Table 1 Technological Development of MCG Devices.

Classification	Development Stage	Key Technological Advances	Application Scope	Key Performance Parameters	Representative Devices and Companies
Superconducting MCG Devices	1970–2000: exploration and foundation	1. First application of SQUID for cardiac magnetic signal detection 2. Multi-channel sensor arrays (from single-channel to approximately 7–37 channels) for simultaneous spatial acquisition 3. Introduction of Magnetic Shielded Room (MSR) technology reduced environmental noise 4. Initial algorithms for cardiac magnetic signal filtering and spatial localization 5. Research on liquid helium cooling systems to maintain superconductivity	Gradual transition from basic research and technical validation to clinical exploration, including non-invasive diagnosis of myocardial ischemia, coronary artery disease, arrhythmia localization (e.g., Wolff-Parkinson-White syndrome), and fetal cardiac activity monitoring	Channels: single to 7–37 Sensitivity: increased from ~100–200 fT/√Hz to ~5–20 fT/√Hz Time resolution: ≤1 ms Spatial resolution: increased from >50 mm to ~10–20 mm	Siemens Krenikon (Germany), BTi Magnes I/II (USA, adapted from MEG technology)
	2000–2020: maturation and initial clinical application	1. Marked enhancement in SQUID sensitivity through improved device structures and materials 2. Maturation of large-scale multi-channel arrays (64–128 channels) 3. Enhanced noise suppression technologies (multilayer magnetic shielded rooms and dynamic magnetic field compensation algorithms) 4. Initial implementation of real-time adaptive filtering, spatial filtering, and basic AI algorithms 5. Optimization of cryogenic systems (increased helium efficiency and introduction of preliminary liquid nitrogen cooling)	Clinical studies expanded to early coronary artery disease diagnosis, myocarditis and cardiomyopathy monitoring, pre- and post-ablation guidance, ion channelopathy screening (e.g., long QT and Brugada syndrome), cardiac resynchronization therapy assessment, and cardiac electrophysiological research	Channels: 64–128 Sensitivity: ~1–5 fT/√Hz Time resolution: 0.1–0.5 ms Spatial resolution: ~5–10 mm	Elekta Neuromag MCG (Finland), Tristan Technologies 621/624 (USA)

Table 1 (Continued)

Classification	Development Stage	Key Technological Advances	Application Scope	Key Performance Parameters	Representative Devices and Companies
	2020 to present: clinical expansion and technological innovation	1. Quantum-limited SQUID sensors and emerging high-temperature superconducting technology 2. Deep integration of AI for real-time signal processing, noise reduction, and abnormality detection [1] 3. Portable and mobile MCG devices using active noise cancellation and AI-based filtering, enabling high-quality measurements with minimal or no fixed shielding rooms 4. Development of helium-free cooling and closed-cycle refrigeration technologies	Further clinical applications including myocardial ischemia assessment for percutaneous coronary intervention strategies, acute chest pain evaluation, coronary microvascular dysfunction, prediction of sudden cardiac death risk, and monitoring treatment response in cardiac amyloidosis and cardiomyopathies [2]	Channels: as many as 128–300+ Sensitivity: <1 fT/√Hz Time resolution: 0.1–0.5 ms (quantum sensors up to 0.01 ms) Spatial resolution: Typically 5–10 mm	CS MAG II/III, Biomagnetik Park GmbH (Germany)
Non-Superconducting MCG Devices	~2010: initial exploratory stage	1. Initial exploration of non-superconducting detection methods including Hall-effect sensors and giant magnetoresistance/tunnel magnetoresistance 2. Atomic magnetometers used in basic physical research stages	Limited to laboratory validation	Channels: single or few Sensitivity: >100 fT/√Hz, strongly affected by noise Time resolution: 1 ms Spatial resolution: low, difficult accurate localization	No commercial systems; laboratory prototypes only
	2010–2020: breakthrough and system development	1. Breakthroughs in atomic magnetometer technology, notably optical pumped magnetometers (OPMs) and spin-exchange relaxation-free (SERF) magnetometers 2. Multi-channel array maturation 3. Enhanced environmental adaptability with localized shielding, gradient meters, and active magnetic field feedback 4. Miniaturization and initial portability 5. Development of advanced signal processing algorithms (independent component analysis, adaptive filtering, and initial machine learning applications) [3]	Non-invasive myocardial ischemia assessment, early coronary artery disease diagnosis, arrhythmia localization (e.g., premature ventricular contractions) [4], fetal arrhythmia monitoring, and multimodal integration with ECG	Channels: 7–37 Sensitivity: 5–20 fT/√Hz (SERF magnetometers <1 fT/√Hz) Time resolution: <1 ms Spatial resolution: 10–30 mm	CardioFlux MCG (Genetesis, USA), QZFM Gen-1 OPM (QuSpin, USA)

Table 1 (Continued)

Classification	Development Stage	Key Technological Advances	Application Scope	Key Performance Parameters	Representative Devices and Companies
	2020 to present: clinical translation and commercialization	1. Mature OPM technologies and initiation of solid-state quantum sensors 2. Implementation of multi-channel vector-array MCG prototypes 3. Accelerated development of portable and wearable systems, some capable of operating without dedicated shielding rooms 4. Extensive AI integration for automated cardiac signal recognition and decision support	General cardiac health screening, acute chest pain rapid triage [2], ischemia detection in borderline coronary artery lesions, coronary microvascular dysfunction assessment [5], and quantitative fetal autonomic nervous system development analysis [6]	Channels: OPM-MCG 16–64, SERF 25+ Sensitivity: <5–10 fT/√Hz Time resolution: 0.1–0.5 ms Spatial resolution: 10–20 mm (some reaching 5–10 mm)	QZFM Gen-3 OPM (QuSpin, USA)

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