Elevated Cerebral Blood Volume Contributes to Increased FLAIR Signal in the Cerebral Sulci of Propofol-Sedated Children


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ABSTRACT

BACKGROUND AND PURPOSE: Hyperintense FLAIR signal in the cerebral sulci of anesthetized children is attributed to supplemental oxygen (fraction of inspired oxygen) but resembles FLAIR hypersignal associated with perfusion abnormalities in Moyamoya disease and carotid stenosis. We investigated whether cerebral perfusion, known to be altered by anesthesia, contributes to diffuse signal intensity in sulci in children and explored the relative contributions of supplemental oxygen, cerebral perfusion, and anesthesia to signal intensity in sulci.

MATERIALS AND METHODS: Supraventricular signal intensity in sulci on pre- and postcontrast T2 FLAIR images of 24 propofol-sedated children (6.20 ± 3.28 years) breathing supplemental oxygen and 18 nonsedated children (14.28 ± 2.08 years) breathing room air was graded from 0 to 3. The Spearman correlation of signal intensity in sulci with the fraction of inspired oxygen and age in 42 subjects, and with dynamic susceptibility contrast measures of cortical CBF, CBV, and MTT available in 25 subjects, were evaluated overall and compared between subgroups. Factors most influential on signal intensity in sulci were identified by stepwise logistic regression.

RESULTS: CBV was more influential on noncontrast FLAIR signal intensity in sulci than the fraction of inspired oxygen or age in propofol-sedated children (CBV: r = 0.612, P = .026; fraction of inspired oxygen: r = −0.418, P = .042; age: r = 0.523, P = .009) and overall (CBV: r = 0.671, P = .0002; fraction of inspired oxygen: r = 0.442, P = .003; age: r = −0.374, P = .015). MTT (CBV/CBF) was influential in the overall cohort (r = 0.461, P = .020). Signal intensity in sulci increased with contrast in 45% of subjects, decreased in none, and was greater (P < .0001) in younger propofol-sedated subjects, in whom the signal intensity in sulci increased with age postcontrast (r = .600, P = .002).

CONCLUSIONS: Elevated cortical CBV appears to contribute to increased signal intensity in sulci on noncontrast FLAIR in propofol-sedated children. The effects of propofol on age-related cerebral perfusion and vascular permeability may play a role.

ABBREVIATIONS: FiO₂ = fraction of inspired oxygen; SSI = signal intensity in sulci

A ccurate detection of leptomeningeal metastatic disease is critical for appropriate risk stratification and treatment of patients with CNS malignancies, particularly childhood posterior fossa tumors such as ependymoma and medulloblastoma, for which the diagnosis of metastasis is critical to staging and treat-
of patients with low fraction of inspired oxygen (FiO₂) having hyperintense CSF compared with 84% in the high-FiO₂ group. A later finding that sulcal signal intensity (SSI) decreased when FiO₂ was reduced from 100% to 30% in intubated children under propofol anesthesia confirmed an influence of hyperoxygenation on SSI, but SSI persisted in 35% of children with FiO₂ of 30%, contrary to a previously established threshold of 50% below which no abnormal SSI was seen. No studies to date have documented a linear relationship between FiO₂ and SSI, to our knowledge.

Physiologic factors may account for a nonlinear relationship of SSI and FiO₂, apparent differences in SSI between anesthesia protocols, and the overlap in SSI with low-versus-high FiO₂. It has been our observation that the diffuse, symmetric FLAIR SSI in anesthetized children resembles the asymmetric FLAIR signal seen in the sulci of patients with intracranial vascular stenosis, found to correlate with angiographically evident pial collaterals. The appearance is also similar to the leptomeningeal “ivy sign” in patients with Moyamoya disease, found to correlate with cerebral perfusion, dilated pial vessels, and decreased cerebrovascular reserve. We hypothesized that cerebral perfusion, known to be altered by anesthesia, may contribute to diffuse FLAIR SSI. The purpose of this study was to investigate whether cerebral perfusion and enhancing pial vessels contribute to diffuse SSI in a relatively homogeneous pediatric neuro-oncology cohort and, if contributory, to explore the relative contributions of supplemental oxygen, cerebral perfusion, and anesthetization to SSI on T2-weighted FLAIR imaging.

MATERIALS AND METHODS

Subjects
A retrospective search of our institutional data base, conducted with institutional review board approval and waiver of consent, yielded 198 children with brain tumors without leptomeningeal metastasis who had pre- and postcontrast FLAIR MR imaging with supratentorial dynamic susceptibility contrast perfusion imaging at our institution between April 2008 and March 2011. MR imaging and anesthesia chart review were conducted in tandem until 50 complete MR imaging examinations without evidence of intracranial tumor or supratentorial resection, ischemia, metallic artifacts, or vascular or other supratentorial brain abnormality, performed with propofol-only anesthesia or no anesthesia, were identified. Patients receiving other anesthetic agents or opioids were ineligible due to potential confounding effects on cerebral perfusion. Two subjects who had intravenous contrast within 48 hours before the graded scan and 6 subjects with remote documented or suspected leptomeningeal disease not captured in our data base search were subsequently excluded. This process yielded 42 total subjects ranging in age from 1.2 to 18 years (mean, 9.66 ± 4.92 years; 48% male). Of these, 25 subjects (12 awake, 13 propofol-sedated) had technically adequate supratentorial PWI. Time-dependent contrast concentration, C(t), was calculated from T₂* signal intensity as described by Østergaard. Following automated arterial input function determination via iterative Kohonen self-organizing map-based pattern recognition, the global arterial input function was used for nonparametric deconvolution by standard-form Tikhonov regularization by using minimized generalized cross-validation for pixel-by-pixel truncation threshold selection. CBF, CBV, and MTT were calculated relative to the arterial input function as

\[
\text{CBF} = \frac{k_{\text{hi}}}{\rho} \times \frac{C(t)}{\int_0^\infty C_\text{a}(\tau) R(t-\tau) d\tau}
\]

\[
\text{CBV} = \frac{k_{\text{hi}}}{\rho} \times \frac{\int C(t) dt}{\int C_\text{a}(t) dt}
\]

\[
\text{MTT} = \frac{\text{CBV}}{\text{CBF}}
\]

where Cₐ(t) is the arterial input function, R(t-\tau) is the tissue residue function, and Cₐ(\tau)R(t-\tau) represents the fraction of contrast in

MR Imaging
Dynamic susceptibility contrast PWI was performed at 1.5T (Magnetom Avanto; Siemens, Erlangen, Germany) during injection of 0.1 mmol/kg gadopentetate dimeglumine (Magnevist; Bayer HealthCare Pharmaceuticals, Wayne, New Jersey) at 0.8–1 mL/s (standardized to be tolerated by all vascular access devices), with TR, 1910 ms; TE, 50 ms; flip angle, 90°; 15 sections; 4- to 5-mm section thickness (0 gap); 128 × 128 matrix; 1.6 × 1.6 mm in-plane voxel size; and bandwidth of 1346 Hz/pixel (86,144 kHz). T₂-weighted fast FLAIR imaging was performed before and ~21 minutes after (mean, 20.90 ± 2.25 minutes) contrast injection, with TR = 7000–9140 ms; Tₑffective = 106–115 ms; TI = 2500 ms; 4- to 5-mm section thickness (0 gap).

Image Analysis
Supratentorial SSI was rated from 0 to 3 (Fig 1) on pre- and postcontrast T₂-weighted FLAIR images by 2 independent board-certified neuroradiologists with Certificates of Added Qualification (N.D.S. and J.H.H., with 9 and 5 years’ experience) blinded to anesthesia and contrast status. Differences were resolved in consensus. Signal intensity was not graded in the basilar cisterns or ventricles due to potentially confounding CSF flow-related artifacts, lack of evidence for significant oxygen effects on ventricular CSF FLAIR signal, and our primary interest in evaluating sulci for factors affecting leptomeningeal metastasis detection. Twenty-five subjects (12 awake, 13 propofol-sedated) had technically adequate supratentorial PWI. Time-dependent contrast concentration, C(t), was calculated from T₂* signal intensity as described by Østergaard. Following automated arterial input function determination via iterative Kohonen self-organizing map-based pattern recognition, the global arterial input function was used for nonparametric deconvolution by standard-form Tikhonov regularization by using minimized generalized cross-validation for pixel-by-pixel truncation threshold selection.
the tissue at time $t$ after contrast injection at time $\tau$, $C_i(t)$ is the total concentration, and $k_{H/P}$ corrects for the attenuation of brain tissue and the difference between large- and small-vessel hematocrit. GM, WM, and CSF were segmented by an automated hybrid neural network method by using axial T1WI, T2WI, proton density, and FLAIR images. CBV, CBF, and MTT were evaluated for cortical GM volumes.

Statistical Analysis

Descriptive statistics include mean and SD (unless otherwise noted) for continuous variables and frequencies and proportions for categoric variables. Wilcoxon rank sum tests were used to examine differences for continuous and ordinal variables between propofol-sedated and awake groups. Univariate analysis based on Spearman rank correlation coefficients was performed to assess the relationships among age, $\text{FiO}_2$, CBF, CBV, MTT, and pre-/postcontrast SSI. Multivariate analysis was performed by backward stepwise ordinal logistic regression modeling to identify the most significant variables influencing SSI from the above potential covariates. The Mantel-Haenszel $\chi^2$ test was used to examine the difference in the proportion of subjects with changes from pre- to postcontrast SSI between propofol-sedated and awake groups. Statistical analyses were performed by using SAS 9.2 software (SAS Institute, Cary, North Carolina). Values of $P < .05$ were statistically significant.

RESULTS

$\text{FiO}_2$ and Age

There was a moderate positive correlation of SSI and $\text{FiO}_2$ before and after contrast in the overall cohort, and SSI appeared to decrease with age (Table 1). However, subgroup analysis demonstrated these correlations to be driven by differences between propofol-sedated and nonsedated children.

Patients under propofol anesthesia were younger, had higher $\text{FiO}_2$, and had significantly greater SSI before and after contrast than awake subjects (Table 2). Contrary to the overall trend, SSI increased with age before and after contrast in anesthetized subjects, and SSI decreased with increasing $\text{FiO}_2$ before, but not after, contrast (Table 1). In awake subjects, $\text{FiO}_2$ was constant at 21%, and there was no correlation of SSI with age.

Age was not a significant influence once the other factors, including CBV, were accounted for in multivariate analysis by stepwise ordinal logistic regression (Table 1).

CBV, CBF, and MTT

Like SSI, cortical CBV and MTT were significantly greater in anesthetized than in awake subjects, though CBF did not differ between groups (Tables 2 and 3). There was a strong positive correlation of SSI with CBV in anesthetized subjects before, but not after, contrast (Table 1). On multivariate analysis, only CBV significantly influenced precontrast SSI in propofol-sedated children once the other factors, including age, were accounted for (Table 1 and Fig 2). CBF, CBV, and MTT had no significant correlation with SSI before or after contrast in awake subjects.

Overall, SSI increased with CBV before and after contrast. These relationships and a positive relationship of MTT with precontrast SSI remained significant by multivariate analysis (Table 1).

Contrast

SSI increased with contrast in 45% (19/42) of all subjects. In propofol-sedated subjects, SSI grade ranged from 0 to 3 before contrast and increased in 9/24 (37%) after contrast. In awake subjects, SSI was nonexistent-to-minimal (grades 0–1) before and after contrast, and it increased with contrast in 10/18 (56%) subjects. The increase in SSI did not exceed 1 grade in any subject.
than FiO₂, both in propofol-sedated children and overall, with on noncontrast T2 FLAIR was more strongly correlated with CBV disease.12-14,24 Asymmetric FLAIR SSI has also been associated disease and carotid stenosis.11,12,14,24 In our study, diffuse SSI perintensity associated with dilated pial vessels in Moyamoya complemental oxygen but resembles the leptomeningeal FLAIR hy-

Hyperintense FLAIR signal in the cerebral sulci of anesthetized children has been attributed to T1 shortening effects of sup-

ternal carotid artery balloon occlusion testing.26 In such cases, sus-

Table 1: Univariate and multivariate analyses for the effects of selected factors on pre-/postcontrast SSI, overall and for propofol subjects

<table>
<thead>
<tr>
<th></th>
<th>Overall</th>
<th>Propofol</th>
<th>Awake</th>
<th>Precontrast SSI</th>
<th>Multivariate</th>
<th>Overall</th>
<th>Propofol</th>
<th>Awake</th>
<th>Postcontrast SSI</th>
<th>Multivariate</th>
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<tbody>
<tr>
<td></td>
<td>R²</td>
<td>P</td>
<td></td>
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<td></td>
<td>R²</td>
<td>P</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>FiO₂</td>
<td>0.442</td>
<td>.003</td>
<td>.0418</td>
<td>.042</td>
<td>.053</td>
<td>1.661</td>
<td>.0954</td>
<td>.2893</td>
<td></td>
<td>.073</td>
</tr>
<tr>
<td>Age</td>
<td>-.372</td>
<td>.015</td>
<td>.523</td>
<td>.009</td>
<td>.523</td>
<td>1.874</td>
<td>.364</td>
<td>.274</td>
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<tr>
<td>GM CBF</td>
<td>0.036</td>
<td>.864</td>
<td>.612</td>
<td>.026</td>
<td>.612</td>
<td>3.964</td>
<td>.1184</td>
<td>.054</td>
<td></td>
<td>.033</td>
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<tr>
<td>GM CBV</td>
<td>0.671</td>
<td>.0002</td>
<td>.0296</td>
<td>.002</td>
<td>.0296</td>
<td>.2397</td>
<td>.0952</td>
<td>.1354</td>
<td></td>
<td>.033</td>
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<tr>
<td>GM MTT</td>
<td>0.461</td>
<td>.020</td>
<td>.331</td>
<td>.269</td>
<td>.331</td>
<td>.331</td>
<td>.269</td>
<td>.331</td>
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<td>.269</td>
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Table 2: SSI, Age, and FiO₂ overall and by anesthesia status

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<th>Awake</th>
<th>Pre-SSI</th>
<th>Multivariate</th>
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<th>Propofol</th>
<th>Awake</th>
<th>Post-SSI</th>
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<tr>
<td></td>
<td>R²</td>
<td>P</td>
<td></td>
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<td></td>
<td>R²</td>
<td>P</td>
<td></td>
<td></td>
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<tr>
<td>FiO₂</td>
<td>.453</td>
<td>.003</td>
<td>.357</td>
<td>.087</td>
<td>.357</td>
<td>.453</td>
<td>.003</td>
<td>.357</td>
<td>.087</td>
<td>.357</td>
</tr>
<tr>
<td>Age</td>
<td>-.374</td>
<td>.15</td>
<td>.600</td>
<td>.002</td>
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<td>-.374</td>
<td>.15</td>
<td>.600</td>
<td>.002</td>
<td>.15</td>
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<tr>
<td>GM CBF</td>
<td>0.062</td>
<td>.770</td>
<td>.180</td>
<td>.557</td>
<td>.180</td>
<td>0.062</td>
<td>.770</td>
<td>.180</td>
<td>.557</td>
<td>.180</td>
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<tr>
<td>GM CBV</td>
<td>0.625</td>
<td>.0008</td>
<td>.376</td>
<td>.205</td>
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<td>0.625</td>
<td>.0008</td>
<td>.376</td>
<td>.205</td>
<td>.376</td>
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<tr>
<td>GM MTT</td>
<td>0.368</td>
<td>.071</td>
<td>.199</td>
<td>.516</td>
<td>.199</td>
<td>0.368</td>
<td>.071</td>
<td>.199</td>
<td>.516</td>
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</table>

Table 3: Perfusion measures overall and by anesthesia status

<table>
<thead>
<tr>
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<th>Propofol</th>
<th>Awake</th>
<th>Precontrast SSI</th>
<th>Multivariate</th>
<th>Overall</th>
<th>Propofol</th>
<th>Awake</th>
<th>Postcontrast SSI</th>
<th>Multivariate</th>
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<tbody>
<tr>
<td></td>
<td>R²</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td>R²</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CBF (mL/min/100 g)</td>
<td>66.86</td>
<td>(15.45)</td>
<td>67.2</td>
<td>(17.7)</td>
<td>66.5</td>
<td>(13.4)</td>
<td>.765</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CBV (mL/100 g)</td>
<td>7.45</td>
<td>(1.46)</td>
<td>8.2</td>
<td>(1.5)</td>
<td>6.6</td>
<td>(0.8)</td>
<td>.008</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>MTT (s⁻¹)</td>
<td>6.69</td>
<td>(1.12)</td>
<td>7.2</td>
<td>(1)</td>
<td>6.2</td>
<td>(1)</td>
<td>.013</td>
<td></td>
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</table>

DISCUSSION
Hyperintense FLAIR signal in the cerebral sulci of anesthetized children has been attributed to T1 shortening effects of sup-

mentral oxygen but resembles the leptomeningeal FLAIR hyperintensity associated with dilated pial vessels in Moyamoya disease and carotid stenosis.11,12,14,24 In our study, diffuse SSI on noncontrast T2 FLAIR was more strongly correlated with CBV than FiO₂, both in propofol-sedated children and overall, with MTT (CBV/CBF) significantly influential in the overall cohort.

These findings are consistent with studies demonstrating a positive correlation of CBV and a negative correlation of cerebrovascular reserve (an index of cerebral perfusion pressure represented by CBF/CBV, the inverse of MTT) with the severity of the leptomeningeal IV sign on noncontrast T2-FLAIR in Moyamoya disease.12-14,24 Asymmetric FLAIR SSI has also been associated with altered cerebral hemodynamics in patients undergoing in-
ternal carotid artery balloon occlusion testing.26 In such cases, autoregulatory mechanisms triggered by decreased CBF lead to compensatory precapillary vasodilation, increased CBV, prolonged MTT, and decreased cerebrovascular reserve.27 Indeed, in Moyamoya disease, the IV sign has been associated with ischemic symptoms and dilated pial vessels at surgery14 and resolves after revascularization.24

We found moderate positive correlations of FiO₂ with SSI before and after contrast in the overall cohort, in keeping with prior studies reporting increased CSF signal intensity with high FiO₂,5,7-10 but these were driven by significantly higher FiO₂ and SSI in propofol subjects, in whom SSI actually decreased with increasing FiO₂. To our knowledge, no prior study has demonstrated a direct correlation of SSI with FiO₂ under anesthesia-specific conditions, which could account for this apparent discordance. Although no subjects received more than the 60% FiO₂ threshold for increased CSF signal described by Frigon4 and most received less than the “all or none” threshold of 50% FiO₂ described by Braga et al,8 SSI was sometimes significant. Because nonsedated children did not receive supplemental oxygen, this study does not exclude a direct influence of FiO₂ on SSI. However, we found no FiO₂ threshold below which SSI was non-
extistent because even some subjects breathing room air had in-
creased SSI.

Typical of clinical practice, propofol-sedated children were younger and had greater SSI than nonsedated children in this study, raising the question of whether younger children are more likely to have increased SSI due to age alone. If this were the case, one would expect SSI to decrease with age, even in propofol-sedated children. We found the opposite (Table 1), consistent with prior reports,4 though CBV had a stronger influence. Age-related changes in SSI were not detected in older nonsedated children but cannot be excluded in young nonsedated children because young children generally require anesthesia for MR imaging.

On the other hand, the overall trend of increasing SSI with CBV is consistent with, and apparently driven by, CBV-related increases in SSI in the propofol group before contrast. SSI was uniformly low in nonsedated subjects, even in the range of CBV overlapping that of sedated children.

Differences between propofol-sedated and nonsedated children unexplained by age, FiO₂, or perfusion alone, suggest propo-

trol as a common thread. Indeed, age-related increases in CBV in propofol-sedated children have been previously described28 and could account for the positive associations of SSI with both age and CBV in our propofol-sedated subjects.

Like SSI, CBV was greater in the younger, propofol-sedated sub-
jects, as previously described (Tables 2 and 3).28 Although CBV is expected to be greater in younger children,29,30 there was no significant difference in CBV between (younger) sedated and (older) awake subjects, likely because propofol reduces CBF.15,31 As a result, MTT (CBV/CBF) was also greater in younger sedated subjects, though MTT is expected to be greater in older children.32 We speculate that
propofol-induced decreases in CBF could lead to compensatory dilatation of precapillary pial vessels, increasing CBV and prolonging MTT and resulting in diffusely increased SSI, as occurs asymmetrically in patients with Moyamoya disease and temporary ICA balloon occlusion.\textsuperscript{24,26} Diffuse SSI may thereby serve as a visual “marker” for general cerebral hemodynamic status in propofol-sedated children without cerebrovascular disease.

SSI increased with intravascular contrast, supporting a vascular contribution to SSI. Greater “stasis” of blood as evidenced by prolonged MTT in sedated children may promote increased diffusion of oxygen to CSF.\textsuperscript{33} Additionally, propofol has been found to facilitate disruption of the BBB.\textsuperscript{34} Propofol-related increases in vascular permeability to proteins or oxygen,\textsuperscript{34} with resultant T1 shortening of CSF,\textsuperscript{35} may account for the finding of Filippi et al\textsuperscript{5} that children sedated with propofol, but not chloral hydrate, exhibited SSI. Differences in perfusion effects may also contribute; unlike propofol, chloral hydrate increases CBF, potentially precluding a compensatory CBV response.\textsuperscript{31,36} Vascular enhancement and leakage of gadolinium across vessel walls rendered more permeable by propofol could obscure more subtle changes related to perfusion or FiO\textsubscript{2}, accounting for the loss of a significant relationship of SSI with CBV after contrast in propofol-sedated children. Age-related changes in vessel wall permeability to gadolinium may also influence postcontrast FLAIR SSI.\textsuperscript{28,37} Thus, as with CBV,\textsuperscript{28} there may be an interactive effect of propofol and age on vascular permeability and SSI.

This study has limitations. The small sample size may have contributed to the lack of a significant association of age with SSI on logistic ordinal regression, for which we could not include subjects without perfusion imaging. However, univariate correlations of age with SSI (by using all subjects) were lower than those for CBV for all but propofol postcontrast, consistent with the multivariate results (Table 1). Dynamic susceptibility contrast measures of CBV are less quantitative than PET, and our low contrast injection rate may have increased variability via a decreased contrast-to-noise ratio,\textsuperscript{20} potentially decreasing the strength of linear relationships of CBF, CBV, and MTT with SSI. Future study with PET-MR imaging may better evaluate these relationships. We calculated FiO\textsubscript{2} from the administration rate of oxygen via face mask, an imprecise relationship. Our findings suggest that decreasing the oxygen-administration rate in nonintubated children under propofol anesthesia will not reliably ameliorate artifactual SSI, perhaps due to this imprecision. Similar to authors of other studies, we did not perform concurrent CSF analysis and did not address the potential contribution of CSF protein levels to SSI, which could contribute to variability not captured by our models. We did exclude patients with known, suspected, or remote CSF abnormalities to minimize potential disruption of relationships of SSI with perfusion and FiO\textsubscript{2}. Because the threshold for CSF protein detection at our TE\textsubscript{effective} of 106–110 ms is \(\sim 250 \text{ mg/dL}\),\textsuperscript{35} far greater than the upper range of normal (60 mg/dL at our institution) and indicative of significant leptomeningeal CNS disease, the contribution of CSF protein to SSI would not be expected to be significant in this study.

**CONCLUSIONS**

Elevated cortical CBV appears to contribute to increased SSI on noncontrast T2 FLAIR brain images in propofol-sedated children. SSI increased with intravascular contrast regardless of anesthesia, supporting a vascular contribution to SSI. Further investigations into the potential of increased FLAIR SSI as a marker for elevated CBV in propofol-sedated children should consider the potentially interactive effects of age and propofol on cerebral perfusion and vascular permeability.

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**Disclosures**

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Zoltan Patay—RELATED: Guerbet LLC Comments: Consulting services.

Guerbet LLC, Comments: consulting services.

National Cancer Institute, Comments: Grant Number CA21765; American Lebanese Syrian Associated Charities, Comments: American Lebanese Syrian Associated Charities is the fundraising arm of St. Jude Children’s Research Hospital.
hence most research conducted at St. Jude is “funded” to some extent by them. Payment for Development of Educational Presentations: Erasmus Course of MRI
raia). *Money paid to the institution.

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