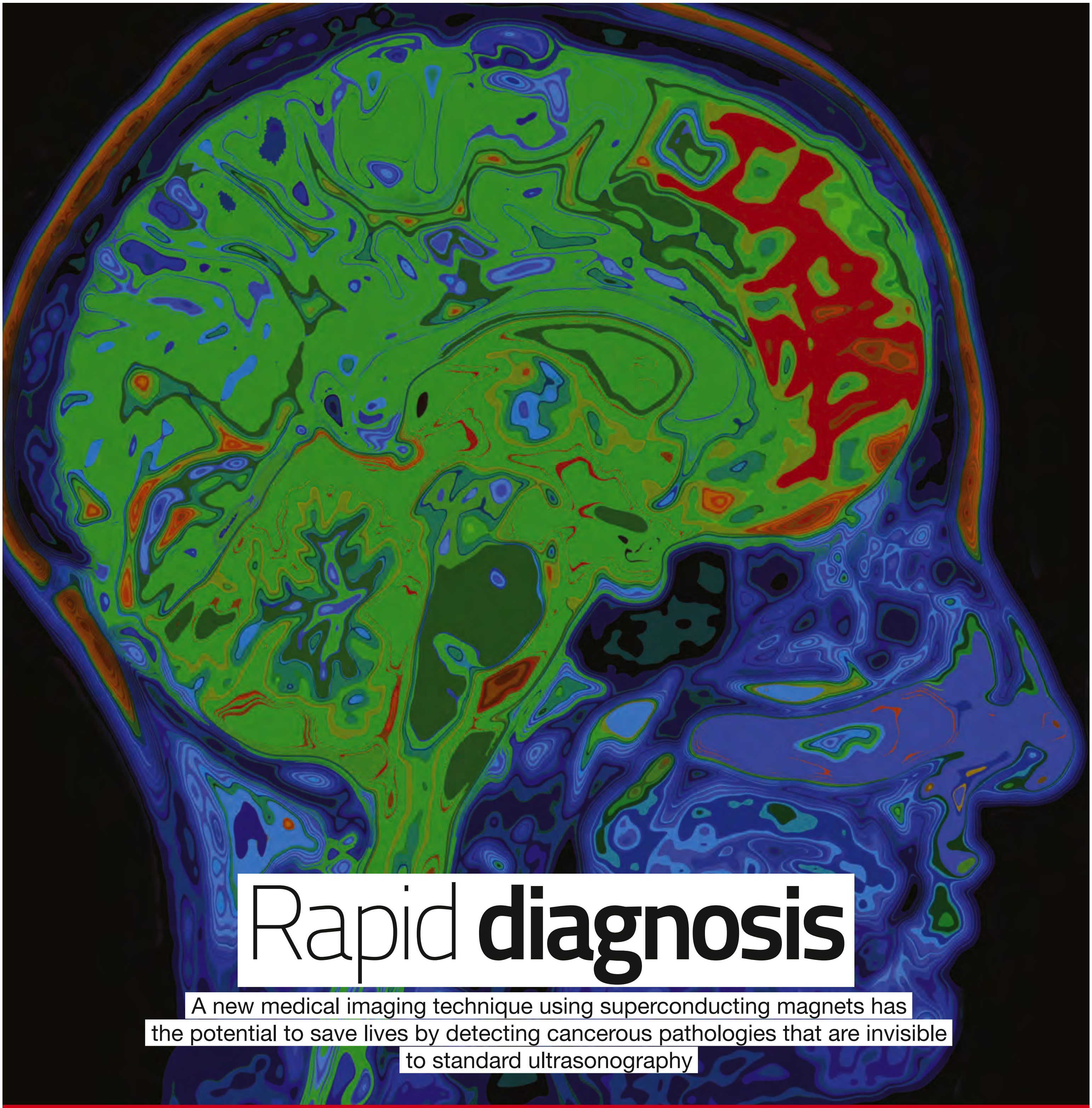
ANNUAL **2016**

MAGNETICS TECHNOLOGY INTERNATIONAL



Rapid **diagnosis**

A new medical imaging technique using superconducting magnets has the potential to save lives by detecting cancerous pathologies that are invisible to standard ultrasonography

The world's leading global review dedicated to advanced magnetics and magnet technologies

Phillip Keller, co-owner, Metrolab

NMR magnetometry **present and future**

The latest generation of NMR magnetometers features tremendous improvements in range, precision and usability. However, key challenges for the future concern measuring inhomogeneous, weak and rapidly varying fields

The phenomenon of nuclear magnetic resonance (NMR) was first observed in the 1940s. It has since found widespread application in NMR spectrometers for chemical analysis and magnetic resonance imaging (MRI) scanners for medical use. In comparison, NMR-based magnetometers, commercially available since the late 1970s, are relatively little known. However, they hold a very special place in magnetometry because they provide the most accurate measurement of flux density, being drift-free and sensitive only to the vector magnitude.[1]

Current technologies

Today the world's most commonly used NMR magnetometer is Metrolab's Precision Teslameter PT2025 (Figure 1). Probes with proton samples (rubber) range up to 2.1T and probes with deuterium samples (heavy water) range up to 13.7T. It achieves a relative precision of 0.1ppm and absolute accuracy of 5ppm.

Figure 1: **The NMR Precision Teslameter PT2025 modulates the magnetic field and adjusts the frequency until it is exactly tuned to the NMR resonant frequency; a timer counter then provides the result**

Figure 2: **MFC3048 Probe Array for the Magnetic Field Camera MFC3045 multiprobe NMR mapping system. The MFC3045 is built around a Direct Digital Synthesizer (DDS) RF generator that sweeps the frequency; the timing of a resonance relative to the frequency ramp provides the result**

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The second most popular NMR magnetometer is a specialty system for mapping MRI magnets, Metrolab's Magnetic Field Camera MFC3045. This instrument supports simultaneous measurement of up to 32 probes, arranged in an array custom-designed for the magnet to be mapped (see Figure 2). The probes provide a relatively narrow measurement range, typically ±2% of the nominal field, which can range from 0.2T to 7T. It achieves a relative precision of 0.01ppm and absolute accuracy of 5ppm.

Recent improvements

Recently Metrolab introduced a new generation NMR magnetometer, the Precision Teslameter PT2026, destined to eventually replace the PT2025 as well as the MFC3045 (Figure 3).

The PT2026 extends the range of proton-sample probes from 2.1T to 24T, and improves the resolution from ±1Hz to ±0.1Hz. It also introduces numerous functional improvements, including access to smaller magnet gaps, rapid acquisition of the NMR resonance, flexible measurement parameters, flexible probe ranges, trigger input/output, reference clock input/output, and standard interfaces with extensive software support.

Multiprobe systems based on the PT2026 provide a higher field range and offer the

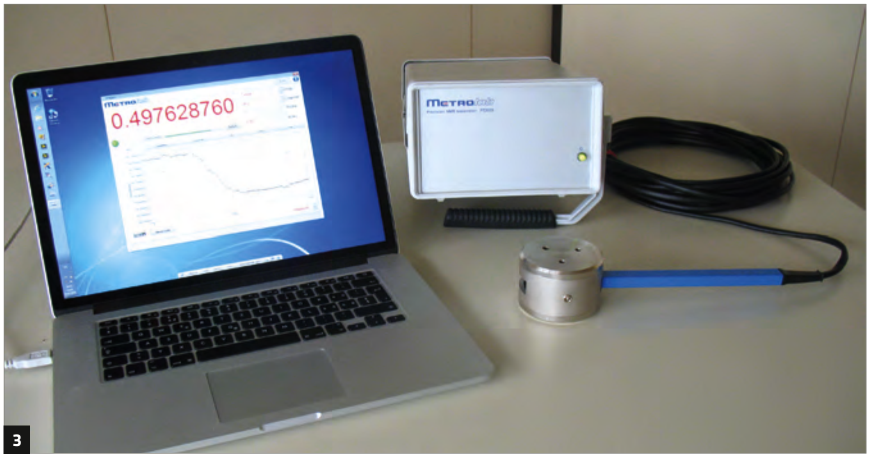

Figure 3: **The NMR Precision Teslameter PT2026 emits a broadband pulse, and captures the RF signal reemitted by the sample. The frequency of this signal provides the result**

possibility of mapping small-bore magnets and placing a wide-range probe on a probe array.

Key challenges

The greatest limitation of NMR magnetometers is that the field to be measured must be uniform. If not, the opposite ends of the sample resonate at different frequencies, causing the NMR response to decay more quickly and therefore broadening the spectral response.

It is relatively simple to redesign the signal processing to accept a broadened spectrum. For highly inhomogeneous fields, reducing the sample size recovers some of the decay time, but dramatically reduces the signal/noise ratio (SNR), which must be recovered. Possible techniques include those used to measure weak fields, but all imply complications and compromises.

Side-by-side comparisons show that the PT2026 tolerates more than twice the field inhomogeneity of the PT2025. Although impressive, this is a modest improvement compared with the order-of-magnitude leaps achieved for other parameters. It is to be expected that progress on this front will continue to be difficult and that field inhomogeneity will continue to be the key limitation of NMR magnetometers.

For weak fields, the NMR resonance signal is drowned out by thermal noise. Consequently the bottom of the measurement range is around 10-100mT. For calibration systems in particular, NMR reference measurements much closer to zero would be highly desirable. There are several proven approaches to this problem: electron-spin resonance (ESR) samples, large sample sizes, a highly sensitive active detector instead of a simple coil, and pre-polarization of the sample in a strong field. ESR, the electron equivalent of NMR, is of interest because the resonant frequencies are roughly 1,000 times higher than for NMR; the remaining methods strive to improve the SNR in some way. Pre-polarization of a flowing liquid NMR sample currently appears to be the most promising approach, 'only' requiring solid engineering for industrialization.

Fast and cold measurements

NMR magnetometers are traditionally slow, optimized for extremely precise measurements of static fields. For example, the PT2025 performs one measurement per second. Although the PT2026 provides better than an order of magnitude improvement in this respect as well, much higher measurement rates should be possible – NMR physics imposes no constraints in this respect. In fact one system to measure MRI field perturbations already achieves kilohertz update rates.[2] Although that system uses very sophisticated and expensive technology, far removed from traditional NMR magnetometers, it demonstrates that measurement rates can be dramatically improved.

As superconducting magnets become more common, their manufacturers and users are demanding cryogenic NMR probes. Unfortunately the decay of the NMR response is much shorter in solid NMR sample materials than in liquids. For example, that of water is several seconds whereas that of ice is roughly a microsecond.[3] In addition, the active electronics of an NMR probe do not function at cryogenic temperatures. However, appropriate sample materials do exist,[4] and the PT2026 allows the passive probe head to be separated from the active electronics by several meters of coaxial cable. Consequently, commercially available cryogenic NMR probes should not be far off.

Outlook: dynamic

Recently introduced NMR magnetometers have not only brought order-of-magnitude performance improvements, but also created a basis for further developments that will enable fundamental limitations of the technique to be pushed back. In short, NMR magnetometers are poised to continue their rapid evolution for some time to come. ■

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