Vision of the future: initial experience with intraoperative real-time high-resolution dynamic infrared imaging

Technical note

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High-resolution dynamic infrared (DIR) imaging provides intraoperative real-time physiological, anatomical, and pathological information; however, DIR imaging has rarely been used in neurosurgical patients. The authors report on their initial experience with intraoperative DIR imaging in 30 such patients.

A novel, long-wave (8–10 μm), narrow-band, focal-plane-array infrared photodetector was incorporated into a camera system with a temperature resolution of 0.006˚C, providing 65,000 pixels/frame at a data acquisition rate of 200 frames/second. Intraoperative imaging of patients was performed before and after surgery. Infrared data were subsequently analyzed by examining absolute differences in cortical temperatures, changes in temperature over time, and infrared intensities at varying physiological frequencies.

Dynamic infrared imaging was applied in a variety of neurosurgical cases. After resection of an arteriovenous malformation, there was postoperative hyperperfusion of the surrounding brain parenchyma, which was consistent with a loss of autoregulation. Bypass patency and increased perfusion of adjacent brain were documented during two of three extracranial–intracranial bypasses. In seven of nine patients with epilepsy the results of DIR imaging corresponded to seizure foci that had been electrocorticographically mapped preoperatively. Dynamic infrared imaging demonstrated the functional cortex in four of nine patients undergoing awake resection and cortical stimulation. Finally, DIR imaging exhibited the distinct thermal footprints of 14 of 16 brain tumors.

Dynamic infrared imaging may prove to be a powerful adjunctive intraoperative diagnostic tool in the neurosurgical imaging armamentarium. Real-time assessment of cerebral vessel patency and cerebral perfusion are the most direct applications of this technology. Uses of this imaging modality in the localization of epileptic foci, identification of functional cortex during awake craniotomy, and determination of tumor border and intraoperative brain shift are avenues of inquiry that require further investigation.

Key Words • dynamic infrared imaging • brain neoplasm • epilepsy • cortical mapping • extracranial–intracranial bypass • arteriovenous malformation

Abbreviations used in this paper: AVM = arteriovenous malformation; CBF = cerebral blood flow; DIR = dynamic infrared; EC = extracranial; FFT = fast Fourier transformation; GBM = glioblastoma multiforme; IC = intracranial; IR = infrared radiation; lCBF = local CBF; MCA = middle cerebral artery; MR = magnetic resonance; PET = positron emission tomography; QWIP = quantum well infrared photodetector; SAA = spot-averaging analysis; SISCOM = subtracheal ictal–interictal SPECT scans coregistered to the MR image; SPECT = single-photon emission computerized tomography; SSA = spot-slope analysis; SSS = superior sagittal sinus; STA = superficial temporal artery; TES = thermoencephaloscopy.
Intraoperative dynamic infrared imaging

Materials and Methods

Patient Population

This study was reviewed and approved by our institutional review board. Thirty patients (16 men and 14 women) between 17 and 80 years of age, who were scheduled to undergo surgery for tumor (16 patients), AVM resection (two patients), EC–IC (STA–MCA) bypass (three patients), or invasive monitoring performed to locate extratemporal seizure foci (nine patients), were included in the initial study group. All patients served as their own controls, because in each individual patient, the healthy brain tissue contained in the operative field was visualized along with the pathological focus of the neurosurgery. Of the 30 patients included in this study, 12 underwent planned awake cortical mapping; however, one of the patients was unable to tolerate the procedure and thus was given a general anesthetic agent. Fourteen procedures were performed with the assistance of MR imaging–guided stereotaxy. Eleven patients underwent infrared imaging during awake cortical mapping of speech and motor function.

Background of the Technology

In the brain, a constant and evenly distributed outflow of heat is maintained by a thermogradient of 0.5˚C between deep and superficial layers. Changes in neuronal activity are likely the initiating event in local alterations of CBF and metabolism. Data from experimental studies of TES, a technique for measuring thermal activity of the brain through the skull, have demonstrated that there are four main sources of amplification of the IR signal in the brain: 1) activity of cortical neurons through transmembrane currents produces 10⁻³ W; 2) local metabolism yields 10⁻⁴ W; 3) ICBF produces 10⁻⁴ W; and 4) thermoconductivity in activated cerebral cortex due to changes in ICBF yields approximately 10⁻³ W. By a 10-fold difference, thermoconductivity is the most important source of thermal energy in the brain. Local increases in thermoconductivity in the cylinder of cortex surrounding a radial vessel create channels for enhanced thermal conduction. These thermal changes, which are caused by fluxes in ICBF, contribute most to the infrared energy captured on infrared imaging.

Dynamic infrared imaging records natural IR from tissue. (Living tissue continuously emits IR as photons.) The intensity of IR is directly proportional to the temperature of the radiating tissue and indirectly proportional to the degree of tissue perfusion. Dynamic infrared imaging records changes in perfusion and reperfusion of human tissues by rapid (> 200 frames/second) measurement of minute changes (< 0.006˚C) in photon flux both spatially and temporally. The brain emits approximately 10 W/cm², 75% of which is dissipated through the circulation and 25% of which is dispersed from its source and radiates in the IR band. At 300˚K, the atmosphere is transparent to wavelengths of IR between 3 and 5 μm and between 8 and 15 μm. At wavelengths below 8 μm, however, there is both significant absorption and reflectance of IR by the human body and other environmental sources. For midrange IR detectors, up to 15% of the information detected can be reflected by environmental sources, compared with less than 2% in the 8 to 10–μm range. Dynamic infrared imaging has superficial similarities to a previous method known as thermography, but the means by which data are collected and processed are so different from those of the former that it is described in the literature as a new and distinct modality that is referred to alternatively as DIR imaging, high-performance infrared imaging, or dynamic area telethermometry.

Technological Basis

For the strategic defense initiative, or Star Wars research program, an extraordinarily sensitive infrared sensor was designed to detect missile flare. The sensor is called the QWIP; a long-wave (8–10 μm), narrow-band, focal-plane-array infrared detector. A typical QWIP consists of a 256 × 256–pixel array with approximately 65,000 pixels/frame that can resolve a 0.006˚C difference in temperature between pixels and a temporal resolution of 100 Hz. The QWIP’s spatial resolution is 40 μm, with more than a 99.5% yield of operating pixels.

The QWIP was incorporated into a self-contained mobile unit composed of a camera, light-emitting diode display, printer; and computer for data analysis, which is called the BioScanIR (OmniCorder Technologies, Inc., Stony Brook, NY)(Fig. 1). The computer was a dual Pentium III 750-MHz machine with 1 gigabyte of random access memory, a writable compact disc with read-only memory, and a frame grabber (PC-IMAGE frame grabber; Matrix Vision, Oppenweiler, Germany). The dimensions of the camera were approximately 16 × 7 × 9 in and it weighed approximately 20 lbs. This integrated unit could obtain 200 frames/second of data with a 14-bit digital output. Integration time was up to 40 msec. The QWIP detector operated at cryogenic temperatures of approximately 60˚K, but the cooling

FIG. 1. A: Photographs illustrating the QWIP (A) and the BioScanIR integrated infrared unit (B).
operation was performed with an entirely sealed, long-life (> 4000 hours), sterling cooling system so that handling of the cryogenic liquids was eliminated. The camera was equipped with a 50-mm f/2 germanium lens.

Data Analysis

Magnetic resonance, computerized tomography, ultrasonography, and conventional x-ray imaging take in and manipulate a known signal and measure its alteration through tissue. A radiating body generates infrared energy. Dynamic infrared imaging is a passive imaging system and therefore cannot control the electromagnetic signal to enhance the image analysis. Instead, the system relies on its ability to filter the raw signal by using biological behavior. The software programs used for both infrared image capture and analysis (Digigrab and the BioScanIR Analysis Program, respectively; OmniCorder Technologies, Inc.) were specifically designed. In this study three algorithms were used. All infrared data were translated into a visual image of 256 colors. Spot-averaging analysis merged neighboring 2 × 2- or 4 × 4-pixel arrays and averaged the temperature for all frames in an acquisition. Spot-slope analysis was used to measure the change in temperature for a 2 × 2-pixel array over the duration of image acquisition. A positive spot slope was translated into colors from the high end of the visible spectrum (white and red), constant temperatures were visualized by colors in the middle range (green and blue), and a negative slope was shown in a color at the low end (black). Note that SSA images did not demonstrate absolute differences in temperature, but only changes in temperature over time. The FFT algorithm gated the intensity of the IR emission to the frequency of known physiological processes such as the cardiac cycle, respiration, and resting vasomotor tone.

Imaging Procedure

Prior to image acquisition, the infrared camera was calibrated to ensure imaging fidelity for body temperature (27–35˚C). Two standardized sets of images of a heat plate set at 27˚C and 33˚C were obtained. After this initial temperature calibration, no other anatomical, physiological, or imaging registration was needed. Following craniotomy and dural opening, the BioScanIR camera was focused on the cortical surface. The camera was mounted on an articulated arm integral to its workstation. No other intraoperative equipment was necessary. With five degrees of freedom, the camera could be focused perpendicular to the cortical surface. The image was zoomed to encompass the entire surgical field, which was approximately 75 cm. A surgical instrument was placed at the edge of the craniotomy for orientation and a 35-mm photograph of the operative site was obtained.

For tumor resections, an intraoperative photograph and a DIR image were obtained after MR imaging–guided stereotactic craniotomy and dural opening. The stereotactic localization of the tumor was used to indicate the tumor outline on the surgical photograph, which was compared with the DIR images. The AVM resections and EC–IC bypasses were also photographed, and infrared imaging was performed after the dura mater was opened. A second postoperative photograph and a DIR image were obtained for comparison. During each EC–IC bypass procedure, the patency of the arterial pedicle was confirmed using a microflow probe (Transonic Systems, Inc., Ithaca, NY). In every case of epilepsy there was a complement of preoperative studies including MR imaging, SISCOM, PET scanning, and electroencephalography. Using the SISCOM images, a craniotomy was planned and a subdural electrode grid array was placed over the presumed epileptogenic region. Before grid placement, a baseline DIR image was obtained along with an intraoperative photograph of the labeled relevant functional cortex. The patient was then instructed either to move his or her hand repetitively or to...
count to 100 rapidly, during which a DIR image was obtained, with image acquisition commencing 20 seconds after initiation of the activity.

**Results**

The images obtained in these patients were analyzed using all three algorithms (SSA, SAA, and FFT).

**Imaging in Cases of Tumor**

Sixteen patients with brain tumors underwent DIR imaging for the following pathological conditions: GBM (seven patients), Grade II oligodendrogloma (three patients), Grade III oligodendrogloma (two patients), gliosarcoma (one patient), complex neuroectodermal lesion (one patient), Grade III breast adenocarcinoma (one patient), and Grade II oligoastrocytoma (one patient). With SAA, 14 (88%) of 16 tumors produced distinct thermal footprints. Eleven (78%) of 14 tumors were cooler than the surrounding healthy brain tissue. In three (21%) of 14 tumors, widened tumor gyri outlined by the cortical vessels in the surrounding sulci could be seen (Fig. 2). One subcortical tumor had a thermal footprint that was cooler than the visualized cortical surface.

Spot-slope analysis demonstrated that five (36%) of 14 tumors had distinct thermal patterns that could be distinguished from the heat of the surrounding healthy brain tissue. Four tumors (29%) displayed a sharp rise in temperature acquisition and one GBM with a large necrotic cavity exhibited a decrease in temperature during imaging sequence acquisition. Fast Fourier transformation analysis demonstrated that four (29%) of 14 tumors had distinct infrared peaks; in two the peaks appeared at 1.75 to 1.86 Hz, in one at 1.17 to 1.36 Hz, and in one at multiple frequencies (Fig. 3).

**Imaging in Cases of Epilepsy**

Nine patients with intractable extratemporal lobe epilepsy underwent infrared imaging. The patients’ profiles and imaging data are summarized in Table 1. The seizure semiology included simple partial seizures in four patients and complex partial seizures in five. In seven (78%) of nine patients, the areas of altered thermal activity tightly correlated anatomically with the epileptogenic zone, as determined by preoperative SISCOm and electrocorticographic data. Topographically, these areas corresponded well to the contours of the electrographically mapped seizure foci. Spot-slope analysis of seizure foci demonstrated significant local changes in temperature in seven cases (Fig. 4). Of these, five seizure foci were determined to be warmer and two to be cooler than the adjacent cortex. Spot-averaging analysis showed corresponding areas of decreased thermal activity in two patients. The FFT analysis demonstrated increased infrared intensity in the area of the mapped seizure focus in two cases at 0.3 to 0.5 Hz, but not as clearly as the SSA. Mild-to-moderate gliosis was found in pathological specimens of eight patients who underwent subsequent focal cortical resection. In three of the seven patients with concordant data on DIR imaging there was more than a 90% reduction in seizure burden after focal cortical resection.

**Imaging in Cases of Pathological Vascular Conditions**

Two patients underwent DIR imaging before and after surgical resection of AVMs. Postoperative angiography confirmed obliteration of the malformation, establishing that postoperative thermographic changes do not represent abnormal shunting from a residual AVM. The patients had uncomplicated intraoperative and postoperative courses. Preoperatively, SAA demonstrated significantly increased temperatures in AVMs. The results of SAA corresponded well with the anatomical limits of the AVM. Both malformations had surrounding areas that were significantly cooler than the lesion prior to resection. In both cases, SSA showed no change in temperature over time in the AVM, but increased temperature over time in surrounding areas that were cooler. The temperatures of cortical draining veins and the SSS remained constant over time (Fig. 5).

Postoperatively, SAA demonstrated the surgical field to be cooler than the adjacent cortex. Spot-slope analysis demonstrated increased temperature over time globally in the field, excluding the surgical bed. The SSS in the first patient and the cortical draining veins in the second patient, which had remained thermally neutral on preoperative findings of the SSA, were now readily seen (Fig. 6).
Two patients with moyamoya disease and one with multiple infarcts following bilateral carotid artery occlusion underwent DIR imaging before and after EC–IC bypass (STA–MCA bypass). During every bypass blood flow was measured with the aid of a microflow probe (Table 2). Doppler signals and recorded blood flows were collected during all three bypasses. Spot-averaging analysis demonstrated that in the two bypasses with the highest flow, the adjacent cerebral cortex increased in temperature after the bypass. A static cortical SAA image was obtained in the patient with the lowest blood flow. The SAA and SSA demonstrated absolute increased temperatures and increased temperatures over time, respectively, in the arterial pedicle; this correlated with bypass patency, as measured using the microflow probe (Fig. 7).

Cortical Mapping

Nine patients who underwent awake craniotomy for tumor also underwent DIR imaging during cortical mapping of speech and motor function. As described earlier, after MR image–guided stereotactic craniotomy and dural opening, the functional cortex was mapped using the Ojemann cortical stimulator.44,50 The DIR image anatomically correlated with the appropriately functionally mapped cortex in three patients during hand movement and one patient during counting (Fig. 8). Both SAA and FFT analysis did not demonstrate any concordance.

Discussion

In the late 19th century, researchers attempting to correlate brain temperature to human and animal activity began using thermometers and thermopiles with reported temperature resolutions of 0.002˚C placed in the cerebral cortex.46 Not until the mid-1980s, however, with the development and refinement of infrared cameras and digital image processing, did Shevelev and colleagues69 describe the technique of TES, during which IR in the brain is detected through bone and skin. Also, their single-point detector, which measured 3 to 5 μm, was prone to significant artifacts.

With the aid of first-generation IR detectors and simple algorithms, six patients with brain tumors and one patient with an AVM underwent intraoperative infrared imaging.36,51 Infrared imaging’s other role in clinical neurosurgery has been the study of thermal asymmetries in skin as a diagnostic tool in numerous conditions including trigeminal neuralgia, radiculopathy, sciatica, postsympathectomy, and syringomyelia.23,52–54,76–78 Experiments in humans yielded no clinically useful data. Their technique was clearly limited by recording through bone and skin. Also, their single-point detector, which measured 3 to 5 μm, was prone to significant artifacts.

There are limitations to the physiological phenomena that DIR imaging can be used to study. Infrared radiation detectors cannot distinguish between excitatory and inhibitory phenomena. Unlike PET scanning, DIR imaging cannot definitively separate metabolic and CBF events. Subcortical structures only influence heat distribution over the cortex and are unable to provide discrete, sharply defined, thermal responses. Additionally, the current integrated camera and data processing unit is large and the time for imaging and data analysis takes minutes. In the setting of as-

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs)</th>
<th>Sex</th>
<th>Disease</th>
<th>Procedure</th>
<th>Doppler Flow (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>40, M</td>
<td></td>
<td>SPS involving face &amp; UE ± GTCS</td>
<td>rt STA–MCA bypass</td>
<td>43</td>
</tr>
<tr>
<td>E2</td>
<td>27, F</td>
<td></td>
<td>SPS involving face &amp; UE ± GTCS</td>
<td>rt frontal</td>
<td>12</td>
</tr>
<tr>
<td>E3</td>
<td>27, M</td>
<td></td>
<td>SPS involving UE &amp; LE ± GTCS</td>
<td>rt insula &amp; temporal neocortex</td>
<td>7</td>
</tr>
<tr>
<td>E4</td>
<td>19, F</td>
<td></td>
<td>CPS</td>
<td>lt frontal</td>
<td>yes</td>
</tr>
<tr>
<td>E5</td>
<td>32, F</td>
<td></td>
<td>CPS</td>
<td>area of encephalomalacia</td>
<td>yes†</td>
</tr>
<tr>
<td>E6</td>
<td>23, M</td>
<td></td>
<td>CPS ± GTCS</td>
<td>rt anterior parietal</td>
<td>yes†</td>
</tr>
<tr>
<td>E7</td>
<td>19, M</td>
<td></td>
<td>CPS ± GTCS</td>
<td>rt frontal</td>
<td>nonlocalizing</td>
</tr>
<tr>
<td>E8</td>
<td>47, F</td>
<td></td>
<td>CPS ± GTCS</td>
<td>rt posterior temporal</td>
<td>nonlocalizing</td>
</tr>
<tr>
<td>E9</td>
<td>20, F</td>
<td></td>
<td>CPS involving UE</td>
<td>rt frontal/parietal</td>
<td>nonlocalizing</td>
</tr>
</tbody>
</table>

* CPS = complex partial seizures; GTCS = generalized tonic–clonic seizures; LE = lower extremity; SPS = simple partial seizures; UE = upper extremity.
† Cooler than adjacent cortex.

**TABLE 1**

Preoperative characteristics and mapping data in nine consecutive patients with presumed extratemporal lobe epilepsy*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs)</th>
<th>Sex</th>
<th>Seizure Semiology</th>
<th>MR Image</th>
<th>SISCOM/PET Localization</th>
<th>Infrared Sequence (concordance)</th>
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<tbody>
<tr>
<td>E1</td>
<td>40, M</td>
<td></td>
<td>SPS involving face &amp; UE ± GTCS</td>
<td>unremarkable</td>
<td>rt parietal</td>
<td>yes</td>
</tr>
<tr>
<td>E2</td>
<td>27, F</td>
<td></td>
<td>SPS involving face &amp; UE ± GTCS</td>
<td>unremarkable</td>
<td>rt frontal</td>
<td>yes</td>
</tr>
<tr>
<td>E3</td>
<td>27, M</td>
<td></td>
<td>SPS involving UE &amp; LE ± GTCS</td>
<td>parietal schizencephalic cleft</td>
<td>rt insula &amp; temporal neocortex</td>
<td>yes</td>
</tr>
<tr>
<td>E4</td>
<td>19, F</td>
<td></td>
<td>CPS</td>
<td>unremarkable</td>
<td>lt frontal</td>
<td>yes</td>
</tr>
<tr>
<td>E5</td>
<td>32, F</td>
<td></td>
<td>CPS</td>
<td>area of encephalomalacia</td>
<td>lt frontal</td>
<td>yes</td>
</tr>
<tr>
<td>E6</td>
<td>23, M</td>
<td></td>
<td>CPS ± GTCS</td>
<td>unremarkable</td>
<td>rt anterior parietal</td>
<td>yes†</td>
</tr>
<tr>
<td>E7</td>
<td>19, M</td>
<td></td>
<td>CPS ± GTCS</td>
<td>unremarkable</td>
<td>rt frontal</td>
<td>yes†</td>
</tr>
<tr>
<td>E8</td>
<td>47, F</td>
<td></td>
<td>CPS ± GTCS</td>
<td>unremarkable</td>
<td>rt posterior temporal</td>
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</tr>
<tr>
<td>E9</td>
<td>20, F</td>
<td></td>
<td>CPS involving UE</td>
<td>unremarkable</td>
<td>rt frontal/parietal</td>
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</tr>
</tbody>
</table>

* Cortical Mapping

Nine patients who underwent awake craniotomy for tumor also underwent DIR imaging during cortical mapping of speech and motor function. As described earlier, after MR image–guided stereotactic craniotomy and dural opening, the functional cortex was mapped using the Ojemann cortical stimulator.44,50 The DIR image anatomically correlated with the appropriately functionally mapped cortex in three patients during hand movement and one patient during counting (Fig. 8). Both SAA and FFT analysis did not demonstrate any concordance.

**TABLE 2**

Characteristics of three patients who underwent EC–IC bypass

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs)</th>
<th>Sex</th>
<th>Disease</th>
<th>Procedure</th>
<th>Doppler Flow (ml/min)</th>
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<tr>
<td>B1</td>
<td>54, M</td>
<td></td>
<td>strokes from bilateral carotid artery occlusion</td>
<td>rt STA–MCA bypass</td>
<td>43</td>
</tr>
<tr>
<td>B2</td>
<td>30, F</td>
<td></td>
<td>moyamoya</td>
<td>lt STA–MCA bypass</td>
<td>12</td>
</tr>
<tr>
<td>B3</td>
<td>17, F</td>
<td></td>
<td>moyamoya</td>
<td>rt STA–MCA bypass</td>
<td>7</td>
</tr>
</tbody>
</table>
Intraoperative dynamic infrared imaging

Fig. 4. Left: Three preoperative SISCOM images. Center: Intraoperative photographs. The boundary of the epileptogenic zone, as identified by electrocorticographic subdural grid monitoring, is delineated by a suture placed on the cortical surface (arrows and asterisk). Right: Dynamic infrared images acquired with the SSA algorithm prior to grid placement (arrows and asterisk correspond to those shown in center panel). Patient 1: A 40-year-old man (Case E1 in Table 1) with simple partial seizures involving his left upper extremity and face. The preoperative MR image was unremarkable, but a SISCOM study revealed an area of hyperperfusion in the right parietal area. The epileptogenic zone and the DIR image were topographically concordant. Patient 2: A 27-year-old woman (Case E2 in Table 1) with simple partial seizures involving her left face and upper extremity. The SISCOM study obtained in this patient revealed an area of hyperperfusion in the right frontal area. The region of increased thermal activity (arrows) in the DIR image in this case corresponds to the epileptogenic area in the intraoperative picture (arrows). Patient 3: A 27-year-old man (Case E3 in Table 1) with a history of simple partial seizures involving his left upper and lower extremities. The MR image demonstrated a parietal schizencephalic cleft. In this case, the SISCOM study was not concordant; however, the electrocorticographically identified epileptogenic zone and the DIR image demonstrated a good correlation.

assessments of cerebral ischemia during aneurysm surgery, it would be difficult to use it efficiently.

Imaging in Cases of Tumor

The intended use of DIR imaging in the intraoperative assessment of brain tumors is to assist the surgeon in the determination of tumor borders, tumor identification with intraoperative brain shift, and functional assessment of adjacent tissue. Other avenues of research include the intraoperative assessment of radiation necrosis compared with tumor, and higher-grade portions of tumors compared with lower-grade portions. A broad pathological spectrum of brain tumors was visualized in this study. It is noteworthy that 14 of 16 tumors, including both low- and high-grade neoplasms, displayed distinct thermal footprints on SAA images. Interestingly, 11 of 14 tumors had thermal patterns
that were cooler than the surrounding healthy (on gross appearance) tissue, whereas three of 14 displayed a cobblestone appearance with widened gyri outlined by sulcal cortical vessels. These results are similar to the earlier thermographic findings of Koga, et al.,\(^3\) which demonstrated that cystic and necrotic tumor areas in six patients were hypothermic with less CBF than surrounding cortex. The TES images of rats with inoculated gliomas obtained by Shevelev\(^6\) demonstrated initial cooling early during tumor growth, followed by increased thermal activity in a broad area of cerebral cortex surrounding a tumor. Perhaps there is a third phase of cooling when a tumor has outstripped its blood supply and is becoming necrotic.

For DIR imaging to be clinically applicable in tumor surgery, the infrared signal-to-noise ratio must be sharpened. A more traditional thermographic analysis, such as SAA, which captures relative temperature at a moment in time, does not suffice. To that end, we performed DIR imaging with SSA and FFT analysis in 14 patients with tumors and observed that in four patients increased heat was detected over time in the lesion compared with the surrounding healthy cortex. One clinically necrotic tumor displayed cooling over time. The results of the FFT analysis correlated with four tumors: in two at 1.75 to 1.85 Hz, in one at 1.17 to 1.36 Hz, and in one at multiple frequencies. No pathological diagnosis corresponded to SSA or FFT concordance; however, every tumor that had a corroborating FFT image enhanced with gadolinium on preoperative MR images.

None of the algorithms yielded tumor margins distinct enough to guide resections without the stereotactic support of MR imaging. Certainly, the feathering of primary gliomas into adjacent healthy brain confounds our ability to define tumor borders clearly with infrared imaging. Additionally, data from ongoing research with infrared imaging in mouse models has indicated that the infrared image patterns associated with malignancy are due to nitric oxide (T Button, personal communication, 2002). With nitric oxide’s quick diffusion into healthy brain tissue, this will likely continue to provide a challenge to refining the infrared data to demonstrate pure tumor. Further refinements in the software designed to improve the signal-to-noise ratio of DIR imaging is critical. Phase-contrast DIR imaging analysis has recently been designed and will, we hope, add further clarity to our images of brain tumor.

**Imaging in Cases of Epilepsy**

Shevelev\(^6\) demonstrated spreading thermal waves and increased IR emission during an induced seizure in a rat model. Seizure activity is associated with significant chang-

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**Fig. 5.** A: An intraoperative photograph of a parasagittal AVM before resection. B: A preoperative SAA image demonstrating the AVM to be warmer than the surrounding cerebral cortex. The black arrow indicates the SSS; the asterisk marks an inferior region that is significantly cooler than the AVM, and the open arrow indicates the AVM. C: A preoperative SSA image showing temperature changes over time. The AVM and the SSS are no longer visible because they are both maximally perfused. The black arrow indicates an inferior region, in which there likely is intact autoregulation demonstrating a positive temperature change over time. D: A postoperative photograph of the AVM resection. E: A postoperative SSA image demonstrating the resection bed to be cooler than the surrounding brain (open arrow). The asterisk indicates that the inferior region, which was significantly cooler than the AVM, has now increased in temperature. The black arrow indicates the SSS. F: A postoperative SSA image demonstrating a diffuse increase in temperature over time in the entire field, including the SSS (black arrow), inferior cerebral cortex (open arrow), and deep white matter (white arrow).
es in local energy metabolism. Neuronal hyperactivity can cause increased cortical perfusion and dysautoregulation of CBF. These changes are evident on angiography, which may show abnormal increased vascularity and "luxury perfusion" during the periictal period. Breakdown of the blood–brain barrier has also been documented in experimental seizure models, whereas gyral enhancement and changes in white matter have been observed on computerized tomography and MR images within hours after clinical seizure activity. Therefore, it is reasonable to hypothesize that the temperature fluctuations seen on DIR imaging are likely to be related to transient vascular changes during epileptiform activity because there was a tight topographic correlation with the grid recording.

Spot-slope analysis records real-time fluctuations in temperature over the cortical surface area during a data acquisition period of 20 seconds. The DIR images were most likely to be acquired during the interictal period, although this could not be confirmed because the subdural electrodes had to be removed from the field to acquire the images. The increased thermal activity in five of these patients would seem to contradict the findings of previous investigators who showed relative hypometabolism in the epileptogenic zone by using fluorodeoxyglucose PET scanning. This inconsistency may be explained by differences between these two techniques. 1) Positron emission tomography scanning reflects a summation of all metabolic activity over the time of acquisition (typically 1 hour), whereas DIR imaging measures real-time changes in cortical perfusion. 2) Only glucose metabolism is measured by fluorodeoxyglucose
PET scanning: this may not reflect the overall metabolic state of the epileptogenic zone, which is undergoing continuous fluctuations in metabolism due to ongoing interictal activity. 4) The spatial resolution of PET scanning is poor when compared with that achieved using DIR imaging. Detection of a decrease or increase in thermal activity may depend on the temporal relationship of image acquisition and interictal cortical epileptiform discharges. Dynamic infrared imaging appears to demonstrate the presence of unique cortical physiological properties of the epileptogenic zone relative to the surrounding cortex, with rapid but small temperature variations. The remote and local hypermetabolic areas caused by seizure activity cannot be separated by DIR imaging. Therefore, it may not be possible to delimit the epileptogenic cortex from cortex involved in seizure propagation. Although patients with extratemporal lobe epilepsy constitute an epilepsy group that is very difficult to treat surgically, in only half of the patients who underwent resection of the DIR imaging–concordant focus was there more than a 90% reduction in seizure burden. Further research is needed to look at a large volume of patients with extratemporal lobe epilepsy to determine the efficacy and resolution of DIR imaging in identifying the epileptogenic zone. Multispectral arrays could also help define local metabolic, oxygenation, and blood-flow perturbations in epileptogenic regions.

Imaging in Cases of Pathological Vascular Conditions

Reports of experimental cardiac and TES studies and a recent paper in which the authors describe infrared images of the cerebral cortex in a primate before and after carotid and middle cerebral artery occlusion have demonstrated a tight correlation between CBF and infrared imaging of cortical vessels. 2)8,58 In an effort to explore this relationship, we used DIR imaging to analyze data in two patients with AVMs and three patients undergoing STA–MCA bypass. Our DIR imaging analysis of AVMs demonstrated two significant findings: 1) there was global hyperemia in a large area of surrounding cerebral cortex after AVM resection; and 2) draining veins that were maximally hyperperfused, suggesting the absence of autoregulation, demonstrated a return of vasoreactivity after AVM resection. Preoperatively, cortical areas adjacent to the AVM were cooler, suggesting a local steal of blood flow. With SSA, these same regions demonstrated increases in temperature over time; the AVM and its draining veins remained thermally static. Postoperatively, large areas of adjacent cerebral cortex exhibited increased basal temperatures and increased temperatures over time after AVM resection, thus suggesting global hyperemia and loss of autoregulation. It is likely that the AVM and its draining veins were maximally perfused, whereas surrounding cortical tissue maintained cerebrovascular autoregulation. This hypothesis was further supported by the increases in temperature over time that were recorded in the SSS and draining cortical veins after the resection, compared with their flat preoperative temperatures over a time slope.

In an early study, Okudera and associates used thermographic cooling of a draining vein in an AVM to demonstrate the cessation of abnormal shunting in one patient. Results from our work concur with these early findings. Previous studies in which authors addressed the origin of postresection AVM hyperemic complications relied on invasive techniques, indirect measurements, and retrospective reviews. 2)3,43,59,61,73,84 Obviously, significant conclusions cannot be based on two cases. With more noninvasive DIR imaging of intraoperative AVM resection, however, we will be able to explore postresection AVM cerebrovascular physiology more fully.

Graft patency was confirmed in all three STA–MCA bypasses by using a Doppler microprobe. This correlated with positive SAA and SSA findings in all three bypasses. Increased perfusion of underlying brain parenchyma was apparent in the two arterial pedicles with the greatest flow. Prior to our experience, DIR imaging was used successfully to identify graft occlusion in a human patient during an off-pump coronary bypass.74 Additionally, in primate models, TES and DIR imaging have been used to localize experimental infarction precisely and to visualize decreased CBF with subsequent reperfusion after carotid artery and middle cerebral artery occlusion and release.56,85 Further study is needed to characterize and quantitate more fully the intraoperative changes in blood flow in the bypassed vessels and the adjacent cerebral cortex. Quantification of increased perfusion could help identify those patients who would benefit from a bypass. Real-time intraoperative assessment of cerebral ischemia in aneurysm surgery, hemispherectomy for nondominant stroke, and traumatic brain injury are other potential applications.

Cortical Mapping

Experimental studies in primates have demonstrated localized thermal responses in primate somatosensory cortex after tibial nerve stimulation and in human visual cortex after light stimulus. 56,64 George, et al.12 explored the activation of the motor cortex in cats during the natural reflex movement of a paw. Their results demonstrated an initial cooling period followed by an increase in temperature above baseline in a focal area of the motor strip contralateral to the side of movement. Compared with currently used intraoperative techniques, thermal imaging has a temporal resolution of seconds (on par with that in direct cortical stimulation) and a spatial resolution of 40 μm (similar to
that in optical imaging).\textsuperscript{21,24,44,75} Our attempt to localize eloquent motor and speech cortex was successful in four patients. Speech localization provided a striking correlation with a cortical map of the language area. This is the first description of DIR imaging–determined speech localization. Additionally, a broad region of motor cortex increased in temperature over time according to SSA in three patients during hand motion. The SAA and FFT algorithms provided no useful data.

**Conclusions**

Dynamic infrared imaging has been used intraoperatively to study cerebrovascular disease, epilepsy, functional cortical activation, and brain tumors. Refinement of infrared data processing, storage, and retrieval will be necessary to advance the applicability of DIR imaging to the setting of neurosurgical procedures. Our early experience suggests that DIR imaging may provide a real-time physiological, anatomical, and pathological imaging modality in neurosurgical patients. Further investigation is necessary.

**Disclaimer**

BioscanIR is a proprietary technology of OmniCorder Technologies, Inc. Nothing in this publication implies that the Mayo Foundation endorses the products of OmniCorder Technologies, Inc. Further, none of the authors has any financial interest in this analysis program or its manufacturer.

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