Effective targeted drug delivery using stable ultrasound-triggered nanocarriers

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Selective delivery of concentrated medication into specified targets would realize the promise of effective personalized medicine with minimal side effects. Low-intensity ultrasound provides noninvasive and practical means to deliver drugs from nanocarriers selectively into its focus. However, which nanocarriers and ultrasound parameters can provide effective and safe drug delivery has been unclear. We found that nanocarriers with highly stable perfluorocarbon cores mediate effective release so long as they are activated by ultrasound of relatively low frequencies. We confirmed the safety of these nanocarriers in non-human primates. This study guides the formulation and release parameters for effective and safe drug delivery into specific parts of the body or brain regions.

Introduction

Treatments of mental, neurological, and other disorders are often curbed by intolerable side effects or low effectiveness of drugs.[1–7] Consequently, millions of patients remain resistant to treatments and suffer from poor quality of life. There is a critical need for approaches that deliver medication selectively into the desired target at a high concentration while sparing surrounding tissues.

Pioneering work in this domain devised temperature-sensitive liposomes[8] that can be activated by heat or radiation. However, localized heating at depth has been challenging to achieve safely and in a controlled manner. Due to this issue, recent efforts have shifted to using low-intensity ultrasound as a safe and practical form of energy for localized drug release. Ultrasound can be remotely focused into a biological target at depth. Impacting circulating drug carriers, ultrasound triggers targeted release with minimal off-target effects (Fig. 1).

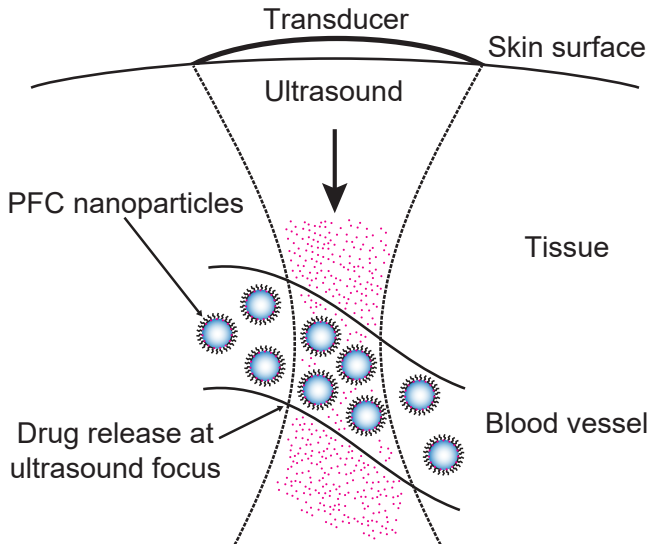

Figure 1. Controlled drug release in a specific body location. Drug-filled biodegradable nanoparticles are introduced into the circulation. Brief pulses of focused, low-intensity ultrasound are applied from the outside of the body using a standard transducer. At the ultrasound target, the focused pressure wave impacts the nanoparticles, which leads to a release of the drug specifically at the target and not elsewhere.

Several groups have shown that ultrasound can trigger drug release from nano-sized structures stabilized with biocompatible shells.[9–21] These nano-sized structures have been commonly filled with perfluorocarbon (PFC) cores. PFCs are highly inert and bestow the resulting nanoparticles with sensitivity to ultrasound. When exposed to ultrasound, the PFC core has been hypothesized to change phase from liquid to gas, greatly expanding in

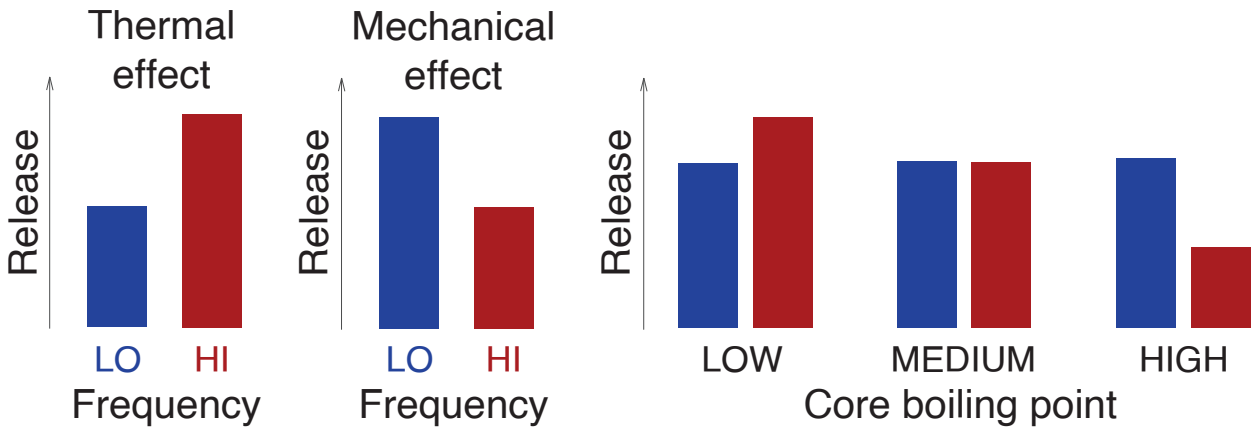

Figure 2. Study design and predictions. The release should increase/decrease with the ultrasound frequency under a thermal/mechanical effect (left). A thermal effect, such as the predominantly hypothesized phase change, should be accentuated by PFCs with lower boiling points (right, red).

volume, and thus mediating drug release.[13,22–25] Harnessing this understanding, a majority of previous studies used nanoparticles with PFC boiling points below body temperature.[9–14,16–20,26] However, these nanocarriers have suffered from instability issues, which has hampered successful translation. For instance, the FDA clearance of PFC-based applications has been limited to PFCs with high boiling points.[27,28] Nonetheless, such nanoparticles have provided relatively ineffective release.[15,21] In this study, we tested whether such nanoparticles could be activated with ultrasound of particular parameters. If so, the specific conjuction of nanoparticle formulation and ultrasound parameters could provide remotely controlled drug delivery that is both effective and safe.

We based this study on two hypotheses. First, drug release from PFC-based nanoparticles may involve mechanical or thermal effects.[13,29–31] The ultrasound frequency can engage these two mechanisms differentially, with high frequencies more likely to engage thermal mechanisms by depositing more energy at the target. Low frequencies are more likely to induce mechanical effects (Fig. 2, left). Second, according to the predominant hypothesis of release, ultrasound delivered at the target induces vaporization of the PFC core.[13,22–24] This implies that the PFC boiling point should be inversely related to release effectiveness and that this effect will be mainly observed at high ultrasound frequencies (Fig. 2, right).

Results

In vitro ultrasound-triggered drug release

We prepared PFC-based, copolymer-stabilized nanoparticles using a similar approach as described in previous studies (see Methods for details). We loaded the nanoparticles with the neuromodulatory drug propofol[16,32] and quantified the effectiveness of its release using an approach described previously in which drug is released from the nanoparticles into an organic solvent.[17] Uniquely, we tested how the critical component of the nanoparticle—its core—governs the amount of drug released as a function of specific ultrasound parameters. Specifically, we tested the release effectiveness of three different PFC cores—perfluoropentane (PFP), decafluoropentane (DFP), and perfluorooctylbromide (PFOB). These PFCs have boiling points of 29°C, 55°C, and 142°C, respectively. Nanoparticles with these cores had comparable sizes: mean±SD of 543.3±23.7, 550.8±91.7, and 473.0±28.4 nm for PFP, DFP, and PFOB-based nanoparticles, respectively.

We used an ultrasonic transducer capable of operating at both low (300 kHz) and high (900 kHz) frequencies focused on vials containing the nanoparticle solutions.[33] We found (Fig. 3, left) that ultrasound of low frequency (300 kHz) triggered more drug release from the nanoparticles than ultrasound of high frequency (900 kHz). The

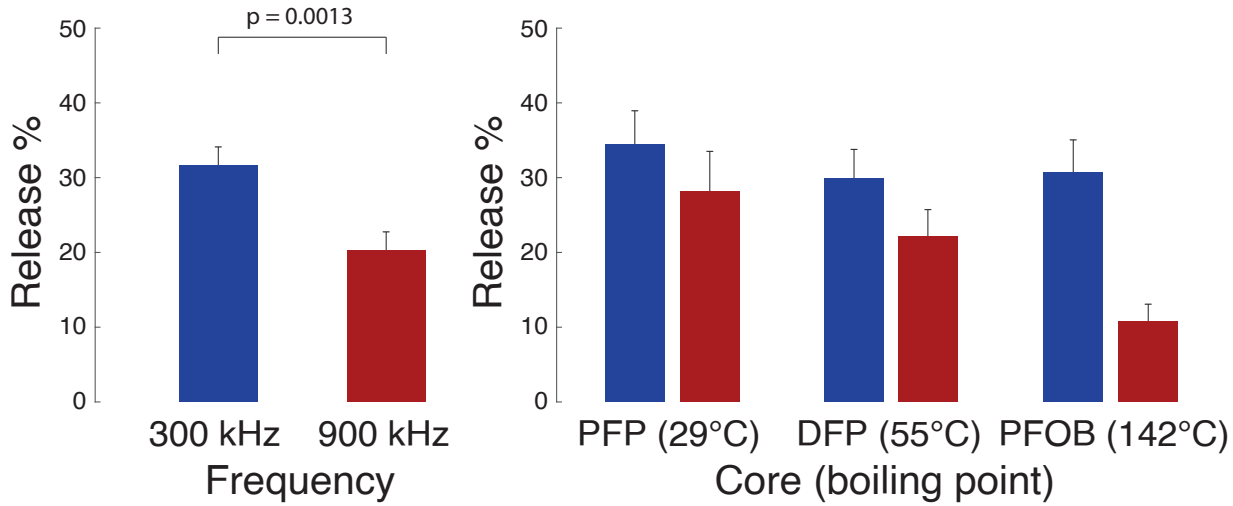

Figure 3. Release from nanoparticles with distinct cores under two ultrasound frequency modes. Mean±s.e.m. propofol release relative to the amount encapsulated (see Methods for details) for the two ultrasound frequencies (left, combined across all cores) and the three cores (right) tested. The ultrasound was delivered in 100 ms pulses repeated 60 times over the period of 1 minute. The p-value denotes the significance of a two-sample two-sided t-test. A complete statistical analysis of the effects is provided in Table 1.

difference in the percentage of drug released at the two frequencies (31.7% and 20.3%, respectively) was significant when averaged across all cores and ultrasound pressures ($t(130) = 3.3$, $p = 0.0013$, two-sample two-tailed t-test). In line with our hypothesis, we found (Fig. 3, right) that at the higher 900 kHz frequency, the release effectiveness strongly depends on the boiling point of the PFC core. The scaling is in the expected direction—the lower the boiling point of the PFC, the higher the release effectiveness. An omnibus ANOVA model (Table 1) that incorporated all factors tested (core, ultrasound frequency, ultrasound pressure) as well as all possible interactions, detected a significant core × frequency interaction ($F(2,90) = 8.05$, $p = 0.00061$).

The scaling of the release effectiveness by the PFC boiling point (red bars in Fig. 3, right) suggests the engagement of a thermal mechanism at the higher frequency, in agreement with previous propositions.[13,18,23,34] If this is the case, the release should also scale with the average ultrasound intensity I delivered into the nanoparticles. For longitudinal waves, it holds $I = \frac{P^2}{2Z}$, where P is the ultrasound pressure amplitude, and Z is the acoustic impedance of the medium.[35] Thus, a thermal effect scales with pressure squared. We indeed found that the data at 900 kHz showed a quadratic dependence on pressure (Fig. 4, right). Specifically, quadratic fits to the data (solid curves) explained 96.5, 93.5, and 94.8% of the variance in the PFP, DFP, and PFOB data points. In comparison, linear fits only explained 80.3, 80.5, and 69.3% of the variance, respectively. The difference in the mean variance explained by the quadratic and linear fits (94.9% versus 76.7%) was significant ($t(2) = 4.83$, $p = 0.040$, two-sided t-test). In contrast, the lower 300 kHz frequency showed a linear dependence of the release on pressure (Fig. 4, left). A quadratic fit did not significantly ($p > 0.16$) differ from the linear fit in terms of variance explained (89.5% versus 89.3%). The linear dependence on pressure at 300 kHz is consistent with a mechanical rather than a thermal effect (see Discussion for details).

We summarize the effects of the three factors tested (core, ultrasound frequency, and ultrasound pressure) as well as all possible interactions in an omnibus ANOVA model (Table 1). This analysis confirms that both the core and ultrasound parameters (frequency and pressure) are important considerations for effective release. In addition, the factors interact: the selection of a specific core must be performed in conjunction with suitable ultrasound parameters.

From the safety perspective, cores with higher boiling points can be expected to be more stable, thus minimizing

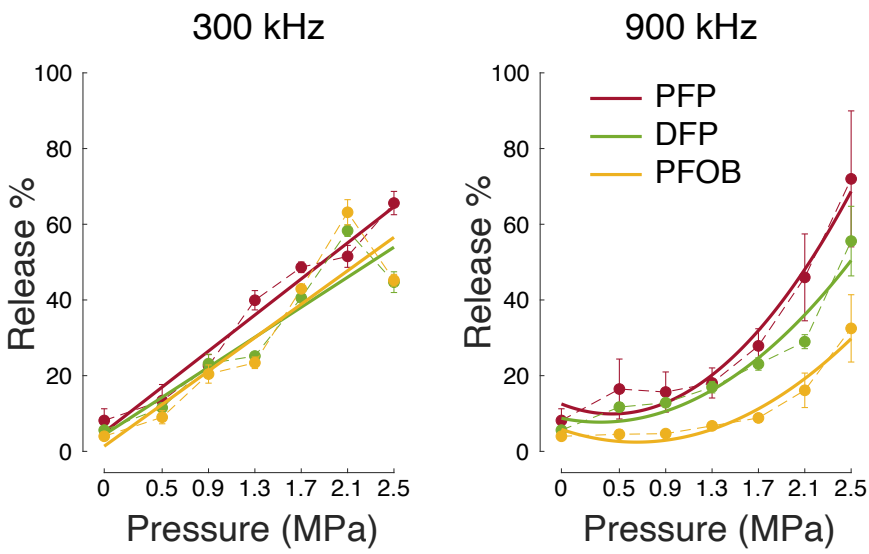

Figure 4. Release across all tested factors. Mean±s.e.m. percentage of the released propofol for the two ultrasound frequencies (left versus right), ultrasound pressure amplitude (abscissa), and the three cores tested (color; see inset). n=3 samples for each core and ultrasound parameter except 0MPa, where n=4. The thick lines represent quadratic fits to the data. Notably, for the 300 kHz data, linear fits were as explanatory as the quadratic fits (see text).

Factor	Significance
Core	**< 0.001**
F	**< 0.001**
P	**< 0.001**
Core × F	**< 0.001**
$F \times P$	**< 0.001**
Core × P	**0.030**
Core × $F \times P$	**0.049**

Table 1. Summary of the effects. The effects of the nanoparticle core, ultrasound frequency (F), and ultrasound pressure (P). These effects were assessed using a three-way ANOVA that featured the three main effects and all possible interactions. Bold entries are significant ($p < 0.05$).

the risk of spontaneous drug release and the potential embolism when injected into the bloodstream. To quantify this notion, we measured the sizes of PFP and PFOB nanoparticles over the course of 24 hours (Fig. 5, left). PFP-based nanoparticles more than doubled in size over the 24 hours, from mean±SD of 428±27 to 914±108 nm ($t(5) = 11.9$, $p < 0.001$, paired two-tailed t-test). In contrast, the size of PFOB-based nanoparticles remained steady, increasing only by 23 nm over the 24 hours (from 421±10 to 444±10 nm; $t(5) = 6.3$, $p = 0.0015$). A repeated measures ANOVA detected a highly significant interaction of PFC core and time ($F(5,50) = 43.54$, $p < 0.001$), confirming that the PFP-based nanoparticles expanded at a higher rate than PFOB-based nanoparticles.

We additionally tested how the stability depends on temperature. Specifically, fresh PFP and PFOB nanoparticles were incubated at 37°C for one hour. We found that temperature did not have a significant effect on the sizes of either PFP ($t(10) = 0.10$, $p = 0.93$, two-sided t-test) or PFOB ($t(10) = -0.48$, $p = 0.64$) particles (Fig. 5, right).

Thus, stable, PFOB-based nanoparticles can be as effective as the relatively unstable PFP-based nanoparticles when driven at a relatively low, 300 kHz frequency. We next assessed the safety, blood clearance kinetics, and organ

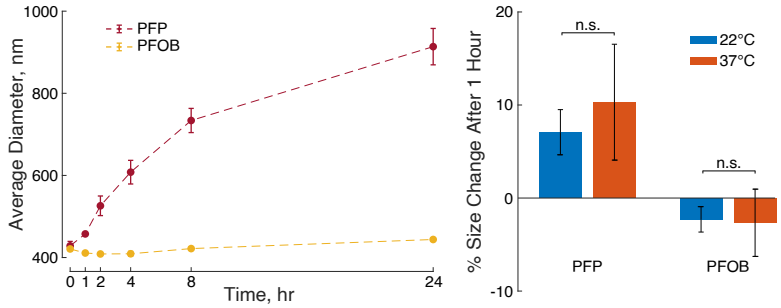

Figure 5. Stability of PFOB and PFP-based nanoparticles over time. Left: Mean±s.e.m. diameter measured at the times as indicated on the abscissa. The times were measured relative to the time of the completion of the nanoparticle production. The data include $n = 6$ samples of PFOB nanoparticles and $n = 6$ samples of PFP nanoparticles. The error bars for PFOB are smaller than the symbols. Right: PFP and PFP nanoparticle average size change after one hour at 22°C or 37°C. There was no significant difference in either case (see text).

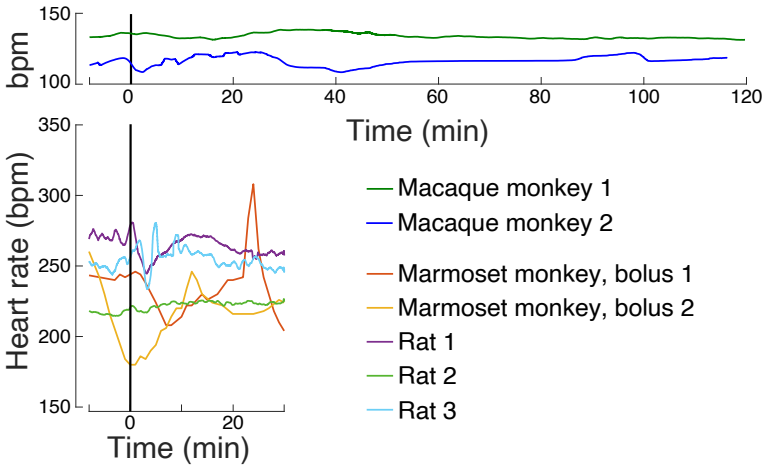

Figure 6. Safety of PFOB-based nanoparticles. The heart rates of two macaque monkeys, one marmoset monkey, and three rats before and after intravenous injections of PFOB-based nanoparticles. The nanoparticles were filled with propofol at a concentration of 1 mg/kg (macaques), 1 mg/kg (marmoset), and 0.5, 1, and 1 mg/kg (rats). The injected volumes were 5 ml (macaque 1), 10 ml (macaque 2), 2 ml (marmoset), and 0.48, 0.53, and 1.1 ml, respectively (rats). In the marmoset, we performed two injections separated by 45 minutes. The EKG was recorded using a portable EKG-monitoring system. The heart rate in the smaller animals (marmoset and rats) tracked the frequently varying levels of isoflurane anesthesia—higher levels led to lower heart rate and reversely.

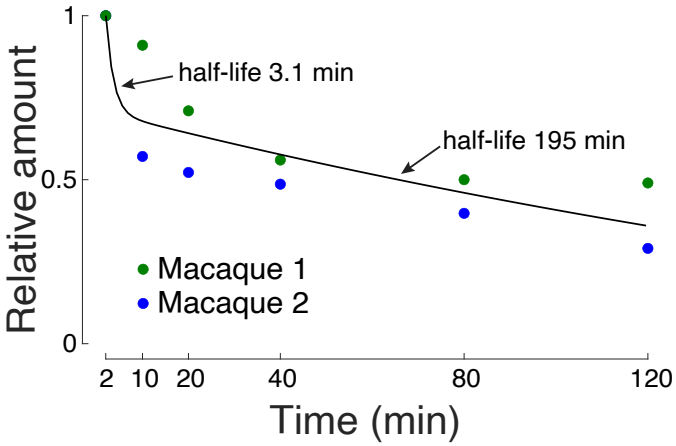

Figure 7. Blood clearance kinetics in macaque monkeys. Relative fluorescence as a function of specific sampling times indicated on the abscissa. The PFOB-based nanoparticles contained propofol and an infrared dye (IR800RS, LI-COR). The nanoparticles were injected via a saphenous vein catheter at time 0 at a volume of 5 ml. Blood samples (1 ml each) were taken at the times indicated on the abscissa and subjected to fluorescence analysis (see Methods). The data points were captured using the superposition of two exponentials. One showed a fast and the other a slow time constant (see inset).

biodistribution of the PFOB-based nanoparticles. These tests involved two macaque monkeys, a marmoset monkey, and 3 Sprague-Dawley rats.

In vivo safety studies

The injection of the propofol-filled PFOB nanoparticles into the bloodstream of the animals did not cause notable changes in vital signs. In particular, Fig. 6 shows the heart rate as a function of time, aligned to the time of the bolus administration. There was no significant difference between the heart rate measured during a 5-minute interval immediately prior to the bolus and the last 5 minutes of the measurements (203.4 compared with 204.5 beats per minute, $t(5) = -0.19$, $p = 0.85$, paired two-sided t-test). The vital signs of the macaque monkeys were particularly steady.

We next investigated the pharmacokinetics of the nanoparticles in the macaque monkeys. To do so, we incorporated a fluorescent dye in the nanoparticles along with propofol (see Methods). While the macaques were anesthetized, we drew blood samples at 2, 10, 20, 40, 80, and 120 minutes following injection. We then quantified the amount of fluorescence from these blood samples relative to the 2 min time point (Fig. 7). This blood clearance curve has an initial half-life of 3.1 minutes followed by a slow decay with half-life 195 minutes, similar to previous reports with PFP-based nanoparticles in rats.[14,30] An accurate fit to these data could only be made by superimposing two exponentials, one with a fast and one with a slow rate of decay (Fig. 7). This suggests that the clearance of the nanoparticles involved two distinct processes or organs.

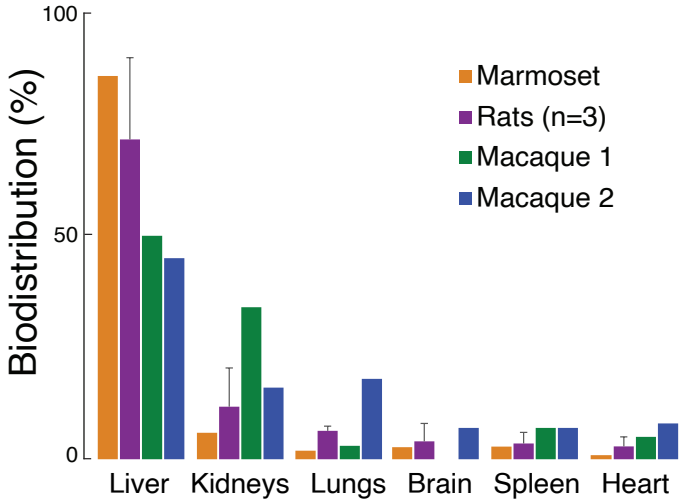

Figure 8. Biodegradation in major organs. Distribution of PFOB-based nanoparticles in major organs of the marmoset and the rats. The presence was assessed using the same infrared dye as in Fig. 7. The figure shows the percentage of total fluorescence (and hence, the relative accumulation of the nanoparticles) measured within the respective organs. The rat data are presented as means±standard deviation.

Finally, we assessed in which organs the PFOB-based nanoparticles degrade. Immediately following the measurements of vital signs (Fig. 6), the animals were sacrificed and their major organs extracted for analysis. The nanoparticles were found predominantly in the liver, in both the primates and rats (Fig. 8). The kidneys were the only other organs where average relative fluorescence exceeded 7%. These findings resemble those obtained using PFP in rats.[16,30]

Discussion

This study investigated the effectiveness and safety of drug release from biocompatible nanoparticles triggered by focused ultrasound. Uniquely, we evaluated the release efficacy from nanoparticles filled with PFCs with distinct boiling points, including boiling points above the body temperature, and investigated the relevant ultrasound parameters that activate them. We found that low ultrasound frequencies (300 kHz in particular) are more effective in mediating release in general and that low frequencies are paramount for effective release from PFCs with a high boiling point. Moreover, we validated the nanoparticles' safety and blood clearance kinetics with a high boiling point in non-human primates and noted no safety issues.

The core has been hypothesized to be a critical factor in governing the effectiveness of ultrasound-based drug release.[11,18,21] Indeed, our 900 kHz data show (Fig. 3, right, red) that at the range of commonly applied ultrasound frequencies ($\geq$ 1 MHz), the core is a key determinant of release effectiveness. We found that the higher the boiling point of the encapsulated PFC, the lower the release effectiveness. This finding is in accord with previous results.[13,18,23,34] Critically, we found that lowering the frequency to 300 kHz increased the release effectiveness at a general, core-independent level (Fig. 3). This effect can also be found in a study that used PFP.[17] The application of low-frequency ultrasound thus opens the path to using high-boiling-point cores (e.g., PFOB) as release actuators. A frequency of 300 kHz provides spatial resolution on the order of several millimeters, which approximates the focal volume of the drug released in tissue by ultrasound.[16,19] While the focal size is larger than ultrasound of higher frequencies, the focal size remains applicable for targets in the brain including the amygdala, which is around 1 cubic centimeter in volume[36] or glioblastoma tumors, which can reach dozens of cubic centimeters.[37]

The majority of studies that applied ultrasound to PFC-based nanoparticles used PFCs with boiling point below the body temperature.[9–14,16–20,26] Although the Laplace pressure of sub-micron particles can effectively increase the boiling point,[38] PFCs with low boiling points may suffer from instability issues, which may raise safety concerns. Our data show that PFP-based nanoparticles not exposed to ultrasound spontaneously increased in size over time, whereas PFOB nanoparticles remained stable (Fig. 5). These data suggest that PFP-based nanoparticles should be

used near-immediately following their production and that their time in the blood stream should be minimized, if possible. Further, low boiling point PFCs can form persistent microbubbles after vaporization by ultrasound.[10,13,20] In fact, with respect to PFC safety, the FDA has thus far approved PFCs with a high boiling point for large-scale use in humans—PFOB in particular. Specifically, PFOB has been used in liter- quantities in humans as agents that deliver oxygen into tissues. The PFOB-based products have included LiquiVent—an oxygen-carrying liquid drug, and Oxygent (both Alliance Pharmaceutical Corporation, San Diego, CA, USA)—a blood substitution agent.[27,28,39] Our finding that PFOB can be used for effective release from nanoparticles at low ultrasound frequencies (Fig. 3, Fig. 4) should mitigate the boiling-point associated concerns. Indeed, we administered PFOB-based nanoparticles to two non-human primates and three rats (Fig. 6) and detected no changes in vital signs.

We evaluated the pharmacokinetics of blood clearance of the PFOB-based nanoparticles in two macaque monkeys. The nanoparticles showed a rapid initial decay with half-life of 3.1 min in the primate and a later phase decay with half-life 195 minutes (Fig. 7). This is on the order of the values reported in other studies that used PEGylated nanoparticles.[14,30] The half-life can be controlled by the type and chain length of the copolymers constituting the shell.[12] Various copolymer shells, and PEG-based copolymers in particular, have been approved by the FDA for a variety of indications.[40]

The monkey blood clearance data were captured with two decaying exponentials (Fig. 7). The dual exponential decay was similar to that reported using PFP-based particles in rats,[14] and suggests an involvement of two distinct clearance processes or organs. In a marmoset, two macaques, and three rats, we found that PFOB-based nanoparticles were primarily degraded in the liver, with notable traces also observed in the kidneys (Fig. 8). This finding aligns with those established using PFC-based nanoparticles in rats.[16,30] Whether these two organs could produce the dual nature of the clearance kinetics observed in Fig. 7 should be tested in future studies. Lungs may also contribute to the clearance.[14,30] In the liter quantities introduced into humans, PFOB can be eliminated from the body in large part through exhalation.[41]

The *in vitro* release data presented here contribute to the understanding of the release mechanism. Thus far, the predominant hypothesis of action has been the vaporization of the PFC droplet upon the impact of focused ultrasound.[11,18,21–24] In this mechanism, the thermal and mechanical aspects of propagating ultrasound exceed the vaporization threshold governed by the PFC boiling point and the Laplace pressure. The PFC core increases in size (up to a 5-fold increase in diameter[38]), which contributes, in addition to any superimposed effects of ultrasound, to the drug release. Indeed, our data at the common range of ultrasound frequencies, 900 kHz, provide two lines of evidence in support of this hypothesis. First, we found that the release increases with decreasing boiling point (Fig. 3, right), as expected from the vaporization hypothesis. Second, thermal energy delivered by ultrasound is known to be proportional to pressure squared.[35] We indeed found a quadratic dependence of the release on pressure (Fig. 4, right).

Our and a previous study[17] suggest that ultrasound of frequencies lower than those in the common diagnostic range may mediate more effective drug release. Lower frequencies are known to accentuate mechanical effects, which can take two forms. First, ultrasound can induce cavitation, the formation of gaseous nuclei from dissolved gasses under the low-pressure epochs of the ultrasound pressure wave.[42] Cavitation can provide useful mechanical forces until it exceeds a threshold at which the formed gaseous nuclei collapse and cause damage.[42] From the FDA's 510(k) Track 3 standpoint,[43] cavitation is unlikely to occur for mechanical index—defined as ultrasound pressure divided by the square root of frequency—values below 1.9. In our hands, a 300 kHz, 1.0 MPa pressure at target yields a mechanical index of 1.83. Despite being below the value of 1.9, this pressure level already drives significant release (Fig. 4, left). Thus, if cavitation is involved, it is either in the safe range or just one of several mechanisms. Second, PFCs are known to strongly bind oxygen.[27,28,39] The negative pressure of the ultrasonic wave can produce an outward motion of the dissolved gas. The resulting forces are likely to mechanically distort the

shell of the nanoparticle on a cycle-by-cycle basis and thus perpetuate release.[11,44] Whether mediated by oxygen or other molecules, the maximal displacement of a particle in the ultrasound path, ξ_m, is linearly proportional to the ultrasound pressure amplitude P: $\xi_m = \frac{P}{Z}\int_0^{T/2}\sin(2\pi Ft)dt = \frac{P}{Z\pi F}$, where F is the ultrasound frequency and Z the acoustic impedance. Indeed, our 300 kHz data show a linear dependence of the release on pressure (Fig. 4, left). This mechanism is supported by high-speed imaging, which did not detect a persistent phase change despite effective release in rodents.[17] Together, our findings indicate that both thermal and mechanical effects can be at play, depending on the applied ultrasound frequency. Higher frequencies accentuate thermal effects (PFC vaporization), whereas lower frequencies accentuate mechanical effects (cavitation or cycle-by-cycle particle displacement).

Interestingly, at 300 kHz, we observed a marginal decrease in drug release from DFP and PFOB nanoparticles at the highest ultrasound pressure tested (Fig. 4, left). This effect has been observed in another study.[19] These high pressure may lead to cavitation—the formation of bubbles—which may consequently block the propagation of ultrasound into the target.[19]

The study has three limitations. First, we tested the effects of ultrasound frequency and pressure, but not the ultrasound waveform. For instance, we have not tested the effects of the duty cycle and only used a fixed value of 10%. Increases in the duty cycle are known to lead to stronger, cumulative effects.[14,17] Second, we quantified the release of a single drug, propofol. We used this drug for two reasons: 1) it is commonly applied in the clinics for neuromodulatory applications[32] and 2) there is an established optical procedure for the quantification of its release.[17] This limitation is mitigated by previous studies that demonstrated that polymer-based nanoparticles could encapsulate a variety of hydrophobic drugs.[45] The more hydrophobic a drug, the higher its efficacy of encapsulation.[17] Using tri-block copolymers (hydrophilic-hydrophobic-hydrophilic), it is also possible to encapsulate hydrophilic drugs.[46–48] Third, we quantified the release of nanoparticles using a single copolymer shell (PEG:PDLLA). This limitation is mitigated by a previous study that found little variability in the release due to specific forms of the polymeric shell.[17] Addressing these limitations lays out our future steps.

Conclusions

In summary, we found that low-frequency ultrasound can effectively release drugs from stable PFC-based nanocarriers. We found that these nanocarriers can be safely introduced into the circulation of non-human primates. This study informs the use of specific PFC-based nanoparticles and ultrasound parameters for effective, safe, and targeted drug release in humans.

Methods

Materials

Methoxy poly(ethylene glycol)-b-poly(D,L-lactide) (PEG-PDLLA) co-polymers with 2,000 : 2,200 g/mol molecular weights, respectively, were obtained from PolyScitech (USA). 2H,3H- decafluoropentane and perfluorooctyl bromide were obtained from Tokyo Chemical Industry Co. (Japan). Perfluoro-n-pentane was obtained from Strem Chemicals (USA). Propofol was obtained from Sigma Aldrich (Millipore Sigma, Canada). Infrared dye IR800RS NHS Ester was obtained from LI-COR Biosciences (USA). HPLC-grade tetrahydrofuran (THF) and methanol were obtained from Fisher Scientific (USA). Phosphate buffer solution (PBS) was obtained from Gibco (Thermo Fisher Scientific, USA).

Nanoparticle production

The process of manufacturing the drug-encapsulating, ultrasound-responsive PFC particles is illustrated at a conceptual level in (Fig. 9) and described in detail in previous studies.[9,17] The process converts small ($<$ 30nm) micelles into much larger ($>$ 300nm) PFC-filled nanoparticles. First, the PEG-PDLLA polymer constituting the basis of the nanoparticle shell is dissolved in THF at a rate of 1mL THF : 16 mg polymer. For the biodistribution and blood clearance studies, infrared dye is added at a ratio of 1:32 (dye:polymer) for the rats and marmoset

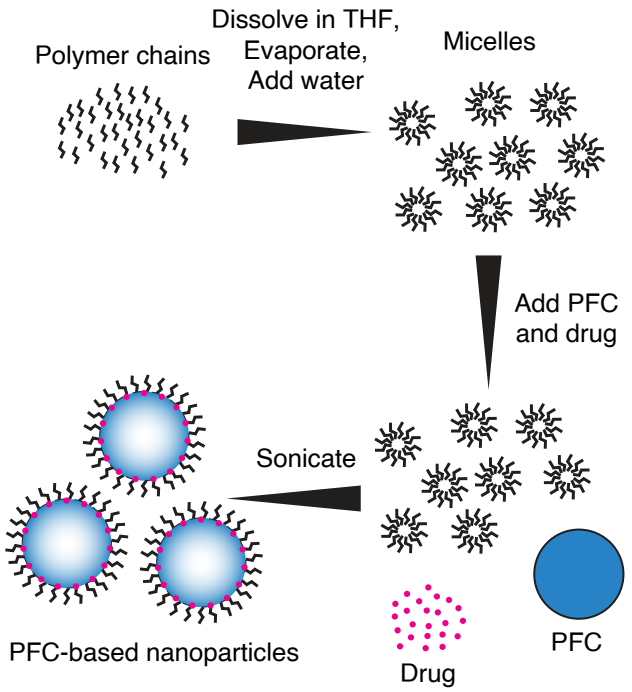

Figure 9. Production of the nanoparticles. The conversion of polymeric micelles into PFC-core-based nanoparticles using ultrasound. The three steps are described in detail in the text.

and 1:110 or 1:89 for the macaques 1 and 2, respectively. THF is then evaporated under vacuum until a gel-like layer remains. PBS is added at a rate of 1 mL PBS : 8 mg polymer and placed on a shaker table at 120 rpm to dissolve for 15 minutes. The addition of PBS orients the hydrophilic copolymer, PEG, toward the water and the hydrophobic, PDLLA, copolymer away from the water, and as a consequence, micelles are formed. Next, the PFC core and propofol are added and emulsified. A ratio of 1 mg propofol : 2 mg polymer was used in all cases. The nanoparticles' diameter can be controlled by the ratio of PFC to polymer, as reported previously.[11] For PFOB and DFP nanoparticles, a ratio of 4.5 μL PFC : 1 mg polymer was used. The ratio for PFP was scaled up to 6.25 μL : 1 mg to account for PFC lost to vaporization before being emulsified. A 20 kHz, 500W sonicator with a cup horn attachment (VCX500, Sonics) was used to perturb the thermodynamic equilibrium of the micellar system, which leads to the incorporation of PFOB into the micelles and the formation of stable nanodroplets or nanoparticles.[49] The PFC and propofol are added to 15 mL centrifuge tubes and gently shaken to combine before adding 8 mL of the micelle solution. The samples are then sonicated in a cold bath at 20% power in 30-second intervals until the solution is cloudy and drug and PFC are fully emulsified (between 60 and 90 seconds in total). A custom temperature-controlled cooling system maintained the bath temperature during sonication at 2°C for PFP and 10°C for DFP and PFOB. PFP must be kept colder to minimize vaporization before emulsification, while DFP and PFOB require higher temperatures to emulsify successfully. We found this controlled temperature approach to maximize the consistency of the nanoparticle sizes, drug encapsulation, and release properties. The resulting solution contains the desired nanoparticles in addition to remaining micelles, dissolved polymer, and free propofol. Nanoparticles are isolated using three cycles of centrifugation at 3,000 relative centrifugal force (RCF) at 4°C. After each cycle, the supernatant is discarded and the pellet dissolved in 5 mL fresh PBS. If the resulting solution contains larger particles than needed, these were removed by a slower centrifuge cycle for 1 minute at 800 RCF, this time keeping the supernatant. Larger particles contained in the pellet are discarded. For animal experiments, the nanoparticle solutions were sterilized for 3 hours under UV light, a protocol previously shown to yield effective sterilization.[50] Sterilization was conducted in glass vials in a custom chamber with an 8W UV lamp (Philips, USA).

Nanoparticle characterization

The sizes were measured using a Zetasizer Nano S (Malvern Panalytical, UK), which reports the intensity-weighted size distribution. The size values reported in the Results section describe the mean ± standard deviation of the distribution of the intensity values measured by the device. To quantify the amount of drug encapsulated, a 50 μL solution of nanoparticles is added to 450 μL of methanol to dissolve all components.[14] A UV-Vis spectrophotometer (NanoDrop 2000, Thermo Scientific) is used to quantify the concentration by comparing the absorbance at 276 nm to a propofol standard curve.

Apparatus

As in a previous study,[17] drug release is quantified in standard 1.5 mL microcentrifuge tubes. Each tube with freshly produced nanoparticles is placed into a plastic holder. A focused ultrasonic transducer (H-115, 64 mm diameter, 52 mm focal depth, Sonic Concepts) was positioned 52 mm below the holder so the sample was within the ultrasound focus. Degassed water (AIMS III system with AQUAS-10 Water Conditioner, Onda) mediated coupling between the ultrasound face and the vial. The transducer was operated at 300 kHz and the third harmonic, 900 kHz. Stimuli were generated using a function generator (33520b, Keysight). The signals were amplified using a 55-dB, 300 kHz–30 MHz power amplifier (A150, Electronics & Innovation).

Ultrasound parameters

The ultrasound carrier frequencies for *in vitro* experiments were 300 kHz and 900 kHz. Continuous pulses 100 ms in duration were repeated once per second for a total of 60 seconds.[14,17] The pressure levels at the vial location, measured in degassed water, were 0, 0.5, 0.9, 1.3, 1.7, 2.1, and 2.5 MPa. The pressure fields were measured using a capsule hydrophone (HGL-0200, Onda) calibrated between 250 kHz and 40 MHz and secured to 3-degree-of-freedom programmable translation system (Aims III, Onda).

For *in vivo* experiments, a similar ultrasound protocol was used to control for changes undergone by the particles as a result of sonication. The same transducer was operated at 248 kHz in 60-second blocks of 100 ms pulses. The animals were shaved and the transducer was coupled to the scalp using a 2% agar cone and ultrasound gel. The maximum pressure was estimated to be 1 MPa for all animals. The pressure was estimated from free-field measurements using results from past studies, which indicate a transmission rate of 76% through the skull of a 780g rat[51] and 66% through a macaque skull.[52] Transmission through the marmoset skull has been less thoroughly studied but is likely similar to rats since they are close to the same weight. For further efficacy studies, pressure at the focus should be more carefully estimated. Ultrasound was applied to the rats at the midline, 2mm posterior to the eyes for 60 seconds 5 minutes after administration of nanoparticles. For the marmoset, ultrasound was applied at the posterior surface of the skull for 60 seconds 5 minutes after each of the two administrations. The right and left visual cortex were targeted independently for macaque 1. Ultrasound was applied in 60-second blocks over 90 minutes for a total of 4 sonication blocks per side starting 2 minutes after nanoparticle administration. Sonication of the left and right sides was interleaved. For macaque 2, the right and left visual cortex were targeted simultaneously using two ultrasound transducers to maximize the sonicated volume. In this macaque, sonications were repeater for only two 60-second blocks separated by two minutes.

Drug release characterization

100 μL of hexane was placed on top of 200 μL nanoparticle solutions prior to sonication to act as a sink for released propofol.[14] After 1 minute, 45 seconds of total incubation time, 50uL of hexane was extracted. The amount of dissolved propofol was quantified using UV-Vis spectrophotometry as described previously. The percent release efficacy is defined as the amount of the drug released into the hexane relative to the amount encapsulated. Each datapoint in Fig. 4 included 3-4 distinct samples.

Subjects

Two adult male old world monkeys (*Macaca mulatta*), an adult male new world monkey (*Callithrix jacchus*), and 3 adult male Sprague-Dawley rats participated in the safety and biodegradability experiments. All procedures were approved by the Institutional Animal Care and Use Committee of the University of Utah. The macaques weighed 10.8 and 16.1 kg, respectively. The rats weighed 900, 830, and 850 g. The marmoset weighed 288 g. Sample sizes were chosen based on animals' availability following completion of other studies.

Animal procedures

All animal procedures described were approved by the University of Utah Institutional Animal Care and Use Committee and performed in accordance with relevant guidelines and regulations including the American Veterinary Medical Association Guidelines for the Euthanasia of Animals. All methods are reported in accordance with ARRIVE guidelines.

For the vital sign experiments, the rats were anesthetized with 80 mg/kg ketamine and 10 mg/kg xylazine administered intraperitoneally. A dose of sterilized PFOB nanoparticles containing 0.5 mg/kg propofol was administered to the first animal and 1 mg/kg to the subsequent animals. A total of 0.48, 0.53, and 1.1 ml of the nanoparticle mixture was injected into the tail vein of the 3 animals. Biodistribution experiments were carried out one week later. The animals were anesthetized with 2.5-3% isoflurane, and dye-loaded nanoparticles were administered at a dose of 1 mg/kg propofol followed by an equal volume of sterile saline. After one hour, the animals were euthanized by coronary exsanguination under 5% isoflurane anesthesia.

The primates were preanesthetized with ketamine (25 mg/kg intramuscularly) and intubated with endotracheal tubes. They were artificially ventilated and anesthesia maintained with 1-4% isoflurane throughout the procedure by veterinary staff. The animals were placed on warmed operating table pads to maintain body temperature. For the marmoset, dye-loaded nanoparticles were injected through the tail vein at doses of 1 mg/kg propofol for each of two injections separated by 45 minutes. A total volume of 2 ml of nanoparticle solution was administered, followed by an equal volume of sterile saline. The marmoset was euthanized by an overdose of sodium pentobarbital and perfused transcardially with 4% paraformaldehyde 82 minutes after the first injection. For macaque 1, one injection of dye-loaded nanoparticles was administered in the right saphenous vein at 1 mg/kg and a volume of 5 mL, followed by an equal volume of sterile saline. For macaque 2, the right and left cephalic veins were used with a 10 ml volumme of dye-loaded nanoparticles. Blood samples were taken from the left saphenous vein 2, 10, 20, 40, 80, and 120 minutes, at a volume of 1 mL each. Following 120 minutes of monitoring, the macaques were euthanized by an overdose of sodium pentobarbital and perfused transcardially with 4% paraformaldehyde.

The procedures were painless and wholly consistent with the recommendations of the Panel on Euthanasia of the American Veterinary Medical Association. In all cases, heart rate was recorded using a portable ECG-monitoring system with electrode pads placed on the upper right and upper left upper abdomen and a reference on the lower left abdomen.

Measurements of blood clearance and biodistribution

Following the euthanasia, major organs were extracted and subjected to infrared fluorescence analysis using an IVIS system (Perkin Elmer) with methods similar to those previously demonstrated.[14] Excitation was set to 745 nm and emission to 820 nm, with 5 seconds of exposure. Extracted organs were placed directly on a dish in the field of view of the camera. In the macaques, the same organs as in the smaller animals were available, with the exception of the brain for macaque 1. Blood samples were pipetted into drops of 100 uL on a dish. Total fluorescence for each of these samples was quantified using Aura software (Spectral Instruments), defining regions of interest incorporating the whole organ or blood sample and subtracting a background region of the same size. Percent biodistribution was computed as the total fluorescence of the region containing the organ divided by the sum of the fluorescence of all

organs. Nanoparticle concentration in the blood was computed as the amount of fluorescence from each sample relative to the first sample, obtained at 2 minutes.

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Author contributions

J.K. and M.G.W. designed the studies and carried out animal experiments. M.G.W. synthesized the nanoparticles and carried out *in vitro* experiments. J.K. and M.G.W. wrote and edited the manuscript.

Competing interests

The authors declare no conflict of interest.

Data availability

Correspondence and requests for materials should be directed to J.K. (jan.kubanek@utah.edu). The methods described herein are subject to a provisional patent.

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