3D-PRINTED RF COILS FOR SOLUTION-STATE NMR: TOWARDS LOW-COST, HIGH-THROUGHPUT ARRAYS

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Target Audience: Engineers and scientists engaged in RF coil construction for NMR or MRI

Purpose: RF coils for solution-state NMR are typically constructed by hand[1] or by lithography techniques[2] borrowed from the silicon integrated circuit industry. These methods yield arrays of perhaps 10s of coils on millimeter- or sub millimeter-scales, but are limited by either labor-intensive manufacturing or predominantly 2 dimensional fabrication methods. We have been exploring stereographic 3D printing as an alternative method, as it has become widely available and benefits from low cost, ease of fabrication, and minimal geometric constraints. Furthermore, a large number of 3D-printed plastics are currently available with build resolutions as small as 25 µm and build envelopes exceeding one cubic meter[3]. Using these capabilities, we have fabricated 3D-printed RF resonators for solution-state NMR at high field. We show that 3D-printing and selective silvering can produce a solid structure (matrix) containing hollow voids that define the RF components and fluidically-addressable sample chambers necessary for NMR experiments. To the best of our knowledge, this is the first application of 3D printing to complete RF coil construction. Importantly, multiple independent resonators can be fabricated in 3D arrays with individually addressable fluid sample chambers, and 3D-printer capabilities allow potentially thousands of mm-scale coils to be fabricated in a single build session. 3D printing therefore provides a manufacturing pathway towards a new generation of high-throughput coil arrays at minimal cost.

Methods: Stereographic 3D printing uses an incident laser beam to photo-crosslink liquid polymer resins in a layer-by-layer manner. 3D parts are formed in an additive fashion by controlling laser spot location in at least 2 axes, as well as liquid resin height. A variety of 3D printing materials were explored from two major manufacturers (Stratasys & 3DSystems). Solid bodies were 3D printed with hollow channels; subsequent to printing, some channels were metallized with a novel silver suspension injection/curing procedure (Fig 1) using PELCO Silver Paint (Ted Pella Co.) that formed ≈10µm silver coatings for electrically conductive pathways. In this manner, solenoids were formed and connected to external tuning/matching networks for NMR observations. Solenoids were tuned/matched to 400 MHz, and ^{1}H FIDs (10kHz BW, 30000 points, 1 acquisition) were collected with a 9.4T Varian/Agilent small animal imaging system. Total build cost was ≈ $20/coil, excluding one-time "batch" fees.

Results and Discussion: The "Somos 11122 Watershed" (DSM Desotech) material has provided the best 3D-printed parts to date, giving excellent adhesion to the silver paint. In practice, consistent builds were achieved with minimal dimensions of 0.75mm for hollow features and 0.5mm for solid bodies, yielding 5mm-diameter/5-turn solenoids with integral sample chambers of 40% filling factor (Fig 2). A Q-factor of 15 at 400 mHz was observed after silvering and tuning/matching. NMR FID measurements on 40 µL H_2O in the sample chamber gave FIDs with ≈20000 SNR and spectra with ≈0.05 ppm linewidth (Fig 3). A small secondary resonance was noted, perhaps arising from the side-cavities used to fill the main sample chamber. Efforts are currently underway to incorporate tuning and matching capacitors into the 3D printing process, which will enable self-contained resonators that can be arrayed easily in 3D at spatial densities of ≈1 coil/cm^3. Different materials are also being explored to minimize coil/sample magnetic susceptibility mismatch and give narrower NMR spectral linewidths. Ultimately, the metallizing process will be incorporated directly into the 3D-printing build for facile construction of large numbers of coils. Recent advances in 3D printing technology have driven minimum build resolutions smaller by 2-fold than what was available here, allowing for microcoil fabrication in the near future.

Conclusions: 3D printing and selective silvering was used to fabricate RF coils with integral sample chambers for solution-state NMR. Given the capabilities shown here, 3D printing is readily applicable to constructing RF resonators useful to both 1) NMR spectroscopy, in the form of mm-scale coils and arrays, and 2) MRI, ranging from cm-scale preclinical resonators to m-scale clinical coil arrays. We anticipate the low cost and build scalability inherent to 3D printing will impact the future of coil fabrication, enabling drastically higher density arrays and novel coil geometries that are not available with conventional fabrication techniques.

Fig 1. Metallizing a 3D-printed matrix to form conductors within hollow channels (cross-section).

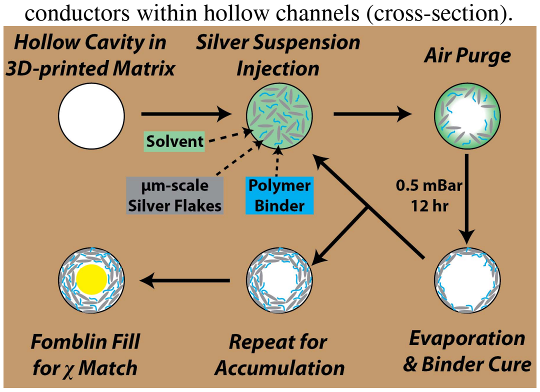


Fig 2. 3D-printed 5mm solenoid and sample cavity.

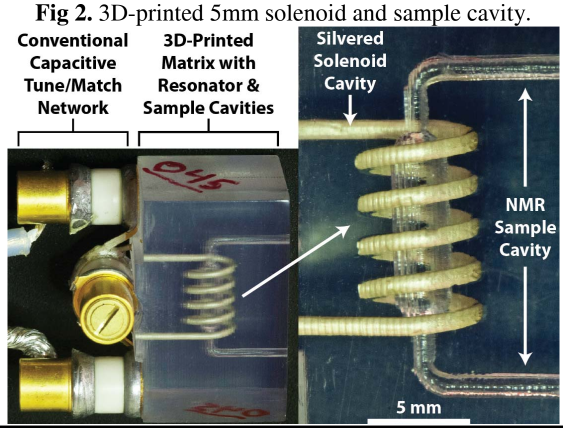
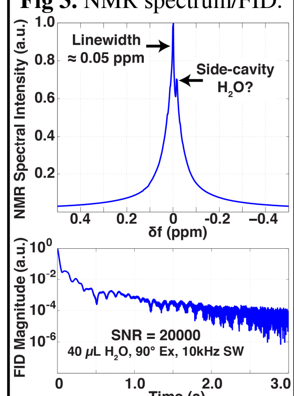


Fig 3. NMR spectrum/FID.



References: 1) e.g. Webb, A. G. *Progress in Nuclear Magnetic Resonance Spectroscopy* **31,** 1–42 (1997). 2) e.g. Lee, H., Sun, E., Ham, D. and Weissleder, R. *Nat Med* **14,** 869–874 (2008). 3) see manufacturer specifications at www.stratasys.com and www.3dsystems.com

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