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6. Criteria for Successful Applications

SQUID magnetometers have been in use for biomagnetic measurements for thirty years, and for nondestructive testing about half that time. SQUIDS

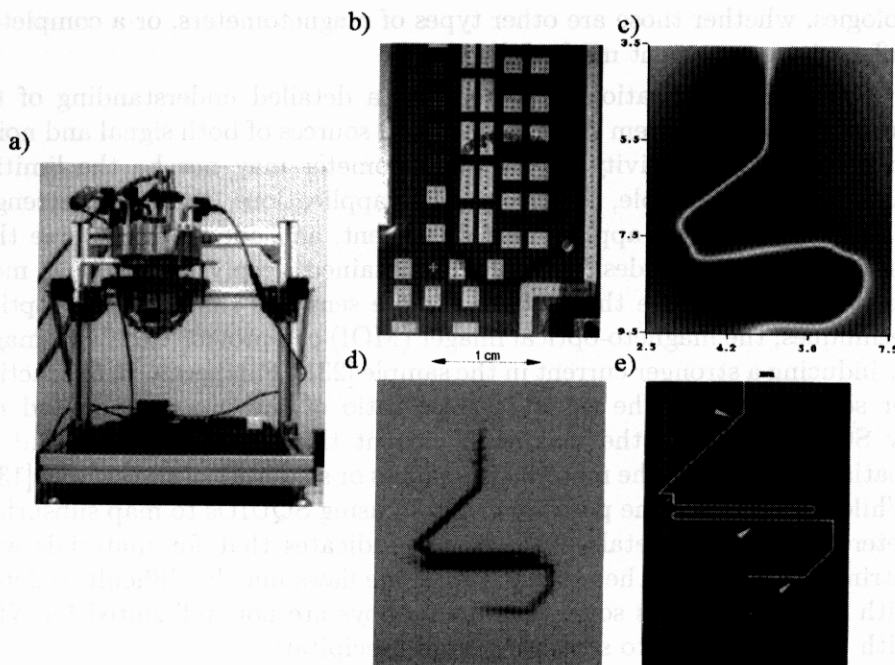


Figure 50. SQUID imaging of integrated circuits obtained by a cryocooled HTS SSM with a working distance of $340\ \mu\text{m}$ between the SQUID and the multilayer circuits within the intact, room-temperature package [70]. a) A prototype of the Neocera HTS SSM developed specifically for imaging integrated circuits. b) An optical photograph of a multichip module (MCM) package. The hand-drawn circle indicates the region where a short was localized with thermography. c) The raw magnetic image obtained from a scan of the component of the magnetic field perpendicular to the area of the sample in (b). The wide white line corresponds to the region of zero field in the z direction, which to a first approximation corresponds to the path of localized current; the magnetic field is of opposite sign on either side of this line. d) The image of the current found from this field using inverse spatial filtering. The spatial resolution measured across the serpentine path of current has a full-width at half-maximum of $75\ \mu\text{m}$ or $\pm 38\ \mu\text{m}$. e) Comparison of the data obtained from the SSM when overlaid with the circuit drawings allowed the location of the circuit fault to be located with an accuracy of better than $\pm 40\ \mu\text{m}$. The computed current path is shown in white on top of the background metalization. (Courtesy of Lee Knauss of Neocera, Inc.)

can provide outstanding sensitivity and spatial resolution, but at a significant fiscal and technical cost. Hence SQUID magnetometers are very good for certain types of measurements, and not terribly good for others. The primary challenge in the successful application of a SQUID to a new problem is to identify as quickly as possible whether SQUIDs would be preferred over another approach. Possibly the most important factor in making this determination is a clear understanding of both the nature and importance of the phenomena being studied and the capabilities of competing tech-

nologies, whether those are other types of magnetometers, or a completely different measurement methodology.

Successful application often requires a detailed understanding of the properties of the system being studied and sources of both signal and noise, such that the sensitivity of the magnetometer may not be the limiting factor. As an example, for many NDE applications, the signal strength is determined by an applied field or current, and one might assume that as large a signal as desired could be obtained simply by applying more current. Hence, while the SQUID is more sensitive than magneto-optical techniques, the magneto-optical imager (MOI) can provide excellent images by inducing a stronger current in the sample [231]. Furthermore, in practice, for some materials the signal-to-noise ratio of the image is limited not by SQUID noise or the maximum current that can be applied, but by spatial variations in the material properties or structure of the sample [139]. While this suggests the possible utility of using SQUIDS to map subsurface heterogeneities in metals [232], it also indicates that for materials with intrinsic conductivity heterogeneities, some flaws may be difficult to detect with SQUIDS, just as some aluminum alloys are not well-suited for NDE with ultrasound due to scattering from precipitates.

In assessing the competition, one must ask "What are the capabilities and limitations of other measurement techniques that do not require the use of superconductivity?" The very best applications of SQUIDS are those for which there is no competition. After twenty years of work, our group has identified several niche areas where SQUIDS offer capabilities that cannot be approached by other measurement techniques: other than by magnetic imaging with SQUIDS, there is no technique capable of determining the spatial distribution and temporal behavior of hidden corrosion activity within aircraft lap joints. There are no clinical techniques, other than magnetoenterography, that can noninvasively diagnose electrical, and hence ischemic, disorders of the human small intestine. SQUID microscopes may be the only technique suitable for high resolution magnetic analysis of thin geological specimens. There are, of course, other applications for which SQUIDS are uniquely suited.

Another class of SQUID applications offers only a differential benefit over other techniques. Fetal magnetocardiography has competition from ultrasound measurements and limited electrical measurements, so the benefits of fetal magnetocardiography will be determined in part by the relative cost of the technique as compared to the other diagnostic modalities, and the clinical utility of the additional information provided by the FMCG. The cost-benefit ratio is determined by engineering, and as SQUID magnetometers and cryogenic refrigerators become more sophisticated, the costs of these systems should decrease and the benefits rise. As another example,

clinically cardiology has the benefit of eighty years of diagnostic experience with the electrocardiogram, which has been used with many millions of patients worldwide. The clinical magnetocardiogram is in its infancy. The benefits of the magnetocardiogram over the electrocardiogram are at present still differential: only when there has been demonstrated a clear clinical advantage of the MCG over the ECG and there is a favorable cost-to-benefit ratio, will the technique become widely accepted.

For both the MCG and the MEG, the first two decades of research were limited to SQUID magnetometers with one or at most several recording channels. With the introduction of multi-channel SQUID arrays, such as the helmet systems for MEG, and the large-array, flat-bottomed system for the MCG, has it been possible to acquire enough high-quality data from a single subject to both learn new science and demonstrate the full capabilities of the technique. Hence one of the criteria for successful application of SQUID magnetometry is that the level of technical sophistication required must rise to the level required to compete with other modalities, some of which are both highly developed and extremely expensive.

The greatest effort in biomagnetism worldwide has been directed toward magnetoencephalography, for which there appear to be clear, albeit differential, benefits. While several dozen helmet systems have been installed worldwide, the technique is not yet universally accepted by the medical community. In part, the MEG has been an example of technology push rather than market pull. The physicists and engineers and businessmen promoting the MEG are working hard for the technique to be accepted. Were the differential benefits of the technique over other diagnostic procedures greater, or the cost-benefit analysis more favorable, the MEG would have become more widely accepted long ago. However, just because the cost-benefit analysis and the differential benefit are not as great as one might hope, there is still ample reason to pursue the development and commercialization of this technology.

In examining the competition to MEG, it is important to be aware that other techniques are developing just as SQUID magnetometry is being advanced (Obviously, the same considerations apply to other SQUID applications) [233]. In the past several years, there have been great advances in quantitative multielectrode electroencephalography [234-237], as well as in positron emission tomography (PET), magnetic resonance imaging (MRI), functional magnetic resonance imaging (fMRI), and single photon electron computed tomography (SPECT). Each of these techniques provide different diagnostic information and different spatial and temporal resolutions as shown in Fig. 51. One must remain aware of the competition, lest a competing technology advance sufficiently to render your technique obsolete!

The challenge is to identify those specific clinical measurements where

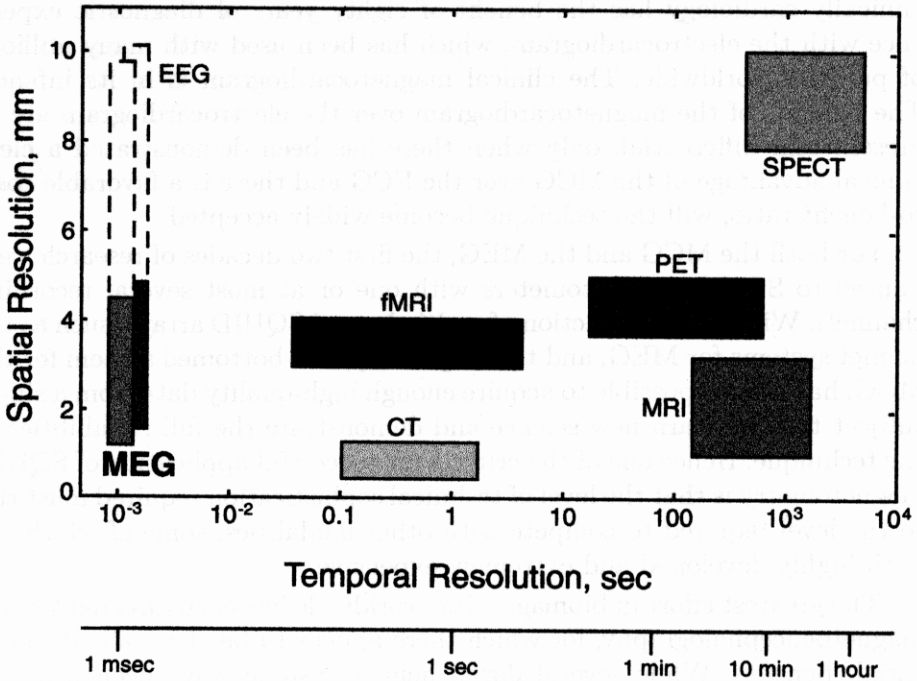


Figure 51. An approximate comparison of the spatial and temporal resolution of various brain-imaging modalities. The dotted boxes for MEG and EEG reflect the differences between localizing (solid) and imaging (dotted) resolution. (Adapted from [109])

the MEG provides information that is sufficiently important to justify the cost. One of the first examples of this limitation is the use of the MEG for a presurgical localization of critical cortical areas prior to the resection of tumors. This is now a proven technique, and is accepted for insurance reimbursement, but is not a sufficiently large clinical problem to justify massive investments in MEG facilities at more than a small number of centers.

An example with potentially favorable economics is the use of MEG to identify the focus of epileptic activity prior to surgical resection [110]. For medically-intractable epilepsy that might be treated surgically, it is important to determine whether there is a single focal source, or at most several sources, that could be treated surgically [238]. At present, the surgical treatment of epilepsy is preceded by a detailed invasive study that costs between \$40,000 and \$50,000, in which electrodes are surgically implanted in the brain and monitored continuously for several days to determine the exact source of the epileptic seizures. Ideally, a noninvasive MEG study would be sufficiently precise so that an invasive study would not be

required. While there are only six thousand or so epilepsy surgeries performed in the US annually, the potential cost savings are significant. There are 25 to 40 epilepsy centers in the United States, most of whose patients would be potential customers for a non-invasive MEG study that might replace the more costly invasive one. However, for this to become an accepted technique, sufficient clinical data must be acquired to demonstrate the utility of the approach, and, most importantly, to obtain the required certification for reimbursement by insurance companies. In the case of the MEG, this might require a multi-center clinical study involving hundreds of epilepsy patients. Should such studies prove successful, MEG systems may be installed in the majority of the medical centers with major programs in epilepsy surgery.

The future of SQUID magnetometers is bright. The technology is continuing to develop in a manner that will improve performance and reduce both cost and technical complexity. The most obvious examples of the improving technology are the clinical systems with hundreds of channels, pulse-tube refrigerators, thin-film SQUID arrays, ultra-high-resolution scanning SQUID microscopes, and even digital SQUIDS. Applications for which SQUIDS are unique or have a clear advantage are being identified, explored, and introduced into the mainstream scientific literature. An important measure of success in the acceptance of SQUIDS as a measurement tool would be their full integration into a scientific or engineering discipline, such that the owners and users of the SQUIDS are not low temperature physicists or engineers, but geologists, biophysicists, physicians, or quality-assurance personnel. To reach that point, it is crucial that SQUID builders either work closely with such individuals, or attempt to make original contributions to those fields. It is not sufficient to build a marvelous SQUID device and expect the world to accept it! As magnetoencephalography has shown most clearly, the SQUID may be only a small part of a complete operating system: the success of the technique will be determined not in the arena defined by SQUID builders, but in the many different arenas that could benefit from a technology.

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