Supplemental Document

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Review of recent advances in frequency-domain near-infrared spectroscopy technologies [Invited]: supplement

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List of abbreviations

AFE	analog front-end
APD	avalanche photodiode
BLL	beer-lambert law
CBF	cerebral blood flow
CBV	cerebral blood volume
CMOS	complementary metal-oxide semiconductor
CPAP	continuous positive airway pressure
CW	continuous-wave
DAQ	data acquisition
DCS	diffuse correlation spectroscopy
DDS	direct digital synthesizer
DOS	diffuse optical spectroscopy
DOT	diffuse optical tomography
DSS	digital synthesis system
ECMO	extracorporeal membrane oxygenation
EEG	electroencephalography
EEL	edge-emitting laser
FD	frequency-domain
fNIRS	functional NIRS
FDPM	frequency domain photon migration
FPGA	field-programmable gate array
GSPS	gigasample per second
HbO	oxy-hemoglobin
HbR	deoxy-haemoglobin
HBT	heterojunction bipolar transistor
HbT	total hemoglobin

IC	integrated circuit
KNN	k-nearest neighbor
LUT	look-up table
MOSFET	metal oxide silicon field effect transistor
MSPS	megasamples per second
NEP	noise equivalent power
NIR	near infrared
NIRS	near-infrared spectroscopy
OEF	oxygen extraction fraction
$PbtO_2$	cerebral tissue oxygen tension
PCB	printed circuit board
PD	photodiode
PDC	phase-to-digital converter
PLL	phase-locked-loop
PMT	photo-multiplier tube
$rcSO_2$	cerebral oxygen saturation
RF	radiofrequency
SCM	sternocleidomastoid
SDS	source-detector separation
SiGe	silicongermanium
SiPM	silicon photomultiplier
SNR	signal-to-noise ratio
SOC	system on a chip
SPAD	single-photon avalanche diode
tDCS	transcranial direct current stimulation
TD-NIRS	time-domain NIRS
TIA	transimpedance amplifiers
TOBI	tomographic optical breast imaging
TTL	transistor–transistor logic (missing)
VCSEL	vertical-cavity surface-emitting laser
VGA	variable gain

Table S1. Sources and Detectors Employed in Reviewed FD-NIRS Technologies.

Author, Year	Source Brand	Source Type	Part No. of Source	Light density of Source (mW)	Size of Source	Power consumption of Source	Detector Brand	Detector Type	Part No. of Detector	Photo-sensitive area of Detector	Size of Detector	Power consumption of Detector	Wavelength
Campbell et al., 2020 [21]	-	LD	-	-	-	-	Hamamatsu	APD	S12060-10	Φ1 mm	Φ5.4 × 3.7 mm^2	-	631, 660, 689, 782, 828, 849 nm
Choe et al., 2009 [23]	-	LD	-	-	-	-	-	APD	-	-	-	-	681, 783, 823,850 nm
Zhang,et al., 2005 [24,25]	-	LD	-	-	-	-	Hamamatsu	APD	C5331-04	Φ3 mm	80 × 45 × 19.6 mm	-	
El-Ghussein et al., 2013 [27]	-	LD	-	2-5	-	-	Hamamatsu	PMT	H9305-3	3.7 mm × 13 mm	53.2 × 50.8 × 19 mm^3	126 mW	660, 735, 785, 808, 826, 849 nm
Carp et al., 2017 [29]	-	LD	-	14, 10	-	-	Hamamatsu	PMT	R9880U-01	Φ8mm	Φ16 × 12.4 mm^2	-	670, 690, 700, 730, 760, 780, 810, 830 nm
Mackey et al., 2020 [30]	-	LD	-	-	-	-	-	PMT	-	-	-	-	-
Lee et al., 2022 [31]	-	-	-	-	-	-	-	-	-	-	-	-	785, 824 nm
Huang et al., 2017 [32]	Amplitude System	Yb-YAG laser	Mikan	-	-	-	Hamamatsu	APD Module	C5658	Φ0.5mm/ Φ3mm(in vivo)	28 × 50 × 60 mm^2	1.2W	700, 750, 800, 1030 nm
Zimmermann et al., 2016 [33]	Thorlabs	LD	HL6750MG/ HL8338MG	12.5	-	50 mW	Hamamatsu	APD Module	C5331-04	Φ3 mm	80 × 45 × 19.6 mm^3	-	685, 830 nm
Thompson et al., 2021 [34]	Thorlabs	LD	HL6738MG/ L852P50	12.5	Φ5.6 × 2.3mm	-	Thorlabs	APD Module	APD430 A	Φ0.5 mm	50.8 × 63.5 × 25.4 mm^3	3 mW	690 nm, 852 nm
Wathen et al., 2021 [36]	Thorlabs	LD	HL6738MG/ L852P50	10	Φ5.6 × 2.3mm	-	onsemi	SiPM	MicroRB-10020	Φ0.5 mm	50.8 × 63.5 × 25.4 mm^3	3 mW	690, 852 nm
Chen et al., 2004 [40]	-	LD	-	-	-	-	Hamamatsu	APD	S3884	Φ1.5 mm	Φ9.1 × 4.7mm^2	-	660, 780, 830nm
O'Sullivan et al., 2017 [42]	Vixar/Thorlabs	VCSEL / EEL	(VCSEL)/LD 808-SA60	11.6-17.8	-	155(Array)/143 (Single) mW	Hamamatsu	APD	S6045-05	Φ3 mm	Φ9.1 × 4.2 mm^2	-	680, 795, 850 nm
Torjesen et al., 2017 [46]	Thorlabs	LD Module	LDM9T	50	78.5 × 73.3 × 45.5 mm	12 W	Hamamatsu	APD Module	C5658	Φ0.5 mm/ Φ3 mm (in vivo)	28 × 50 × 60 mm^3	1.2 W	658, 690, 785, 808, 830, 850 nm

Istfan et al., 2019 [50]	Vixar	VCSEL	(Custom)	1.2-7.84	Φ5 mm	-	Hamamatsu	Compact APD	S13282-01CR	Φ0.2 mm	5.3 × 3.0 × 1.2 mm^3	-	660, 680, 775, 795 nm
Applegate et al., 2021 [51]	-	LD	-	-	-	-	Hamamatsu	APD	S11519-30	Φ3mm	Φ13.9 × 4.9 mm^2	-	690, 730, 785, 808, 830, 850 nm
Stillwell et al., 2021 [58]	Thorlabs/ Vixar	EEL/VCSEL	HL6738MG, L785P090, L808P200, L850P030, L980P030	35-100 (Factory)	Φ5.6 × 3.5 mm^2 (EEL)	240mW (EEL)	Hamamatsu	APD	S2384	Φ3mm	Φ9.1 × 4.2 mm^2	-	690, 785, 808,850, 940 980 nm
Miao et al., 2018 [63]	Thorlabs	LD	HL8338MG/ L785P090/H L6750MG	2.5	Φ5.6×2 .3mm^2 for all	-	Hamamatsu	APD	S9251-15	Φ1.5mm	Φ9.1 × 4.2 mm^2	-	685, 785, 830 nm
Kılıç et al., 2022 [64]	Thorlabs	LD	HL6750MG/ HL8338MG	-	-	50 mW	Hamamatsu	APD	S9251-15	Φ1.5mm	Φ5.4 × 3.6 mm^2	-	690, 830 nm
Yazdi et al., 2017 [65]	BlueSky Research/Tho rlabs/ Qphotonics	LD	VPSL0690-035X5A, VPSL0830-050X5A/L78 5P090/QLD-980-150S	35-50, (Factory)	Φ5.6×3 .5mm^2 (Thorla bs)	240 mW	Hamamatsu	APD	S12023-02	Φ0.2mm	Φ5.4 × 3.7 mm^2	-	690, 785, 830, 980 nm
Chen et al., 2022 [66]	Thorlabs	LD	HL6750MG	-	-	50 mW	Hamamatsu	APD	C12703	Φ1.5mm	80 × 50 × 21.6 mm^3	-	685 nm
Koh et al., 2022 [67]	-	VCSEL	-	-	-	-	-	APD Module	-	-	-	-	-
Scammon, 2022 [68]	Thorlabs	LD	L785P25	25 (Factory)	Φ5.6 × 2.3mm	-	Thorlabs	APD Module	APD430 A	Φ0.5 mm	50.8 × 63.5 × 25.4 mm^3	3 mW	785 mm

Table S2. Phase Measurement Components Employed in Reviewed FD-NIRS Technologies.

Author, Year	Brand	Name	Part Number	Components Frequency Range	Number of Measurement channels	Size of Component
Campbell et al., 2020 [21]	Agilent	Network Analyzer	8753ES	30kHz-3GHz	1	222 mm × 425 mm × 457 mm
Choe et al., 2009 [23]	-	-	-	-	-	-
Zhang et al., 2005 [24,25]	-	I/Q Demodulator with PC	-	-	-	-
El-Ghussein et al., 2013 [27]	National Instruments	PC with signal down converted (With DAQ)	PCI 6031E	-	-	DAQ, 307 × 254 × 43 mm
Carp et al., 2017 [29]	-	PC with signal down converted	-	-	-	-
Mackey et al., 2020 [30]	-	PC with signal down converted	-	-	-	-
Lee et al., 2022 [31]	-	PC with signal down converted	-	-	-	-
Huang et al., 2017 [32]	Stanford Research	Lock-in Amplifier with signal down converted	SR830	1 MHz	1	-
Zimmermann et al., 2016 [33]	Xilinx	FPGA (With PC)	Spartan-6 LX9/(MATLAB)	-	1	FPGA, < 20mm × 20 mm
Thompson et al., 2021 [34]	-	PC with signal down converted	-	-	12	-
Wathen et al., 2021 [36]	-	PC with signal down converted	-	-	32	-
Chen et al., 2004 [40]	-	PC with signal down converted	-	-	-	-
O'Sullivan et al., 2017 [42]	-	Network analyzer	-	50 - 500 MHz	-	-
Torjesen et al., 2017 [46]	MircoZed	FPGA SoC Platform (With PC)	Xilinx Zynq-7010/(MATLAB)	-	1	FPGA, 10×6cm^2
Istfan et al., 2019 [50]	Agilent	Network Analyzer	E5061B	100 kHz - 3 GHz	1	-
Applegate et al., 2021 [51]	MircoZed	FPGA SoC Platform (With PC)	Xilinx Zynq /(MATLAB)	-	-	-
Stillwell et al., 2021 [58]	Krtkl Snickerdoodle	FPGA SoC Platform	Xilinx Zynq 7020	-	1	FPGA, 88.9×50.8 mm
Miao et al., 2018 [63]	-	130nm Custom Chip with PC	-	80MHz	1	2.25 mm^2
Kılıç et al., 2022 [64]	-	PC with signal pre-processing on custom chip	-	80MHz	1	-
Yazdi et al., 2017 [65]	-	180nm Custom chip	-	50-1000MHz	1	~5 × 5 mm
Chen et al., 2022 [66]	-	180nm Custom chip	-	10MHz	1	-
Koh et al., 2022 [67]	-	180nm Custom chip	-	150MHz	1	FD part, 2.5mm × 2.5 mm
Scammon, 2022 [68]	Xilinx	FPGA SoC Platform (With PC)	ZCU102	-	1	-