling System 90, TA Instruments, New Castle, DE) and dynamic mechanical analysis (DMA, Q800 TA DMA, TA Instruments, New Castle, DE).⁴⁶ Because the wet T_g is most appropriate for our *in vivo* application, we followed standard protocols for a wet T_g DSC measurement, using a hermetically sealed pan to prevent volatilization. DSC samples were submerged in water at 50 °C overnight, blotted dry, weighed, and sealed in a Tzero pan before being heated from -40 °C to 80 °C at 10 °C per minute. The half-height transition of the DSC thermogram was used to determine the T_g . DMA samples were submerged in a water bath and heated from 0 °C to 100 °C at a heating rate of 2 °C/min, using the compression mode to avoid edge effects. Overnight submersion in water was also performed in the DMA and Brillouin experiments to ensure measurement of the wet T_g .

The Brillouin microscope (Fig. 1) has been described extensively in previous publications.³¹ Briefly, a single mode laser was electronically locked to the D₂ line of Rubidium 85 ($\lambda = 780.24$) and directed by a polarizing beamsplitter through a quarter-wave plate and into an objective lens. The focal plane of the objective was centered approximately 2 mm through a glass-bottomed custom heating cell, fashioned from a 3D-printed reservoir and sealed on the bottom using a microscope slide. A heating element, made by adhering a low-Ohmage resistor to an aluminum block and applying a laboratory DC power supply in the constant current mode, was immersed in the bath as a heat source. An incident power of <20 mW was focused on the sample. The backscattered light was collected and split spectrally using a 785 nm long pass filter to spectrally isolate Brillouin photons. As we have previously reported, our microscope is capable of simultaneously measuring the

FIG. 1. Schematic diagram of the Brillouin microscope. A custom heating cell holds the submerged polymer sample, pressed against the glass bottom to eliminate signal due to water only. Backscattered light is split into distinct Raman and Brillouin spectrometer arms using a long pass filter, LPF. A quartz cell filled with Rubidium vapor ("Rb Cell") is used to filter elastically scattered light to improve the SNR of the Brillouin signal. A VIPA etalon disperses the Brillouin component spectrally across an sCMOS detector array. PBS is a polarizing beam splitter, and $\frac{\lambda}{4}$ is a quarter-wave plate.

Brillouin and Raman spectra from a single optical volume.³¹ The long pass filter efficiently separates the Brillouin signal, which is detuned by only a few GHz, from the Raman photons which are detuned by several THz.

Typically, substantial numbers of elastically scattered photons easily overwhelm the nearby Brillouin signal. For this reason, previous studies utilizing Brillouin light to examine polymers were limited to carefully prepared samples with extremely fine optical smoothness and near-ideal transparency.⁴⁵ In this study, we utilize a Rubidium atomic vapor notch filter with a narrow D₂ absorption line at 780.24 nm in vacuum. The source laser is then electronically locked to the D₂ transition of Rubidium so that the output wavelength and thus the elastically scattered light are strongly absorbed by the Rb vapor, with extinction exceeding −100 dB over a narrow (~500 MHz) bandwidth. In this way, the Brillouin peaks are made clearly visible despite our sample exhibiting an unpolished surface and appearing cloudy to the naked eye. For Brillouin microscopes used in previous polymer T_g studies, it is highly unlikely that a sample of this quality would produce any useable signal. Thus, the use of a Rb vapor notch filter allows for characterization of a much wider range of polymers than any previous implementation of Brillouin spectroscopy.

The unfiltered Brillouin light is injected via a cylindrical lens into a VIPA etalon (Light Machinery, Inc, Free Spectral Range 20 GHz) which provides angular dispersion as a function of frequency shift. The dispersed Brillouin spectrum is then imaged onto an sCMOS detector array (Andor Neo 5.5 sCMOS) for post-processing.

Because the dispersion of VIPA etalons is nonlinear across the camera, care must be taken to ensure that accurate shifts are being measured. Here, we utilize the dispersion relations of the VIPA etalon for precise determination of the Brillouin shift. The intensity of the VIPA output can be described under the Fresnel paraxial approximation⁴⁷ by

$$I_{out}(x_F, \lambda) \propto \frac{1}{(1 - Rr)^2 + 4(Rr)\sin^2\left(\frac{k\Delta}{2}\right)} \times \exp\left(-\frac{2f^2x_F^2}{F^2W^2}\right), \quad (1)$$

where $\Delta = 2tn_r \cos(\theta_{in}) - [(2t \tan(\theta_{in}) \cos(\theta_i)x_F)/F] - [(t \cos(\theta_{in})x_F^2)/(n_r F^2)]$. Here, x_F is the lateral displacement across the image plane, λ is the wavelength, R and r are the front and back reflectivities of the VIPA, respectively, k is the wavenumber, f is the focal length of the cylindrical lens, F is the focal length of the imaging lens, W is the radius of the collimated beam prior to the cylindrical lens, t is the thickness of the etalon, n_r is the refractive index inside of the VIPA, and θ_i and θ_{in} are the tilt angle of the VIPA and the internal angle due to refraction, respectively. From the intensity equation, peak transmission occurs when $k\Delta = 2\pi m$, or

$$k \left[2tn_r \cos(\theta_{in}) - \left(\frac{2t \tan(\theta_{in}) \cos(\theta_i)x_F}{F} \right) - \left(\frac{t \cos(\theta_{in})x_F^2}{n_r F^2} \right) \right] = 2\pi m. \quad (2)$$

Using this equation, we can derive an expression for the wavelength difference of two lateral positions in a given free spectral range of the VIPA

$$\Delta\lambda = -\lambda_0 \left[\frac{\tan(\theta_{in})\cos(\theta_i)}{n_r \cos(\theta_{in})} \left(\frac{x_F}{F} \right) + \frac{1}{2n_r^2} \left(\frac{x_F}{F} \right)^2 \right], \quad (3)$$

where λ_0 is the source wavelength, $m\lambda_0 = 2tn_r \cos(\theta_{in})$, and m is the diffraction order. To derive a pixel-to-wavelength mapping, we fit the parameters m and θ_i to the acquired spectrum. A correct fit is one which minimizes the standard deviation of three frequency separations (Stokes to anti-Stokes, Stokes to Stokes, and anti-Stokes to anti-Stokes) across the four free spectral ranges of the VIPA measured on the sCMOS. The Brillouin shift was then extracted using the maximum value of the Brillouin peak, with a rolling average filter (width = 18 pixels) applied to reduce the impact of noise on the peak location. Using this technique, frequency measurements exhibit a typical standard deviation on the order of 2 MHz, and the typical diffraction order is $m \approx 18,636$ given a 5 mm thick VIPA, $n_r = 1.4678$ and $\lambda_0 = 780.24$ nm.

The glass transition temperature can be derived from a plot of Brillouin shift as a function of temperature by looking for an abrupt change in slope. To remove any bias caused by nonlinear heating and sampling, the sample points were filtered to include only one measurement every 0.5 °C, chosen as the median data point within each half-degree region. To find the local slope of the temperature-Brillouin curve, a 5-sample rolling derivative was calculated using the slope of five data points around each sample, corresponding to a temperature range of ± 1 °C. The temperature-Brillouin curves, along with their rolling derivatives for the identification of T_g, are shown in Fig. 3.

The results of the DMA analysis are summarized in Fig. 2. DMA users generally report one or more of three parameters: Storage Modulus G' , Loss Modulus G'' , or loss tangent $\tan\delta = G''/G'$. The T_g was determined according to each of these parameters as either (1) the inflection point of the storage modulus curve, (2) the global maximum of the loss modulus curve, or (3) the global maximum of the loss tangent, respectively. Each of these is a common metric reported for characterizing polymer thermal properties.²⁴ The range of T_g values for each of these measurements, both heating and cooling ($N \geq 4$), is shown as a shaded region in Fig. 2. Because DSC curves are common, the curves themselves are not included in this paper, but instead their results are summarized in Fig. 3 along with the DMA and Brillouin results for comparison. From the same bulk material as the samples characterized by DSC and DMA, SMP samples were placed in a water bath and frozen. The frozen polymer was then heated from −20 °C to 45 °C using a custom heating element. Brillouin measurements were made through the bottom of the water bath, through an optical window created from bonding a microscope slide to a 3D-printed heating cell using a waterproof epoxy, and simultaneous temperature measurements were made using a K-type thermocouple. Brillouin spectra were taken continuously during the heating process, with an integration time of 15 s to maximize SNR of the Brillouin signal. The resulting data were filtered to account for nonlinear heating and plotted against temperature. The most abrupt change in the slope of this line occurs at the glass transition temperature of the polymer. This point was calculated, and the result was compared with the results from the DMA and DSC analysis.

FIG. 2. DMA curves for the SMP showing storage modulus (top row), loss modulus (middle row), and $\tan \delta$ (bottom row), all vs. temperature. Both heating (left, red) and cooling (blue, right) are included to show hysteresis effects. T_g range is shown as a shaded region (mean $\pm$ SD) to show variability between common glass transition metrics.

FIG. 3. (Top Left) Brillouin shift measurements of the SMP polymer versus temperature over the glass transition. The T_g is readily identified at 21.91°C by a substantial discontinuity in the slope of the temperature-Brillouin curve. (Bottom Left) Validation of our technique by measuring the freezing temperature of water molecules which have permeated the polymer. As expected, a sharp slope is observed at $T \sim 0^{\circ}\text{C}$. (Right) A comparison of DMA-derived T_g (by parameter) along with the transition as measured using DSC and Brillouin spectroscopy. The Brillouin-derived T_g agrees best with DSC and the most commonly used DMA parameter ($\tan \delta$) with less agreement among less common parameters. Heating and cooling are shown for DMA measurements to show hysteresis. Because SMPs are activated by heating in a medical context, Brillouin shift measurements were taken during heating only.

To verify the synchronicity between our thermocouple and spectrometer, we examined the Brillouin shift of our polymer sample in a region spanning -10°C to 10°C . Because our polymer was submerged in water overnight, we expected permeating water molecules to freeze at 0°C , drastically altering the Brillouin shift of the bulk sample. As expected, a sharp drop in the slope of the Brillouin-temperature curve occurred near 0°C , with a local minimum of $-0.12\text{ GHz}/^{\circ}\text{C}$ at 0.07°C . This tiny error falls well within the accuracy of K-type thermocouples ($1\text{--}2^{\circ}\text{C}$) and validates the accuracy of our measurements.

Brillouin spectroscopy has proven to be an effective method for determining the T_g of these shape memory polymers. As shown in Fig. 3, the slope of the temperature-Brillouin curve exhibits a strong extremum of $-0.005\text{ GHz}/^{\circ}\text{C}$ at 21.9°C ,

indicating that the Brillouin-derived T_g falls squarely between the T_g calculated from DSC ($19.1 \pm 1.4^{\circ}\text{C}$) and the maximum loss tangent from DMA ($24.6 \pm 2.4^{\circ}\text{C}$), which are the two most common glass transition metrics. Brillouin scattering measurements compare less favorably against the less common DMA metrics of maximum loss modulus ($17.2 \pm 1.8^{\circ}\text{C}$) and decaying storage modulus ($30.0 \pm 2.0^{\circ}\text{C}$) which have been suggested as alternatives to the use of $\tan \delta$ for more accurately modeling the T_g in some polymer species.

While the Brillouin shift is proportional to the square root of the elastic modulus, the Brillouin linewidth is related to the acoustic attenuation coefficient and is proportional to the loss modulus, albeit in the GHz frequency range. Unfortunately, we did not observe a sharp shift in the Brillouin linewidth near the glass transition point. This could

be expected, however, as our observed loss modulus varied smoothly as a function of temperature (Fig. 2) during DMA.

While we have demonstrated the utility of Brillouin spectroscopy for T_g determination of SMPs, it is important to acknowledge the limitations of the technique. The necessity of a high-quality source and detector pair may present a cost-concern for some users. Furthermore, the use of a water bath for uniform sample heating fundamentally limits the acceptable range of temperatures ($<100^\circ\text{C}$) which can be examined. An improved sample chamber with rapid, uniform heating and a broad temperature range will improve the utility of this technique.

In this work, we maximized the integration time of the detector (15 s), resulting in 100% identification of the Brillouin peaks across 850+ individual scans. Recent work from our group demonstrated the ability to sense the Brillouin shift as quickly as 50 ms,⁴⁸ suggesting that the theoretical speed of T_g determination is limited by the maximal rate of uniform heating rather than the detector integration time. Because our thermocouple was positioned millimeters from the focal region of the objective lens, we severely restricted our heating rate to $0.3^\circ\text{C}/\text{min}$ to ensure homogeneous temperature throughout. This resulted in a sampling rate of ~ 13.2 samples/ $^\circ\text{C}$, which was then filtered to 2 samples/ $^\circ\text{C}$ as described in previous paragraphs. Future miniaturization of both the sample and the heating system will allow for uniform temperature distribution, permitting characterization of the glass transition in under ten minutes.

To summarize, Brillouin spectroscopy has proven an effective method of measuring the glass transition of shape memory polymers for use in medical devices. By sweeping the temperature of the sample and searching for a slope change in the Brillouin shift as a function of temperature, SMPs of arbitrary shapes, sizes, and volumes can be characterized without any sample preparation, destruction, or mechanical stress. These results suggest Brillouin spectroscopy as an ideal method of evaluating the T_g of SMPs for use in medical devices. While this study was limited to benchtop evaluation, future work could involve collection of the Brillouin-scattered light from the optical fiber used during device actuation, allowing for real time monitoring of phase transformation *in vivo*. Brillouin spectroscopy has the potential to become a powerful tool for medical device engineers as the use of shape memory material devices becomes widespread.

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