

Appendix 1

Properties of NMR-Visible Isotopes and their Biological Content in Human Tissues

Table 1. NMR properties of common biologically observable nuclei at natural abundance at 1.0 T

Nucleus/isotope	¹ H	² H	¹³ C	¹⁴ N	¹⁷ O	¹⁹ F	²³ Na	³¹ P	³⁵ Cl	³⁹ K	⁴³ Ca
NMR frequency	42.577	6.536	10.705	3.076	5.772	40.055	11.262	17.235	4.172	1.987	2.865
Abundance (%)	99.98	0.0156	1.109	99.64	0.0373	100	100	100	75.40	93	0.135
Isotopic weight	1.008	2.014	13.003	14.003	16.999	18.998	22.990	30.974	34.969	38.964	42.959
Spin, <i>I</i>	1/2	1	1/2	1	5/2	1/2	3/2	1/2	3/2	3/2	7/2
Relative sensitivity	1	9.64 × 10 ⁻³	0.0159	1.01 × 10 ⁻³	0.0291	0.834	0.0927	0.0664	4.71 × 10 ⁻³	5.08 × 10 ⁻⁴	0.0639
Relative SNR ^a	1	0.0628	0.0632	0.0139	0.2144	0.885	0.3498	0.1639	0.048	0.0109	0.0951

Notes: The frequency is in megahertz. The isotopic weight is used for calculating molar concentrations.

^aThe signal-to-noise ratio relative to ¹H for an equal number of NMR nuclei (say, 1 mol) assuming: 100% NMR-visible signals at equilibrium; monochromatic chemical shift dispersions; no polarization enhancement; and detection via a noiseless receiver with the same bandwidth for each nucleus (see **The Basics**). Note that $SNR \propto \gamma^2 I(I+1)$ where γ is the gyromagnetic ratio ($=2\pi$ times the NMR frequency listed per Tesla) to account for frequency-dependent sample-dominant noise. This differs from the 'relative NMR sensitivity' $\propto \gamma^3 I(I+1)$ listed above and reported variously. The relative SNRs are the same as the relative equilibrium magnetizations at 1 T.¹

Table 2. Water, fat, specific gravity (shaded), and elemental content of common biological tissues from healthy adult humans

Tissue	H ₂ O %	Fat/lipid %	SG	H%	O%	C%	N%	P%	Cl%	Ca%	Na%	K%
Total body	60	19	1.06	10.0	61.4	22.9	2.57	0.829	0.136	1.429	0.143	0.200
Brain	77.4 (76–79)	11	1.03–1.04	10.7	71.4	12.1	1.29	0.343	0.229	0.00857	0.179	0.300
Brain – GM	84–86	5.3	1.039									
Brain – WM	68–77	18	1.043									
Brain – CSF	99	0.00	1.007									
Blood	80.5–80.8	0.65	1.058	10.8	91.7	0.0133	0.00450	0.002	0.442	0.00458	0.500	0.010
Fat/adipose	15 (11–21)	80	0.916	10.0	74.5	9.82	2.91	0.035	0.273	0.00564	0.182	0.160
Heart	72 (63–83)	10 (3–17)	1.03	12.0	23.3	64.0	0.8	0.016	0.120	0.00227	0.051	0.032
Liver	71 (64–74)	6.9 (1–12)	1.05	10.3	69.7	16.4	2.67	0.145	0.164	0.00364	0.121	0.218
Skeletal muscle	79 (69–80)	2.5 (2.2–9.4)	1.041	10.0	66.7	14.4	2.83	0.261	0.200	0.00500	0.100	0.250
Kidney	76 (71–81)	5 (1.8–7.2)	1.05	10.0	75.0	10.7	2.75	0.179	0.079	0.00311	0.075	0.300
Prostate	83	1.1 (0.7–1.5)	1.045	10.3	74.2	12.9	2.74	0.161	0.239		0.200	0.190
Pancreas	71 (67–73)	8 (2.9–20.4)	1.045	9.38	75.0	8.8	2.38	0.100		0.0219	0.200	0.188
Marrow – red	~40	~40	1.027	9.70	67.0	13.0	2.10	0.230	0.160	0.00910	0.140	0.230
Marrow – yellow	~15	35 (26–38)	0.974	11.3	22.7	63.3	0.64	0.014	0.107		0.044	
Spleen	77 (72–79)	1.6 (0.9–3)	1.054	10.0	72.2	11.1	3.11	0.222	0.161	0.00667	0.122	0.311

Notes: Values are percent wet tissue weight, obtained by dividing in vitro assayed elemental masses by the standard tissue masses (listed in the first column of Table 3) using data from Reference 2. The specific gravity (SG),² is used for converting magnetic resonance spectroscopy voxel volumes to gram tissue weight.

Table 3. Molar concentrations of common biologically observable NMR isotopes at natural abundance in healthy adult humans

Tissue	Standard (wt, g)	[¹ H ₂ O] (mol kg ⁻¹)	¹ H (mol kg ⁻¹)	² H (mmol kg ⁻¹)	¹⁷ O (mmol kg ⁻¹)	¹³ C (mmol kg ⁻¹)	¹⁴ N (mmol kg ⁻¹)	³¹ P (mmol kg ⁻¹)	³⁵ Cl (mmol kg ⁻¹)	⁴³ Ca, (mmol kg ⁻¹)	²³ Na (mmol kg ⁻¹)	³⁹ K, (mmol kg ⁻¹)
Total body	70 000	66.6	99	7.75	13.5	195	18.3	268	29	45	62	43
Brain	1400	85.9	106	8.30	15.7	104	9.1	111	49	0.27	50 ^a	72
Brain – GM		94.4									55 ^b	
Brain – WM		80.5									44 ^b	
Brain – CSF	120	109.9	107	8.39	20.1	0.11	0.032	0.5	95	0.14	127 ^b	2.8 ^a
Blood	5500	89.5	99	7.75	16.4	84	20.7	11.2	59	0.18	132 ^a	4.3 ^a
Fat/adipose	15000	16.7	119	9.30	5.1	546	5.7	5.2	26	0.071	19 ^b	7.7
Heart (myo)	330	79.9	102	7.98	15.3	140	19.0	47.0	35	0.11	43	52
Liver	1800	78.8	99	7.75	14.6	123	20.2	84.3	43	0.16	43	60
Muscle	28000	87.7	99	7.75	16.5	91	19.6	57.7	17	0.10	27 ^b	72
–skeletal												
Kidneys (2)	310	84.4	102	8.00	16.3	110	19.5	52.1	51	0.29	87	46
Prostate	16	92.1	93	7.26	16.5	75	16.9	32.3		0.69	87	45
Pancreas	100	78.8	96	7.51	14.7	111	14.9	74.3	35	0.29	61	55
Marrow – red	1500	44.4	99	7.75	9.1	353	22.8					
Marrow – yellow	1500	16.7	112	8.78	5.0	540	4.6	4.5	23	0.061	19	
Spleen	180	85.5	99	7.75	15.8	95	22.1	71.7	35	0.21	53	74

Notes: Determined from $1000 \times (\% \text{ elemental weight}) \times (\% \text{ isotopic abundance}) / (\text{isotopic weight})$ in moles per kilogram wet tissue weight using data in Reference 2, or from ^aclinical data and from ^bin vivo ²³Na magnetic resonance imaging measurements summarized in **Sodium MRI in Man: Technique and Findings**.³ [¹H₂O] is the concentration of ¹H in the tissue water moiety (note unit change between ¹H and other nuclei). The first column lists the standard adult tissue weights used in Tables 2 and 3 (e.g., an average 70 kg adult has a 330 g heart, excluding chamber blood, with [¹⁴N] = 19 mmol kg⁻¹). The product of the molar tissue concentrations in this table, with the relative SNR in Table 1 (shaded), divided by the ¹H (or ¹H₂O) concentration, is the expected SNR for the nucleus (assumed monochromatic) relative to ¹H (or the ¹H water signal) in the tissue of interest.

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