Supporting Information for "Optically robust and biocompatible mechanosensitive upconverting nanoparticles"

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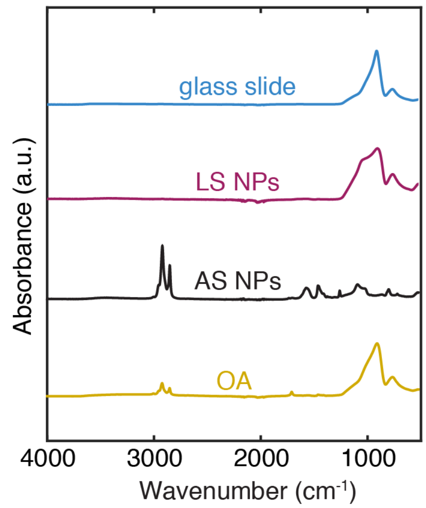

Figure S1: FTIR spectrum of glass slide Each FTIR spectrum is normalized to its maximum peak. Samples are prepared on a glass slide for characterization (See Methods). The glass slide itself has broad peaks around 910 cm^{-1}, which can also be seen in the spectra for LS NPs and OA.

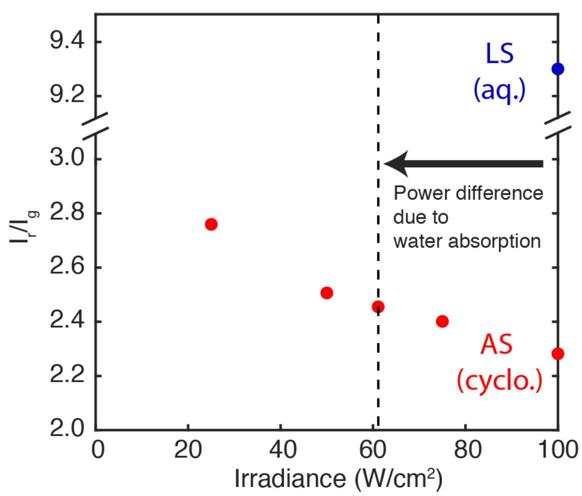

Figure S2: Power-dependence of the red-to-green ratio
We tune the incident power on particles suspended in cyclohexane down to 25% of the original irradiance (100 W/cm^2) to determine the power-dependence of our UCNPs. For a quartz cuvette with 10 mm path length, the incident power on a sample in water is ∼62% (dashed line) of that incident on a sample in cyclohexane using absorption coefficient, $\alpha = 0.485$.[1] The resulting change in the red-to-green ratio from power loss is 2.3 to 2.5, which does not fully explain the drastic color change seen in the main text, Figure 1c. OA-coated particles in cyclohexane have an initial red-to-green ratio of 2.3. Once ligand-stripped and suspended in aqueous media (S-Medium), the ratio becomes 9.3. Therefore, solvent-induced surface effects dominate over changes in power. Notice the break in the y-axis required to compare the red-to-green ratio of AS and LS UCNPs at 100 W/cm^2.

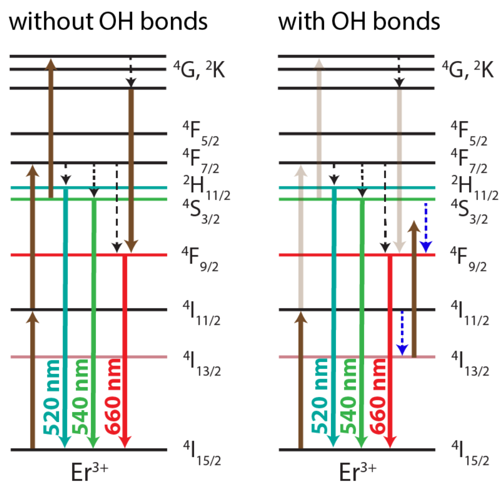

Figure S3: Energetics of upconversion with OH bonds
Solid arrows indicate laser excitation or radiative transitions, while dashed arrows represent nonradiative relaxation. In solvents without OH bonds (left diagram), the proposed mechanism for populating the red state ($^4F_{9/2}$) is by a 3-photon process.[2] In contrast, OH bonds introduce new pathways to achieve red emission. Specifically, OH stretching modes are located around 3500 cm^{-1}, coupling effectively to Er^{3+} green states ($^4S_{3/2}$, $^4H_{11/2}$) and near-infrared state ($^4I_{11/2}$).[3,4] By new nonradiative relaxation pathways (blue dashed arrows) and subsequent excitation in the latter case, the red state becomes more likely to be populated than the green. Hence, particles in aqueous media have higher red-to-green ratios.

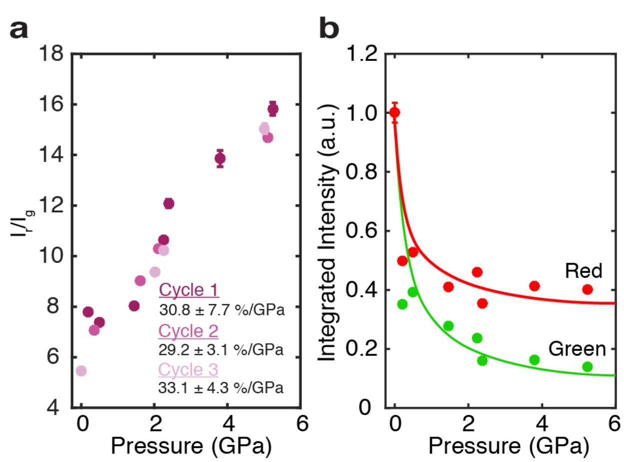

Figure S4: Detailed look at the mechano-optical response a) The absolute red-to-green ratio is plotted over three compression and release cycles of the DAC measurement. Mechanosensitivity values are calculated per cycle, showing fairly consistent responses. b) The pressure-dependence of intensity for the red and green emission bands. Both decrease monotonically, as highlighted by the guides-to-the-eye, indicating that particles become dimmer with increasing pressure. However, green intensity is more sensitive to pressure than red intensity, leading to changes in the overall red-to-green ratio or emission color.

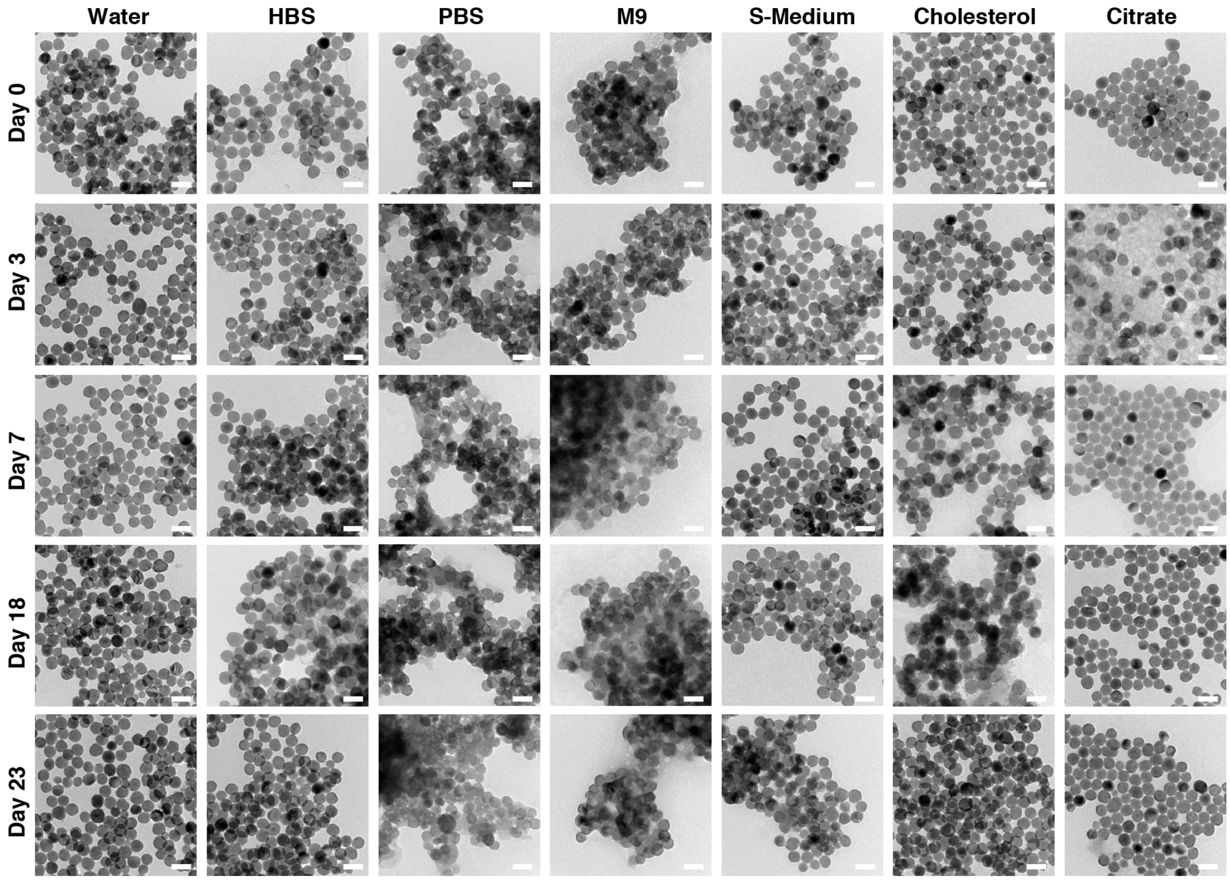

Figure S5: TEMs of nanoparticles stored in aqueous media for over three weeks For specified dates after ligand-stripping, diluted aliquots of nanoparticles suspended in aqueous media are dropcast on the less hydrophobic side of ultra-thin carbon TEM grids. The scale bars are 50 nm.

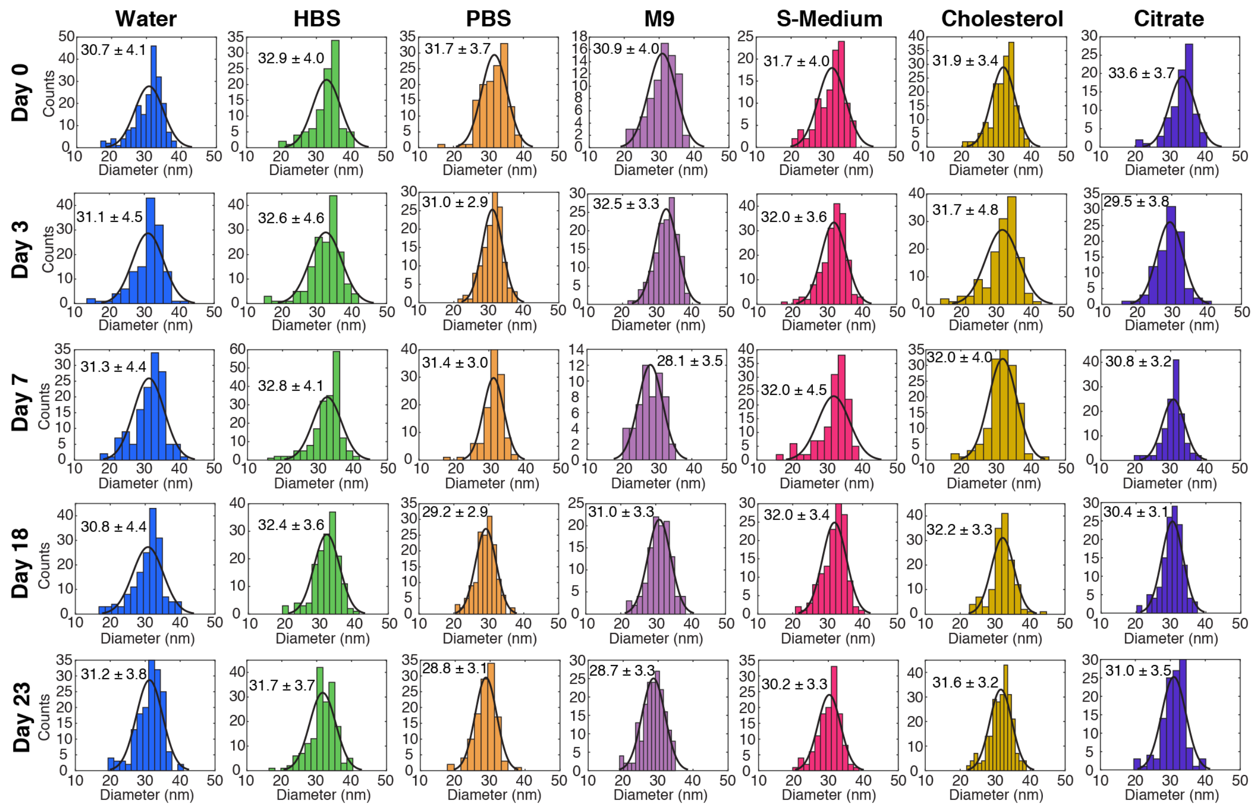

Figure S6: Size distribution of nanoparticles from image analysis of TEMs Per the Methods section, TEMs in Figure S5 were manually analyzed using Image J processing. The size distribution of ∼100-200 nanoparticles are plotted and fitted to find an average particle diameter and standard deviation. The results are summarized in the main text, Figure 3a.

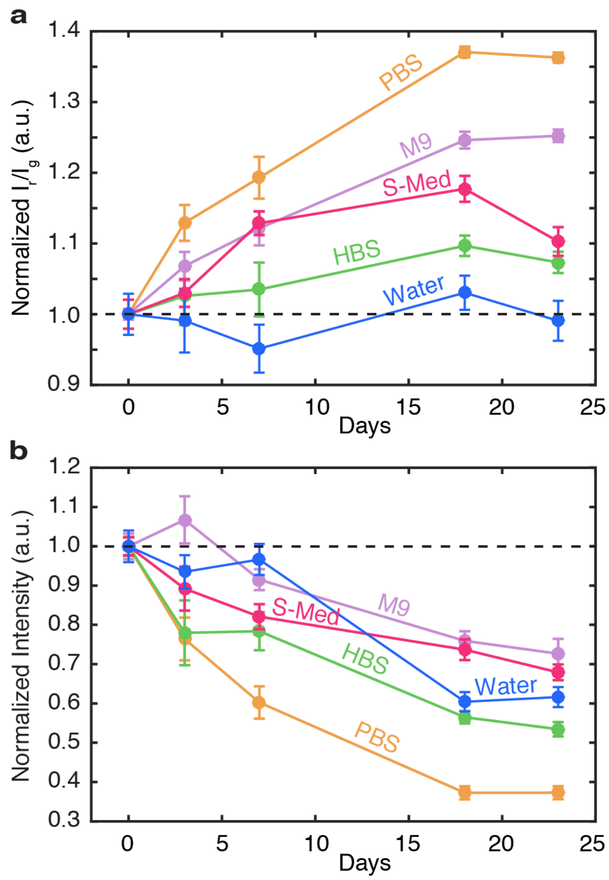

Figure S7: Optical stability of UCNPs in aqueous media, including water UCNPs suspended in water perform quite well in terms of a) emission color and b) intensity. However, it is unrealistic to perform biological experiments without buffered solutions.

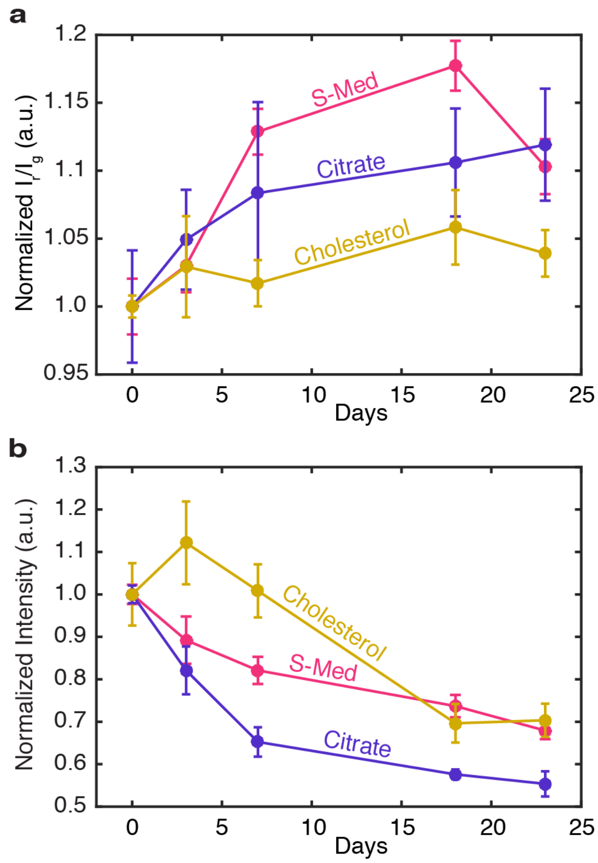

Figure S8: Independent effect of cholesterol and citrate LS UCNPs are suspended in water containing cholesterol ($\sim$ 0.005 mg/mL) or sodium citrate ($\sim$ 3 mg/mL, 0.01 M) for comparable concentrations found in S-Medium. Note that cholesterol was initially suspended in chloroform. Chloroform was allowed to evaporate before adding water. Consistent with other buffers presented in the main text, the a) normalized red-to-green ratio increases while b) normalized intensity decreases over 23 days. Here, we attempt to separate the contribution of cholesterol and citrate on the stability of UCNPs in S-Medium, since they are ingredients not found in the other buffers. Cholesterol, for example, allows for more consistent red-to-green ratio over time and may present a more biocompatible option to improve the longevity of particles, rather than introducing excess fluorine.[5]

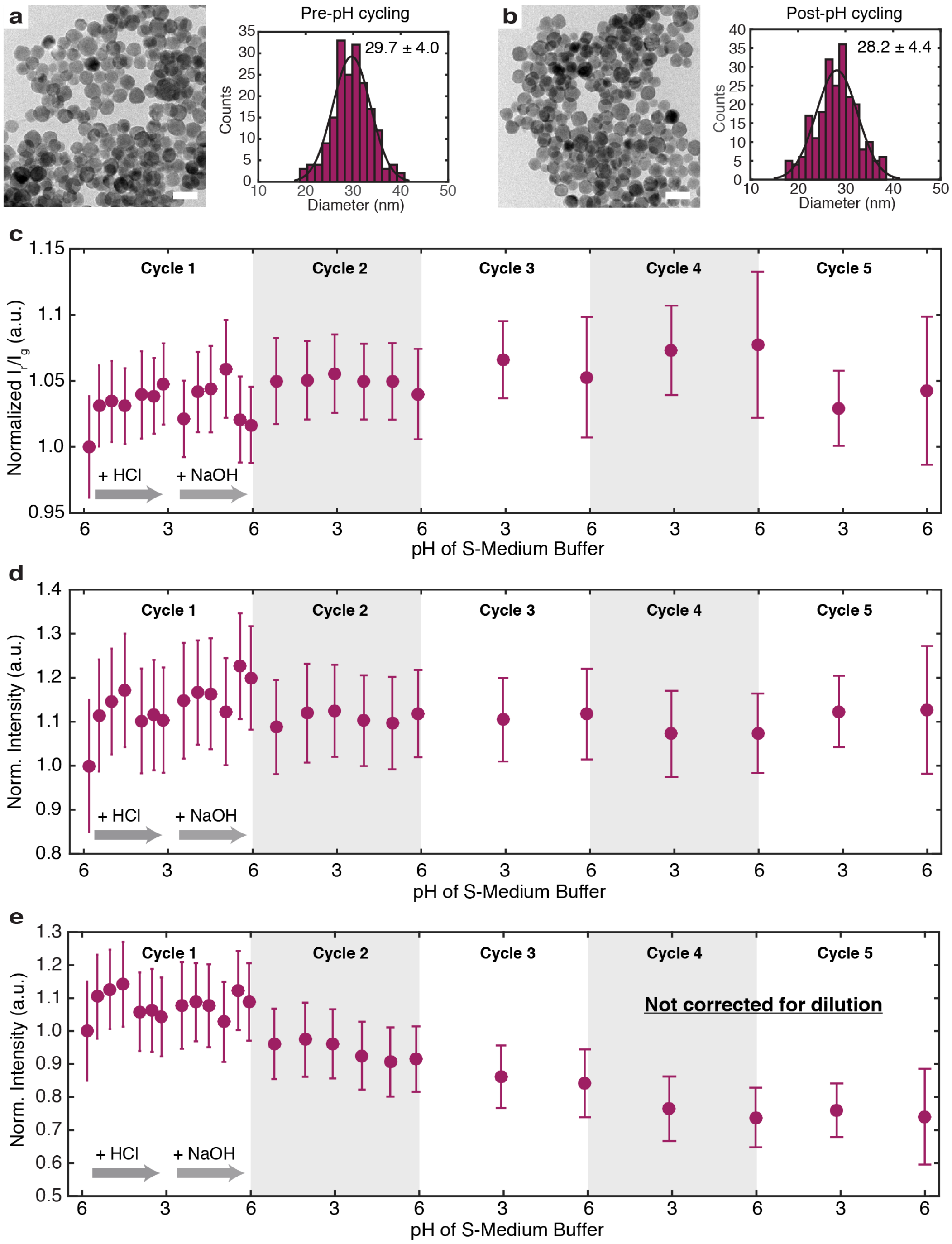

Figure S9: Effects of pH-cycling on structural and optical integrity TEMs of particles and their corresponding size distribution for UCNPs a) before and b) after the entire pH-cycling experiment (2 hours long). Based on these results, there is no significant decrease in the average diameter. Over 5 acidification and basification cycles between pH 6 and pH 3, both the upconversion c) red-to-green ratio and d) intensity are consistent, with error bars of ∼5% and ∼15% respectively. In d) the intensity values are corrected for dilution of nanoparticle concentration as acidic (HCl) and basic (NaOH) solution are added to tune pH. Thus, in e) we present the raw changes to intensity.

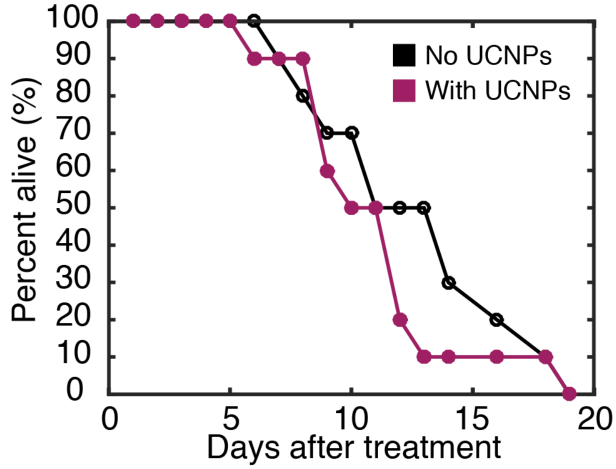

Figure S10: Lifespan toxicity assay for one trial Lifespan is another metric for chronic toxicity, albeit more variable.[6] Starting with 10 worms per treatment condition, we track the percent of worms alive day-to-day. Day 1 of treatment corresponds to a maturity stage of Day 1 Adults. For Trial 2, the survival rate is 50% at Day 10 after treatment for worms treated with UCNPs and Day 11 after treatment for the control. By Day 19 after treatment, all worms have died. Between the control and UCNP-treated worms, the survival curves are quite similar.

References

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(2) Anderson, R. B.; Smith, S. J.; May, P. S.; Berry, M. T. Revisiting the NIR-to-visible upconversion mechanism in β-NaYF4: Yb3+, Er3+. *The Journal of Physical Chemistry Letters* **2013**, *5*, 36–42.

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(6) Lithgow, G. J.; Driscoll, M.; Phillips, P. A long journey to reproducible results. *Nature News* **2017**, *548*, 387.