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Abstract. Excision of arteriovenous malformations (AVMs) is known to carry a risk of postoperative hemorrhage, postulated to be the result of normal perfusion pressure breakthrough. It is also possible that AVMs may cause a steal effect, reducing perfusion in nearby vessels. There is currently no simple method of visualizing the presence or absence of steal effect intraoperatively. We hypothesized that the infrared thermographic (heat sensitive) imaging of perilesional brain may be useful for detecting reduced perfusion due to steal. Moreover, we hypothesized that if steal effect was present, it could impact on ocular perfusion and thereby temperature. Our objective was, therefore, to investigate whether perilesional cortical and ocular temperature (OT) may be a marker of steal effect. We intraoperatively acquired conventional and thermal images of the surgical field and eyes bilaterally, pre- and post-excisions of a large left hemisphere AVM. We found OT asymmetry preoperatively, which was absent after the AVM was excised. Intraoperative thermal images showed an increase of perilesional temperature, although this could be confounded by generalized changes in cortical perfusion due to anesthetics or surgery. © 2014 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JBO.19.11.110503]

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1 Introduction

Arteriovenous malformations (AVMs) are probably the most recognized of the brain vascular malformations. They represent serpiginous collections of abnormal, congenital blood vessels, often with normal intervening brain parenchyma.¹ Specifically, AVMs are vascular lesions that are tangles of arteries and veins directly shunting blood from the arterial to the venous

circulation.² Brain AVMs are of variable size, and their arterial feeders, venous drainage pattern, and structural complexity make their excision among the most challenging of surgical procedures.³ AVM excision carries a significant risk of postoperative hemorrhage (POH) beyond that expected as a natural consequence of major neurosurgery. This increased risk is believed to arise from the phenomenon of normal perfusion pressure breakthrough (NPPB),^{4,5} occlusive hyperaemia,⁶ or a combination of both.⁷ NPPB occurs when perilesional vascular beds are subject to lengthy periods of reduced perfusion pressure due to the “steal effect,” resulting in diminished arteriolar autoregulatory capacity⁵ and increased capillary density.⁴ The steal effect represents a hemodynamic disturbance whereby the surrounding tissue has less perfusion.⁸ This phenomenon is thought to be a result of the AVM having markedly less resistance than other regions of any given total cerebral blood flow, hence, a “disproportionate flow will be directed toward the low-resistance area and away from the other areas” (Ref. 9, p. 779). Accordingly, when AVMs are excised, perilesional vascular beds become hyperaemic, increasing the risk of swelling and hemorrhage.¹⁰

Visualization of the perilesional vascular response to AVM excision cannot be readily achieved intraoperatively. Indocyanine green fluoresces under near-infrared light, and its use in the visualization of AVM feeding and draining vessels has been previously described.¹¹ However, the requirement for an equal distribution of dye throughout the vascular territory can complicate its use for assessment of tissue perfusion.¹² Alternative techniques include injections of cold normal saline, which can be frequently applied to cause local temperature changes, however, these are still invasive.¹³

By contrast, it has been shown that a heat-sensitive (i.e., infrared or thermographic) camera is able to monitor differences in perfusion and distribution of supplied blood due to the measurable temperature change, for example, after extracranial-intracranial bypass surgery.¹⁴ Intraoperative infrared functional imaging of the human brain has also been reported.¹⁵

We hypothesized that the presence of a significant steal effect with a consequently abnormal response to normalization of perilesional perfusion pressure may be observable as a relative increase in perilesional cortical temperature. Moreover, we hypothesized that the presence of vascular steal in an AVM fed by vessels originating from an ipsilateral carotid artery may impact on ocular perfusion pressure, flow, and therefore, temperature, which is easily measured noninvasively using thermography. Therefore, we sought to measure OT, AVM and perilesional cortical temperature pre- and post-AVM excisions.

2 Experimental Setup and Results

The subject was a 60-year-old female who presented with 2 weeks of headaches. Brain magnetic resonance imaging (MRI) demonstrated a large parieto-temporo-occipital AVM (Spetzler Martin Grade II) with a nidus measuring $3.5 \times 2.2 \times 1.6$ cm (Fig. 1). Venous drainage was via superficial veins to the superior sagittal sinus. A 1.5T Signa MRI scanner (General Electric Healthcare, Milwaukee, Wisconsin) was used for conventional T1-weighted and T2-weighted axial imaging. After discussion with the radiotherapy team, the patient was referred for surgical excision of the AVM. A Testo-875i infrared thermographic camera (Testo AG, Titisee, Germany; spectral sensitivity of 8

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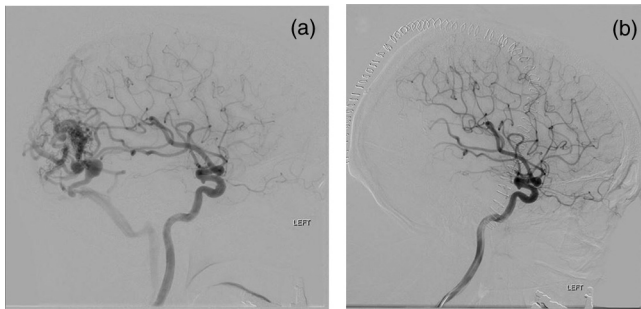


Fig. 1 Digital subtraction angiography (DSA) of left internal carotid artery, demonstrating preoperative parieto-temporo-occipital arteriovenous malformation (AVM) (a), fed from branches of the distal left middle cerebral artery. Postoperative DSA (b) demonstrates complete surgical removal of the AVM, apart from a small draining vein that is not shown in the current phase.

to 14 μm , resolution of 160×120 pixels, precision within the temperature range -20 to 100°C , accuracy of $\pm 2^\circ\text{C}$, thermal sensitivity of <80 mK) was used intraoperatively to acquire images pre- and post-excisions of the AVM, from which cortical temperature measurements were taken. Eye temperature was measured bilaterally using the same camera; eye images were captured near the patient’s bed on the hospital ward at a constant 20°C ambient temperature and constant humidity level, with emissivity on the camera set to 0.98.^{16,17} A conventional digital camera was also used to capture images of the AVM intraoperatively.

Confirmation of AVM excision was obtained from postoperative digital subtraction angiography (Fig. 1). Intraoperative and pre-post-excision intracranial [Figs. 2(a) and 2(c)] and OT thermographic images (Fig. 3) suggest a change in the temperature

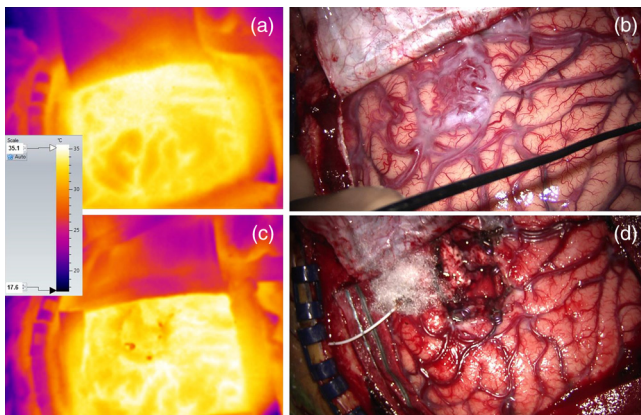


Fig. 2 Colored thermographic images (a and c) and visual images (b and d) suggest a redistribution of blood flow post-excision. (a and b) pre-excision; (c and d) post-excision.

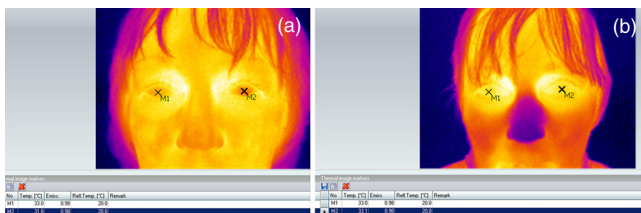


Fig. 3 Preoperative (a) and postoperative (b) ocular imaging demonstrates a change in temperature on the side of AVM resection.

Table 1 Cortical and ocular temperatures before and after AVM excision.

Region	T (C)	T difference between pre- and post-excisions
Cortical surface (pre)	32.3	1.8
Cortical surface (post)	34.1	
Right ocular (pre)	33.0	0.0
Right ocular (post)	33.0	
Left ocular (pre)	31.8	1.3
Left ocular (post)	33.1	

Note: T = temperature; precision of the thermographic readings is $\pm 2^\circ\text{C}$.

distribution (1.8°C intracranial and 1.3°C ocular) within the blood vessels (Table 1). Core temperature intraoperatively was 36.0°C before AVM removal and 37.0°C after removal.

3 Summary and Discussion

Conventional magnetic resonance neuroimaging and intraoperative visual spectrum images suggest successful AVM excision and thermographic imaging indicates a change in the distribution of blood flow before and after excision; however, contrast-enhanced perfusion studies would be necessary to confirm this. Furthermore, ocular thermal images demonstrated that the left eye (side of the AVM removal) was raised and equal to the OT of the right eye after AVM removal. This suggests that the OT may be a proxy for blood flow in the vicinity of the AVM and hence a marker of whether the AVM has been successfully removed.

The results suggest that there was a steal effect by the major feeding arteries to the AVM that was causing hypoperfusion to other regions within the left hemisphere, such as the ocular region. As perfusion was restored to the left hemisphere after AVM removal, it is sensible to extrapolate that the eye region was no longer hypoperfused and the OT returned to normal as indicated by its rise to the same OT as the non-AVM hemisphere (right hemisphere).

The most important finding of this study is the change in OT rather than the change in tissue temperature. Tissue temperature can change due to changes in vessel diameter (changes in metabolism, carbon dioxide, etc.) or flow, or because of the surgery itself (not AVM resection, just the fact that the brain is being disturbed). These render the tissue temperature differences much less diagnostic than the eye temperature asymmetry.

Although intraoperative thermography has been shown to be useful for identifying brain tumor margins or size (e.g., Refs. 18 and 19), or during extracranial-intracranial bypass surgery,¹⁴ or craniectomy,¹³ the technology has not previously been shown to be useful in the context of AVMs. Hence, this is the first report of the use of thermography intraoperatively and to relate the findings to OT pre- and post-AVM excisions.

The OTs we measured are well within the range reported by previous studies of human OTs (e.g., Refs. 20 and 21), although this is the first to measure OT in the context of neurosurgery. As the core temperature changed after AVM removal but the right eye temperature did not, it suggests that the OT was not simply a proxy for core temperature.

We have introduced a potential method for investigating AVM status before, during, and after neurosurgery has been performed by using thermographic technology. Thermography is noninvasive, portable, and cost-effective in visualizing perfusion changes. Furthermore, our results suggest that the ocular thermography may be a marker of successful AVM excision without POH. Using this technology in a larger cohort of AVM patients will aid in validating whether this is the case.

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