Effect of Iron Nanoparticle Concentration, pH, and Buffer Strength on the Gelation Kinetics and Mechanical Strength of PPODA-QT Hydrogels for Aneurysm Embolization

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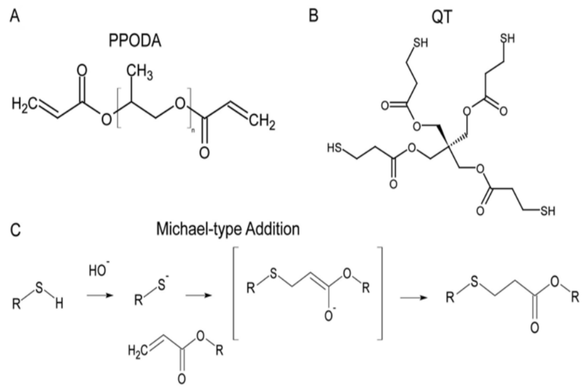
Introduction

Intracranial aneurysms affect about **3% of the general population** and can become life-threatening if rupture leads to subarachnoid hemorrhage [1], [2]. Current treatments include **microsurgical clipping** and **endovascular approaches** such as coiling, stent-assisted coiling, and flow diversion, but **wide-neck aneurysms** remain difficult to treat and often require more complex devices or procedures [2], [3].

This research investigates **PPODA-QT hydrogels** as a potential liquid embolic material for aneurysm treatment. Specifically, it examines how **iron nanoparticle concentration, pH, and buffer strength** affect **gelation time** and **mechanical strength** in order to identify formulations that balance rapid curing with strong final stiffness. The long-term goal is to support development of a **magnetically guidable, image-compatible, and mechanically robust embolic system** for safer aneurysm treatment.

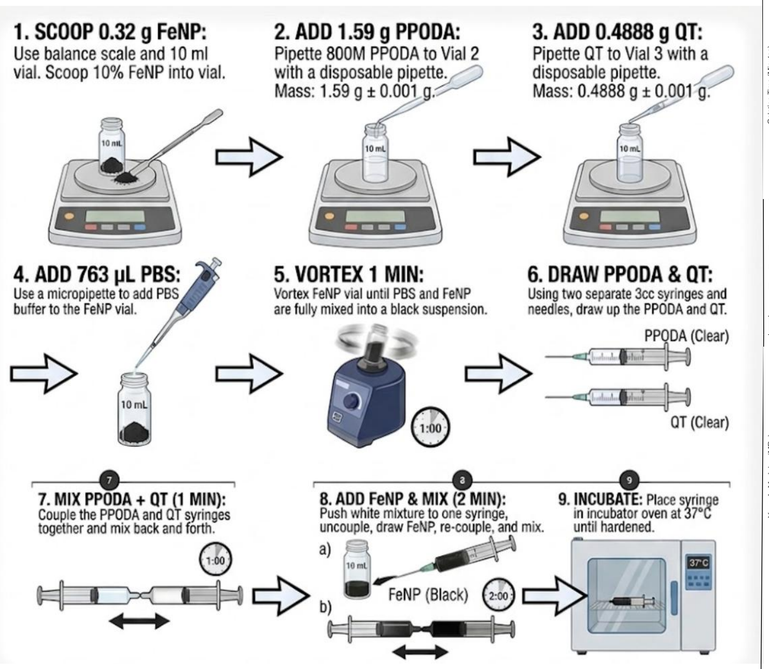
Methodology

- Experiments were performed using a FeNP-loaded PPODA-QT hydrogel formulation composed of 0.32 g 10% FeNP, 1.59 g 800M PPODA, 0.4888 g QT, and 763 µL PBS at different PH and Buffer Strength.
- The final reacting precursor was incubated at 37°C and monitored until hardening. Gelation was checked every 2–5 minutes, and for slower-forming samples, every 10–15 minutes after 30 minutes.
- Major Reaction:

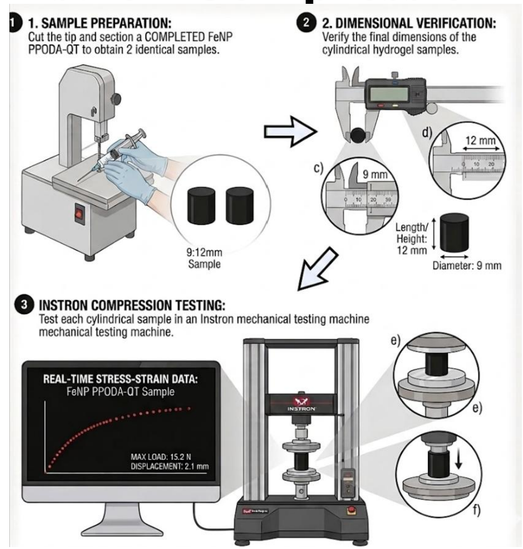


Methodology

Gel Formualtion: Step by Step



Instron Compression Testing



Equations:

Youngs Modulus:

$$E=\sigma/\varepsilon$$

Compressive Stress:

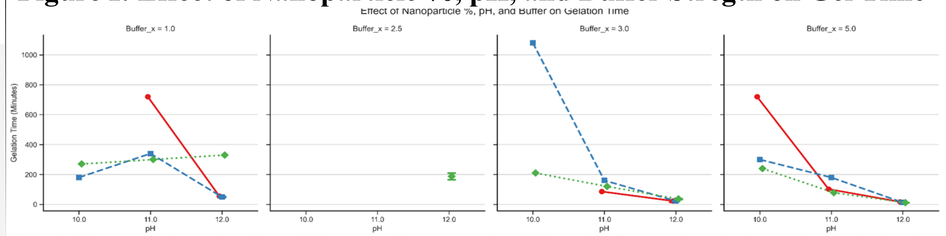
$$\sigma=F/A0$$

Compressive Strain:

$$\varepsilon=\Delta L/L0$$

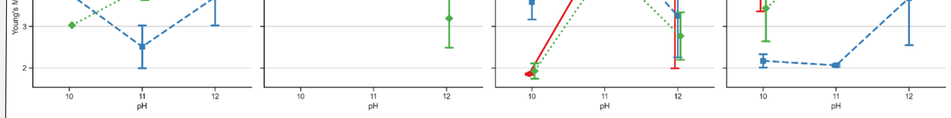
Results

Figure I: Effect of Nanoparticle %, pH, and Buffer Stregth on Gel Time



This plot illustrates the interactive effects of pH, nanoparticle concentration (NP%), and buffer strength on the time required for hydrogel formation. The data demonstrates that gelation kinetics are primarily driven by pH and buffer strength; increasing both parameters simultaneously drastically accelerates gelation, dropping times from several hours to under 15 minutes. Notably, there is a strong interactive effect at low buffer concentrations (1x), where high nanoparticle loading (10% NP) severely inhibits and delays gelation. The most rapid, consistent gelation times (~10–12 minutes) are universally achieved at the maximum pH (12) and highest buffer strength (5x), regardless of nanoparticle presence.

Figure II: Effect of Nanoparticle %, pH, and Buffer Stregth on Youngs modulus



This plot illustrates the interactive effects of pH, nanoparticle concentration (NP%), and buffer strength on hydrogel stiffness. The data demonstrates that the stiffest networks (exceeding 5.0 MPa) are synergistically produced by combining high pH (11–12), high buffer strength (5x), and maximal nanoparticle loading (10% NP). While increasing pH generally improves stiffness across most samples, the effect of buffer concentration is highly dependent on NP loading, highlighting that optimal mechanical rigidity requires a precise balance of all three environmental variables.

Conclusion & Future Work

PPODA-QT hydrogel gelation is mainly driven by pH and buffer strength, with higher levels causing the material to gel faster and become stiffer. The best-performing formulation, containing 10% nanoparticles at pH 12 with 5× buffer, showed both fast gelation in under 15 minutes and strong mechanical performance above 5 MPa, suggesting a strong balance for embolic use. Buffer strength was especially important for supporting effective crosslinking when nanoparticle concentration was high.

In addition, magnetic stabilization could help extend working time during delivery without requiring prolonged balloon occlusion, which may allow for more controlled injection even when gelation occurs at a moderate rate. Future studies will examine the hydrogel microstructure using SEM, further optimize formulation conditions, and assess long-term stability under physiological conditions.

References

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