

Modular transmission line probes for microfluidic nuclear magnetic resonance spectroscopy and imaging

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Abstract

Microfluidic NMR spectroscopy can probe chemical and bio-chemical processes non-invasively in a tightly controlled environment. We present a dual-channel modular probe assembly for high efficiency microfluidic NMR spectroscopy and imaging. It is compatible with a wide range of microfluidic devices, without constraining the fluidic design. It collects NMR signals from a designated sample volume on the device with high sensitivity and resolution. Modular design allows adapting the detector geometry to different experimental conditions with minimal cost, by using the same probe base. The complete probe can be built from easily available parts. The probe body mainly consists of prefabricated aluminium profiles, while the probe circuit and detector are made from printed circuit boards. We demonstrate a double resonance HX probe with a limit of detection of $1.4 \text{ nmol s}^{-1/2}$ for protons at 600 MHz, resolution of 3.35 Hz, and excellent B_1 homogeneity. We have successfully acquired ^1H - ^{13}C and ^1H - ^{15}N heteronuclear correlation spectra (HSQC), including a ^1H - ^{15}N HSQC spectrum of 1 mM ^{15}N labeled ubiquitin in 2.5 μl of sample volume.

1. Introduction

NMR (Nuclear Magnetic Resonance) is a well established technique used in chemical analysis [1, 2, 3], molecular structure determination [4], metabolomics [5, 6], reaction monitoring [7] etc. Microfluidic lab-on-a-chip (LOC) devices are increasingly finding applications in chemistry and the life sciences [8, 9]. They provide a convenient way to integrate complex chemical and biochemical processes. In particular, microfluidic technology allows detailed control over growth conditions in the culture of cells, cell aggregates, and small organisms [10, 11, 12]. Lab-on-a-chip devices can also enable high experimental throughput by parallelisation. In spite of its analytical power, NMR has so far only rarely been used in microfluidic systems. In general, information is extracted from microfluidic devices only at the end point of the experiment. Typically, this is done using fluorescent probes, which bind to one or a few analytes of interest. This approach can reach very high sensitivity, with limits of detection down to femtomolar concentrations. However, it is usually destructive, since the sample is affected by the addition of the marker, and can only be done once, at the end of the experiment. Following kinetic processes therefore requires using multiple samples. By contrast, NMR spectroscopy is non-invasive, generic (virtually all organic molecules give an NMR signal), and highly specific (no two metabolites share the same NMR spectrum), and can therefore provide a useful complementary readout capability for microfluidic devices. For example, the metabolic activity of cell cultures can be followed non-invasively by NMR throughout the course of the experiment [13], while effects on cell differentiation can

still be analysed by a (destructive) transcriptomic analysis at the end. Unfortunately, the sensitivity of NMR is much lower than that of optical techniques. The small volumes involved in microfluidic systems (typically in the range of 1 μl) compound this problem. As is well known, the mass limit of detection of inductive NMR detectors improves as they are scaled down [14]. On this basis, a number of different micro-NMR detector designs have been proposed and characterised in the literature [15, 16]. In most cases, these are based on micro-solenoid [17, 18], planar [19, 20, 21], or stripline detectors [22]. Significant research has gone into developing micro-NMR detectors for flow probes, where the sample container takes the form of a fixed capillary into which the sample must be injected. Only a few designs that allow insertion of a removable microfluidic device into the detector have been described [23, 24, 25].

In this paper we present a novel modular probe designed for generic microfluidic-NMR experiments. The design is based on a transmission line detector [22, 25] using inexpensive printed circuit board (PCB) technology. A modular design ensures that detectors of different geometry and size can be easily exchanged. The NMR detector (including the tuning and matching circuit) is connected to the probe skeleton through detachable connectors. Modularity of the probe not only allows fast optimisation of the detector but also facilitates the use of dedicated detectors for different microfluidic devices on a single probe base. Once the probe base is in place, additional detectors can be manufactured within 2-3 days for less than ~ 200 €. The probe is designed for proton detected double resonance. The second channel can be tuned to different nuclei

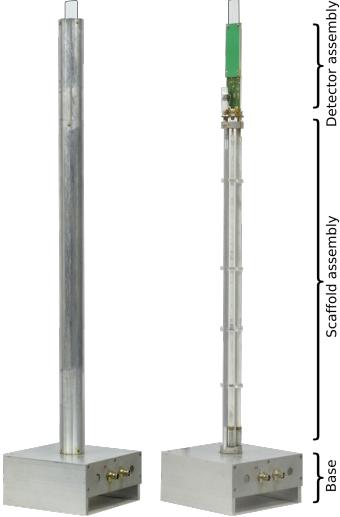


Figure 1: The probe with and without sleeve.

such as ^{13}C , ^{15}N , or ^{31}P . The probe skeleton is made almost entirely from easily obtainable raw materials such as aluminium profiles of standard size, with only a small number of custom-machined parts holding the structure together. Detailed construction drawings and a complete set of CAD files is available for download at [26]. The planar geometry of the detector accommodates exchangeable microfluidic devices which can be designed freely for specific experimental requirements as long as the overall shape of the device is maintained.

In the remainder of this paper, we discuss the probe design in more detail, and characterise its performance in terms of sensitivity and resolution. We also demonstrate its application in microfluidic cell culture, protein NMR spectroscopy, and micro-imaging.

2. Probe Design

The probe assembly design is based on readily and easily available materials and parts with minimal need for customised fabrication. All mechanical and electronic components are readily available from commercial sources, with the exception of a small number of precision-machined parts which are used to hold the assembly together. These can be ordered from commercial prototyping manufacturers or machined in-house if mechanical workshop facilities are available.

The probe is composed of three main assemblies: A) probe base; B) scaffold assembly; C) detector assembly (Fig. 1). The base (blue in Fig. 2) and the scaffold assembly (green in Fig. 2) together make the skeleton of the probe. Both the base and scaffold assembly are made from standard aluminium profiles. The base contains the BNC connectors for RF (Radio Frequency) input. These BNC connectors are connected to semi-rigid coaxial cables for RF transport in the probe.

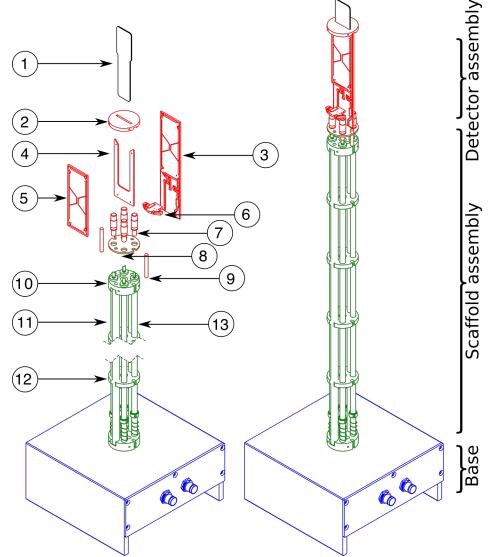


Figure 2: Exploded view of the probe design (left) and assembled probe (right). Probe base (blue) and scaffold assembly (green) with TMPCB (brown, 8) provides a generic mounting point for the NMR detector assembly (red). A microfluidic device (1) can be inserted from the top of the probe. The device is held in place by a spacer (4) between the detector planes (3 and 5) ensuring alignment of the sample chamber with the sensitive area on the PCB planes. The X channel frequency is controlled by a modular PCB insert (6). The modular NMR detector is made up of parts 3 to 6 and is connected to the TMPCB (8) through standard coaxial (SMP) connectors. The scaffold assembly is made up of aluminium tubes (11), scaffold support disks (10) and, auxiliary support disks (12).

The scaffold assembly is made up of two hollow aluminium tubes (11) held together with precision machined parts at both ends (scaffold support disks (10)). The semi-rigid cables are threaded through these hollow aluminium tubes to reach the detector assembly. Auxiliary support disks (12) provide additional rigidity for the scaffold assembly. In our case, these were laser cut from 5 mm thick PMMA sheets, but they may also be made by conventional machining. A tuning and matching PCB (TMPCB, 8) is held in place on the top of the probe skeleton by the detector support rods (9), with the semi-rigid coaxial cables providing additional support. The TMPCB is permanently fixed to the probe base, and serves as attachment point for the exchangeable detector assembly. It also provides capacitors (7) for secondary tuning and matching of the detector. The detector assembly is connected to the TMPCB through a pair of low-loss SMP connectors (14 in Fig. 3). While each detector assembly is roughly tuned and matched with fixed circuit elements soldered onto it, the adjustable capacitors on the TMPCB are used for fine tuning and matching at the magnet through tuning rods (13) which reach all the way to the probe base.

The base, the scaffold assembly and the tuning and matching PCB all have a free circular axial bore providing access from the bottom of the probe, which can be used for temperature and environmental control and/or fluidic connections to the sample as needed. The detector

assembly is made up of two PCBs (3 and 5), a spacer between them (4) and an RF-insert (6). The detector used here is based on a planar transmission line geometry as described elsewhere [25, 22]; other structures such as spiral coils and Helmholtz pairs are also possible, and can easily be realised on a PCB. The transmission line detector consists of a pair of copper planes, each with a constriction at the centre. This geometry gives rise to an electromagnetic eigenmode with a strong anti-node of the magnetic field between the two planes at the site of the constriction. This concentrates the rf field and the detection sensitivity onto the sample area. The shape and size of the copper structures have been chosen such as to produce an eigenfrequency of this mode around 630 MHz. The PCBs have been designed with solder points at the back side for chip capacitors; these can be used to tune the resonance down to the desired proton Larmor frequency (500 or 600 MHz in the present case). Both the PCBs (3 and 5) also carry circuitry for channel separation and primary matching of the detector. A copper or brass auxiliary disk (2) holds the PCBs together at the top, and forms the top end of the probe assembly. The probe sheath (not shown in Fig. 2) is fixed to the auxiliary disk (2) and the scaffold assembly with screws. An exchangeable microfluidic device (1) can be inserted from the top of the detector. Microfluidic devices can be used as passive sample holders, filled before putting them into the probe, or the device can be actively perfused and operated in-situ. The microfluidic device is held in place by the spacer between the two PCB planes coinciding the sample chamber with the constriction on the detector. The 45-degree edges of the device outline help with precise and reliable alignment. Since the detector assembly is attached to the probe base through SMP connectors, it can easily be exchanged. Using standard PCB processes to manufacture the detector provides great flexibility to optimise detector performance for different applications, including different microfluidic sample sizes, and different combinations of target nuclei.

Fig. 3 shows two different versions of the probe with and without the RF insert (6) for the X channel. In (A) the X channel can be tuned to different nuclei by exchanging 6. However, in (B) the circuitry of the RF insert (6) is integrated on the PCB plane (5), making the design more compact. Probe (A) is compatible with a Varian 600 Premium shielded 14.1 T magnet, with an outer diameter (O.D.) of 44.45 mm including the sheath. Probe (B), with an O.D. of 38 mm including the sheath, is designed to fit inside a Bruker narrow bore shim stack. Probe (B) also fits inside a Bruker micro-imaging gradient unit. Naturally, B can also be used with wide bore magnets with spacers or gradient stack to keep the probe centred.

Microfluidic devices are made from inexpensive PMMA sheets by laser cutting and thermal bonding, as described in detail elsewhere [27]. Briefly, the devices consist of a 0.5 mm thick middle layer between a top and bottom layer of 0.2 mm thickness each. The sample chamber and fluidic network are cut into the middle layer. The fluidic network

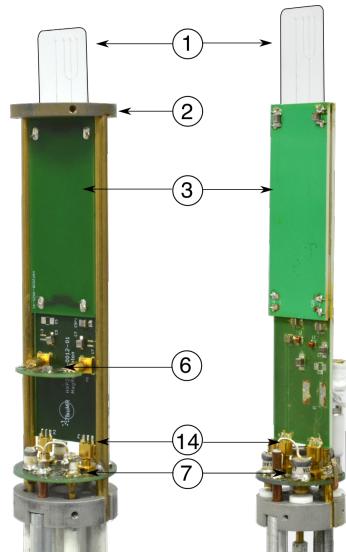


Figure 3: Dual channel probes with (A) and without (B) modular RF insert (6) for X channel. O.D. of A is 44.45 mm and B is 38 mm. Circuit elements of X channel are integrated on the PCB in B making it compact. Detachable SMP connectors (14) are used to connect the RF insert (6) and the detector assembly.

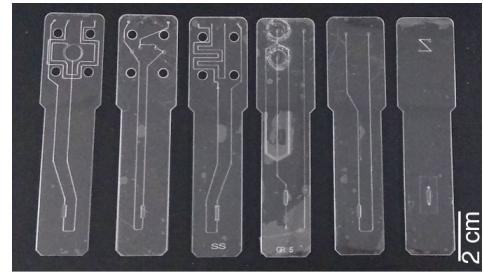


Figure 4: Microfluidic devices for different applications compatible with the current setup. From left: Devices for perfusion of tissue slice on a chip, peristaltic pumping to induce flow, hydrogenation on a chip, droplet generator, simple design to fill the sample chamber and, to grow cells on the device.

on the device can be designed freely as long as the overall shape of the device is preserved, and the location of the sample chamber is maintained.

The double resonance circuit is based on the design shown in Fig. 5. The transmission line detector is tuned to the desired proton Larmor frequency by chip capacitors located at its four corners, as well as a non-magnetic trimmer capacitor (C_6). Two primary matching capacitors (C_5 and C'_5) bring the impedance into the vicinity of 50Ω . A short microstrip with a specific impedance of 50Ω on the PCB then provides a connection to the secondary tuning and matching elements on the TMPCB (C_1 and C_2). The lower frequency channel is connected to the detector through a high-frequency band reject (C_7 , L_7). Tuning is achieved by L_1 and C_4 , which are both located on the exchangeable insert, in combination with the complex admittance of the detector at the X channel frequency. To maximise efficiency, L_1 should have as high a Q -factor as

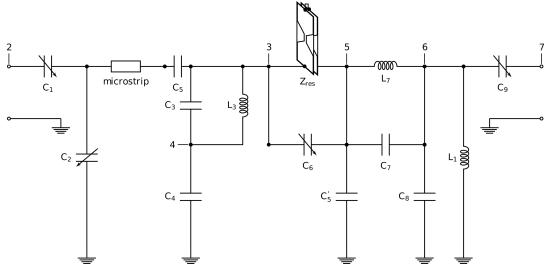


Figure 5: Circuit diagram of the double resonance probe. Proton frequency is fed in from the left (port 2) and X frequency is fed in from right (port 7).

possible. We have used commercially available flat copper coils of 5 mm diameter and 4.5 turns in the case of ^{15}N at 60 MHz. Tuning to ^{13}C , either at 125 or at 150 MHz could be achieved without L_1 .

3. Materials and Methods

All the parts and the probe assembly were designed in Solidworks (Solidworks, Dassault Systèmes). Prefabricated profiles made from 6061-T3 aluminium (Aluminum Warehouse, UK) were used for the mechanical structure of the probe (base platform, scaffold tubes, sleeve). A few customised precision-machined parts (scaffold support disks, top disk) were obtained from ProtoLabs (Telford, UK) after providing CAD files. A small number parts were machined in-house (detector support rods, auxiliary support disks). All electronic components including semi-rigid transmission lines were purchased from DigiKey Ltd. Cell cast PMMA sheets for microfluidic devices were bought from Weatherall Equipment (Wendover, UK). Microfluidic devices were designed on AutoCAD. PMMA sheets were cut to desired size and functionality (holes or channels) using a laser engraving system (HPC Laser L3040), and then bonded using the protocol described in [27].

The precise dimensions of the detector were optimised for a given sample volume using finite element calculations in COMSOL, as described in [25]. The RF response of the probe circuit was simulated using a symbolic network analysis code [28] in order to estimate appropriate component values. Final tuning was done by trial and error using an Agilent FieldFox 4 GHz network analyser. PCB layouts were designed using KiCAD, and then sent to beta-layout GmbH (Aarbergen, Germany) and P.W. Circuits Ltd. (Wigston, UK) for manufacturing. Easily and inexpensively available FR4 PCB material (Fig. 3(A)) proved adequate for some purposes, but limited resolution to about 10 Hz. A high-quality Teflon-based RF PCB material (RO3035, Rogers Corp., USA) was therefore used for optimal performance in both sensitivity and resolution (Fig. 3(B)). The probe skeleton was assembled from prefabricated aluminium tubes held with the precision-machined scaffold disks using brass screws. Semi-rigid transmission lines were then threaded through the tubes,

and the TMPCB plate was soldered on top. The detector planes (3 and 5) and the PMMA spacer between them were assembled using short bits of 0.5 mm magnet wire, which were soldered to the appropriate pads in the four corners of the detector structure.

NMR experiments were performed on a Varian VN-MRS console attached to a Varian 600 premium shielded 14.1 T magnet. Imaging experiments were performed on Bruker AVANCE III spectrometer on a Bruker Active Shield II wide bore 11.7 T magnet. Sodium acetate and ^{15}N labeled urea were purchased from sigma-aldrich, UK and Dulbecco Modified Eagle's Medium (DMEM) supplemented was purchased from Life Technologies, USA.

Precision-cut murine liver slices (PCLS) were obtained by first extracting a tissue core of 8 mm diameter using a biopsy punch. PCLS of 250-300 μm thickness were cut from the core using a Krumdieck Tissue slicer, and then reduced to 3 mm diameter using a smaller punch. The slices were incubated in well-plates at 37°C and 80% O_2 , 5% CO_2 for 2 hours before imaging.

4. Results and Discussion

The probe is designed for double resonance, with proton-detected experiments in mind. The circuit is optimised for efficiency and sensitivity at the high-frequency channel, while allowing RF pulses to be applied at the X frequency as well. As already explained, the X channel tuning frequency can be changed by simply exchanging either only a small RF-insert or the complete detector assembly. Fig. 6 shows the measured reflection and transmission scattering coefficients (S -parameters) as a function of frequency for two combinations of proton (600 MHz, 500 MHz) and X channel frequencies (60 MHz and 125 MHz), corresponding to the Larmor frequencies of ^{15}N and ^{13}C at magnetic fields of 14.1 T and 11.7 T respectively. The measurements were performed in the pairs of 600 MHz and 60 MHz and 500 MHz and 125 MHz. The loaded Q factors, determined from the -3dB points of the reflection curves, are 42, 49, 32, 36 at 600 MHz, 500 MHz, 125 MHz and, 60 MHz respectively. The channel separation is better than -15dB at all operating frequencies.

Initially, FR4 PCB material was used for the detector assembly because of its low cost and easy availability. Inhomogeneities in the B_0 field due to the glass fibre rovings in FR4's composite backing can be seen as fringes in Fig. 7 (A). B_0 field maps of the sample chamber were constructed from 2 gradient echo (FLASH) images having echo times (t_e) of 6 and 16 ms and repetition time (t_r) of 100 ms for both FR4 and RO3035 PCB materials with the same chip (Fig. 7). The brightness of each pixel is proportional to the sum of the magnitude of the two images, whereas the colour encode the phase difference between them. The full colour range from red to blue spans phase differences from $-\pi$ to $+\pi$.

To avoid the inhomogeneities of FR4 and therefore to achieve better resolution, detectors were made from

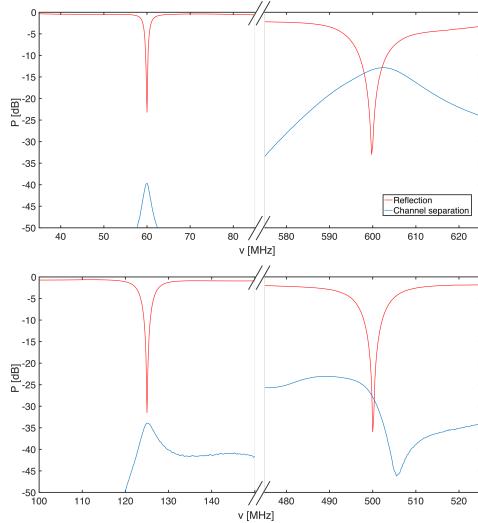


Figure 6: Experimental tuning and matching curves measured at 600 MHz, 500 MHz, 60 MHz (^{15}N frequency at 14.1 T) and 125 MHz (^{13}C frequency at 11.7 T). Probe can be tuned to 2 frequencies at a time, above results were measured in pairs of 600 MHz with 60 MHz and 500 MHz with 125 MHz. Decoupling can be performed at all the frequencies as the channel separation is better than 15 decibels at all frequencies.

RO3035 material. While RO3035 provides better resolution, it is more expensive and takes longer to obtain compared to FR4. It therefore makes sense to first prototype new detector designs in FR4, and only use the more expensive RO3035 once the design has been validated.

The RF field at proton frequency shows excellent homogeneity, with a $810^\circ/90^\circ$ ratio of more than 90% measured from ^1H nutation of the water peak in an aqueous solution of 100 mM ^{15}N -urea at 600 MHz. The probe generates 100 kHz nutation frequency from 100 W input power both at 600 MHz and 500 MHz, corresponding to RF field efficiency ($B_1/\sqrt{\text{power}}$) of $10 \text{ kHz}/\sqrt{W}$. The detector geometry has been optimised for a sample volume of $5 \mu\text{l}$. It compares reasonably well to the value of 22

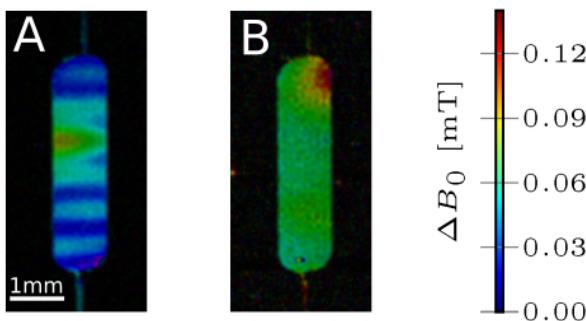


Figure 7: B_0 field map of the sample chamber for FR4 (A) and Rogers RO3035 (B) PCB material. Both the field maps were constructed from 2 gradient echo images acquired on a chip filled with 130 mM sodium acetate dissolved in H_2O through same parameters and pulse sequence.

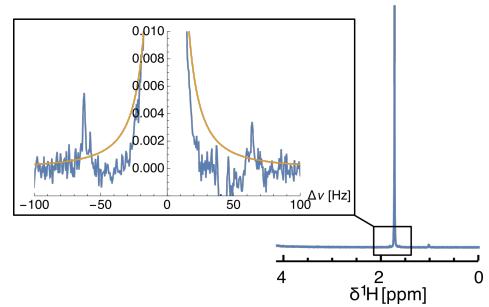


Figure 8: Spectrum of 130 mM sodium acetate dissolved in water acquired in 32 scans with water presaturation. Carbon satellites can be seen in the expanded base of the acetate line. The orange curve shows a lorentzian lineshape with full width at half maximum of 3.35 Hz.

kH/\sqrt{W} that has been reported by Finch et al. [25] for single-frequency detector of half this size at a Larmor frequency of 300 MHz. For X channel, 100 W of input power produces nutation frequencies of 6 kHz for ^{15}N and 14 kHz for ^{13}C . No signs of arcing were observed at this power level for pulses up to 1 ms duration.

Fig. 8 shows proton spectrum of $2.5 \mu\text{l}$ of 130 mM sodium acetate dissolved in H_2O acquired at 600 MHz. The spectrum was acquired with water presaturation at 100 Hz. 32 transients were averaged with a repetition delay of 3 s. The inset shows an expanded view of the base of the acetate peak. Carbon satellites can be seen well above the noise level. The orange curve corresponds to a Lorentzian lineshape with full width at half maximum of 3.35 Hz, corresponding to 0.0056 ppm. This is very similar to the resolution reported by Finch et al. at 300 MHz. While the residual cause of broadening is still under investigation, we have reason to suspect imperfections in the fabrications of the PMMA microfluidic devices to play a major role. Efforts to mitigate these and to achieve more highly resolved proton spectra are currently underway in our laboratory and will be reported at a later occasion. The limit of detection $nLOD_\omega = \frac{3n\sqrt{\Delta t}}{SNR}$ (n is the number of spins and Δt is 1/linewidth of the observed resonance) is $1.4 \text{ nmol s}^{1/2}$ of protons at 600 MHz, slightly better than the value reported for a smaller detector by Finch et al. [25].

Even though the resolution of the proton spectra still needs to be improved, it is sufficient to analyse complex mixtures. The proton spectrum of DMEM (Dulbecco modified Eagle's medium) cell growth medium acquired with 256 scans in 20 mins is shown in Fig. 9. This demonstrates the suitability of this probe for metabolomic studies of microfluidic cultures of cells, tissues, and small organisms.

Fig. 10 demonstrates proton-detected double resonance experiments in the current setup. The left panel shows a $^{13}\text{C}-^1\text{H}$ heteronuclear single quantum correlation (HSQC) spectrum, acquired in 12 mins (32 t_1 increments and 16 scans) from a $2.5 \mu\text{l}$ sample of 100 mM ^{13}C -glucose dissolved in water. The right panel shows a $^{15}\text{N}-^1\text{H}$ -HSQC spectrum, acquired in 400 mins (64 t_1 increments and 128

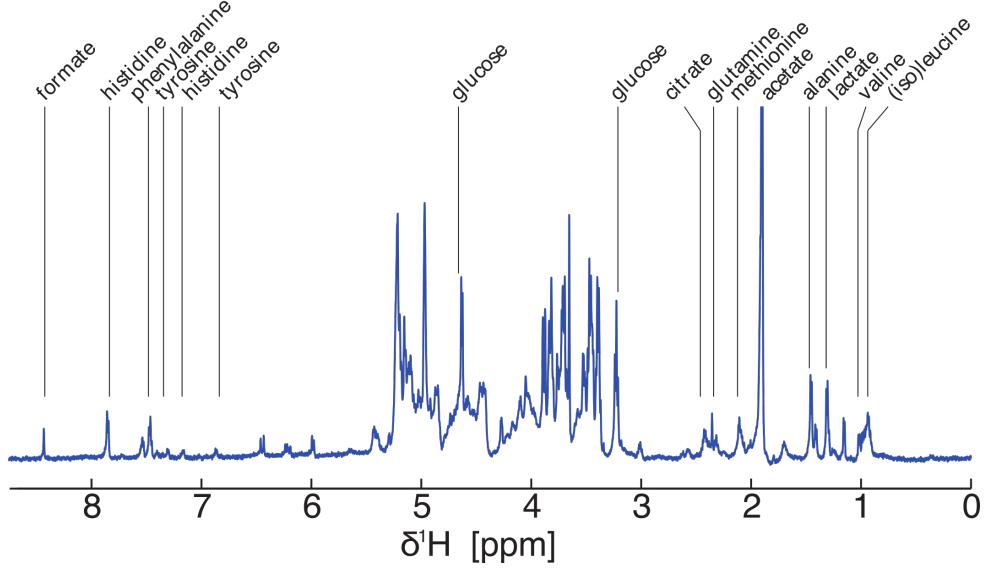


Figure 9: Spectrum of culture growth media recorded in 256 scans with water presaturation. The total experimental time was 20 min for 2.5 μl sample volume.

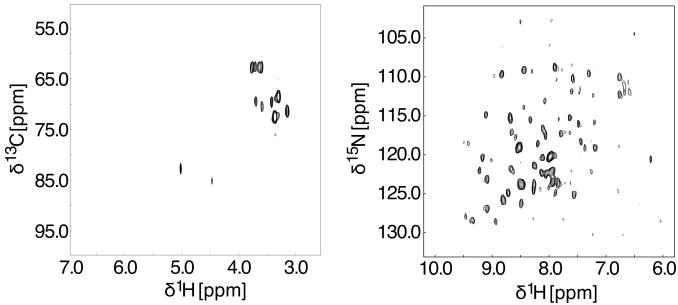


Figure 10: ^1H - ^{13}C HSQC spectrum of ^{13}C labeled glucose (left) and ^1H - ^{15}N HSQC of ^{15}N labeled Ubiquitin (right) both acquired from 2.5 μl sample volume at 14.1 T. Glucose HSQC spectrum was acquired in 12 minutes from a 100 mM sample. Ubiquitin HSQC spectrum was acquired in 400 minutes from a 1 mM sample.

scans) from 2.5 μl sample of 1 mM ^{15}N -ubiquitin (17 μg) dissolved in 10 mM phosphate buffer at pH 7. All expected cross peaks are present in the spectrum. The ability to obtain meaningful ^{15}N - ^1H correlation spectra from such small samples could prove very useful in the context of proteins that are difficult to express and therefore only available in small quantities. The integration of protein NMR and microfluidic technology also opens new possibilities for high-throughput kinetics and binding studies.

The probe can also be used to acquire micro magnetic resonance (MR) images using a Bruker micro-gradient unit. To this effect, the aluminium probe sleeve must be replaced by an electrically insulating material in order to avoid image distortions due to eddy currents in the sleeve. Fig. 11 shows MR images of mouse liver tissue slice immersed in DMEM cell growth medium. The slice was placed in a mi-

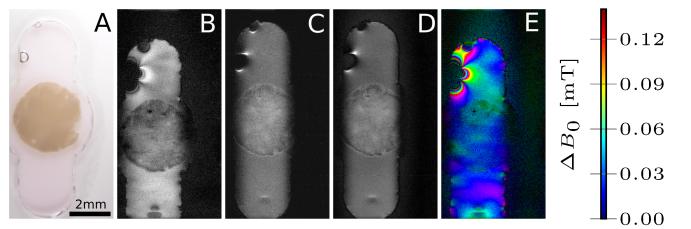


Figure 11: MR images of a freshly cut live slice from a mouse. A: optical micrograph; B: Gradient echo image acquired in 1 minute; C: RARE8 image acquired in 8 minutes; D: Spin echo image acquired in 30 minutes; E: magnetic field map.

crofluidic device with circular sample chamber centred at the detector location, as shown in Fig. 11(A). The image shown in Fig. 11(B) was acquired using a FLASH pulse sequence with $t_R = 120$ ms and $t_E = 15.3$ ms. The slice thickness of 1 mm encompasses the entire thickness of the tissue; the lateral dimensions of all MR images in Fig. 11 are 512×512 pixels at a resolution of 30 μm . Fig. 11(C) shows a RARE image using the same parameters, with 8 echos acquired per scan, thus reducing the acquisition time to 8 minutes. A spin echo image is shown in Fig. 11(D), acquired over 25 min. Finally, Fig. 11(E) shows a B_0 field map, which has been obtained by acquiring two separate FLASH images with echo times $t_E = 5.3$ ms and 15.3 ms, respectively. , corresponding to local field variations of $\Delta B/B_0 = \dots$ **compute value and insert here**.

5. Conclusions

We have presented a novel modular NMR probe assembly for generic high sensitivity microfluidic NMR experiments. The probe is built from the readily accessible materials, using only a minimum of custom-made parts. The modularity of the probe enables to use different detectors tailored for specific experimental requirements on the same probe skeleton. The detector itself is made from easily available PCB materials. The use of PCB technology offers great flexibility, and allows to modify the probe circuit and design without affecting the probe geometry. The probe has excellent B_1 homogeneity and its sensitivity is in line with the best performances that have been reported in this range of probe volumes.

Using simple microfluidic devices made from PMMA sheets by laser cutting, spectral resolution around 0.005 ppm is achieved in proton spectra at 600 MHz. This is sufficient for primary metabolic studies, but some applications could benefit from better resolution. The probe has already been used for various experiments including reaction monitoring [29], micro-imaging of mouse liver tissue slices, and metabolic studies of mammalian cells. The probe is designed for double resonance, and acquisition of proton-detected heteronuclear correlation experiments has been demonstrated for small molecules as well as proteins. In the future we intend to add a field-frequency lock channel, as well as additional functionality for advanced microfluidic perfusion with temperature and flow control.

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