Size does matter: The role of decompressive craniectomy extent for outcome after aneurysmal subarachnoid hemorrhage

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Abstract

Background and purpose: In previous studies in patients with traumatic brain injury and ischemic stroke, the size of decompressive craniectomy (DC) was reported to be paramount with regard to patient outcomes. We aimed to identify the impact of DC size on treatment results in individuals with aneurysmal subarachnoid hemorrhage (SAH).

Methods: The extent of DC in 232 patients with SAH who underwent bifrontal or hemi-craniectomy between January 2003 and December 2015 was analyzed using semi-automated surface measurements. The study endpoints were course of intracranial pressure (ICP) treatment after DC, occurrence of cerebral infarcts, in-hospital mortality, and unfavorable outcome at 6 months (defined as modified Rankin scale score >3). The associations of DC size with the study endpoints were adjusted for DC timing, patient age, clinical and radiographic severity of SAH, aneurysm location, and treatment modality.

Results: The mean DC surface area was 100.9 (±45.8) cm². In multivariate analysis, a large DC (>105 cm²) was independently associated with a lower risk of cerebral infarcts (adjusted odds ratio [aOR] 0.30, 95% confidence interval [CI] 0.16–0.56), in-hospital mortality (aOR 0.28, 95% CI 0.14–0.56) and unfavorable outcome (aOR 0.51, 95% CI 0.27–0.98). Moreover, SAH patients with a small DC size (<75 cm²) were more likely to require prolonged (>3 days, aOR 3.60, 95% CI 1.37–9.42) and enhanced (aOR 2.31, 95% CI 1.12–4.74) postoperative ICP treatment.

Conclusion: This is the first study showing the impact of DC size on postoperative ICP control and patient outcome in the context of SAH; specifically, a large craniectomy flap (>105 cm²) might lead to better outcomes in SAH patients requiring decompressive surgery.

KEYWORDS
decompressive craniectomy, intracranial aneurysm, outcome research, subarachnoid hemorrhage, surface
INTRODUCTION

A number of early and late complications of aneurysmal subarachnoid hemorrhage (SAH) contribute to the considerable morbidity and mortality associated with this disease [1]. Pathologic increases in intracranial pressure (ICP) present one such complication, affecting over half of patients with SAH [2]. ICP increase reduces cerebral perfusion pressure, promoting cerebral ischemia, which is, in turn, strongly associated with risk of unfavorable outcome after SAH [3–5].

Decompressive craniectomy (DC) is a well-established neurosurgical procedure for intractable ICP [6,7]; however, evidence of DC utility in SAH is poor and limited to small retrospective case series and two meta-analyses [8,9]. Of the factors contributing to SAH outcomes after DC, patient age, initial clinical condition and DC timing are the most consistently reported [2,9,10].

The importance of DC size for functional outcome was shown for patients with traumatic brain injury (TBI) and ischemic stroke [11–16]. In contrast, less is known about the clinical value of DC size in SAH patients undergoing decompressive surgery. To date, there are only two case series based on surface measurements (n = 16) [5] or maximum DC diameter (n = 19) [17] in SAH patients. These studies, which were limited to very small sample sizes, did not find any associations between DC size and SAH outcome. The aim of the present study, therefore, was to analyze the clinical influence of DC size on functional outcomes of SAH in a large monocentric series using software-based semi-automatic surface measurements.

MATERIALS AND METHODS

Patient population

This was a retrospective study based on our institutional observational SAH database (registered in the German clinical trial register, unique identifier: DRKS00008749), which contains all consecutive patients with ruptured intracranial aneurysms treated at our institution between January 2003 and December 2015. All individuals who underwent DC due to SAH were eligible for the study. The exclusion criteria were: (i) craniectomy prior to admission/SAH onset; (ii) craniectomy due to any complication not related to ICP control (i.e., postoperative infection); (iii) SAH with suboccipital DC; and (iv) no or insufficient perioperative computed tomography (CT) data necessary for surface measurements. The approval of the institutional ethics committee (Ethik-Kommission, Medizinische Fakultät der Universität Duisburg-Essen, registration number: 15–6331-BO) was obtained for this study.

Subarachnoid hemorrhage management

All patients were initially admitted to our neurosurgical intensive care unit. Conservative SAH management was performed according to the latest guidelines [18,19] and included oral nimodipine and maintenance of euvolemia for 3 weeks. An external ventricular drain (EVD) was placed: (i) initially at the presence of acute hydrocephalus; or (ii) for the monitoring and conservative treatment of ICP prior to/during DC. Management of cerebral vasospasm after SAH has been discussed previously elsewhere [20]. The bleeding source was confirmed by means of digital subtraction and/or CT angiography. Treatment decisions were made after consultation between the neuroradiologist and the vascular neurosurgeon on duty.

Conservative and surgical ICP management

Continuous ICP monitoring of the patients was performed via the EVD. In case of sustained ICP >20 mmHg, baseline conservative treatment was initiated including the maintenance of cerebral perfusion pressure at >60 mmHg by infusion and catecholamines, normothermia, elevation of the head to 30°, deep sedation, osmotherapy with 20% mannitol, and forced cerebrospinal fluid drainage. According to the institutional standard operating procedures, patients with refractory ICP despite baseline conservative treatment and DC surgery underwent enhanced medical ICP treatment (EMIT) using second-line measures (relaxation, application of tromethamine, and barbiturate coma, guided by a burst-suppression EEG pattern).

Decompressive craniectomy was performed: (i) on admission (primary DC), based on clinical (poor neurological grade) and radiographic features (brain swelling with/without intracerebral hemorrhage [ICH]) and (ii) as a further course (secondary DC) in the presence of intractable ICP resistant to the baseline conservative treatment described above.

The patients underwent a large fronto-temporo-parietal hemi-craniectomy (HCE) or bifrontal bone flap craniectomy (BFCE) with expanded duroplasty, as previously reported [2]. The cranioplasty was usually performed 3 months after DC.

According to our institutional standard operating procedures, all patients underwent routine postoperative CT within 24 h after aneurysm treatment, DC or any other intracranial intervention. Moreover, additional CT imaging was performed in cases of any neurological deterioration, prolonged impairment in the conscious state and during EVD weaning.

Data management

As primary endpoints of the study, we evaluated the impact of DC type and extent on the following events: (i) occurrence of new cerebral infarctions on follow-up CT; (ii) in-hospital mortality; and (iii) unfavorable outcome at 6 months after SAH (modified Rankin scale [21] score >3). Secondary endpoints of the study were: (i) associations between DC extent and timing and type (BFCE vs HCE) of DC; (ii) impact of the type and extent of DC on the course of ICP after DC, with regard to (a) the duration of medical management of ICP and (b) the need for EMIT.
The following variables were collected from the institutional observational SAH database and in-house electronic medical records: age; clinical grade on admission according to the World Federation of Neurosurgical Societies (WFNS) scale [22]; presence of ICH on initial CT; treatment modality; DC timing (primary/secondary) and type (BFCE/HCE); functional outcome at discharge and 6 months after SAH; and conservative ICP management before and after DC. All CT scans up to 6 weeks after SAH were reviewed by the first author (R.J.) for the occurrence of new cerebral infarctions [23].

Surface measurements

Surface measurements were performed by the second author (S.-Q.H.) using a semiautomatic method of surface measurement with the Materialise Mimics Medical image processing software for three-dimensional (3D) reconstruction of the skull (version 21.0; Materialise NV, Leuven, Belgium) and 3-matic Medical (version 13.0; Materialise NV). Preoperative and postoperative CT imaging were used to reconstruct 3D models of DC flaps and semiautomatic surface size calculations (Figure 1).

Statistical analysis

Extent of DC and duration of postoperative ICP management were analyzed both as continuous variables and in a dichotomous manner using the cutoff based on the receiver-operating characteristic (ROC) curve analysis. The initial clinical condition was analyzed in a dichotomous manner as good (WFNS grades 1–3) and poor (WFNS grades 4–5). Regarding the radiographic severity of SAH, based on the results of the previous study [2], the use of the variable “presence of ICH” was preferred over “original Fisher scale” [24] as a more relevant outcome predictor for DC patients.

For univariate tests, categorical variables were analyzed using the chi-squared test or Fisher’s exact test, where appropriate. Student’s t-test and the Mann–Whitney U-test were performed for normally distributed and non-normally distributed continuous data, respectively. Thereafter, the associations between the variables of interest and the study endpoints were tested in a multivariable binary logistic regression analysis, adjusted for relevant confounders: patient age; DC timing (primary vs secondary); initial clinical (WFNS grade) and radiographic (presence of ICH) severity of SAH; aneurysm location (anterior cerebral artery); and treatment modality.

Differences with a p value of ≤0.05 were regarded as statistically significant. Variables were expressed as mean ± standard deviation (SD) or percentage of patients, as appropriate. Data analysis was performed using the statistical software PRISM (version 5.0, GraphPad Software Inc.) and SPSS (version 25, SPSS Inc., IBM).

RESULTS

Population characteristics

After exclusion of non-eligible cases (DC/treatment prior to admission: n = 2; craniectomy due to infection: n = 1; suboccipital DC: n = 4; insufficient data for surface measurement: n = 6), 232 SAH patients with DC were included in the final analysis (see Table 1 for the baseline and outcome characteristics of the patients).
Decompressive craniectomy characteristics

The mean (±SD) DC surface was 100.9 (±45.8) cm². Primary DC was necessary in 163 patients (70.3%), whereas 69 individuals (29.7%) underwent secondary DC. There was no difference in DC surface between primary and secondary DC cases: 103.4 (±48.9) versus 95.2 (±36.8) cm² (p = 0.3998).

The majority of the patients underwent HCE (n = 199, 85.8%). The mean (±SD) DC surface of 33 BFCE cases was 92.1 (±37.2) cm², which was not significantly different from the mean surface of the HCE cases (107.2 ±85.3) cm² (p = 0.2949). In the subgroup analysis, there was also no difference between BFCE and HCE among the primary (p = 0.3200) and secondary (p = 0.8228) DC cases (Figure 2).

In the multivariate analysis, DC type was not associated with the primary (Table S1) and secondary (Table S2) study endpoints.

Association between DC size (as a continuous variable) and SAH outcome

Cerebral infarction

In the univariate analysis, the patients with CT infarcts presented with smaller DC size: 92.7 (±43.6) versus 120.5 (±45.1) cm² (p < 0.0001). The multivariate analysis confirmed an independent association between DC size and infarct risk (p < 0.0001; Table S3).

In-hospital mortality

Univariate analysis showed a larger DC size among hospital survivors: 105.1 (±48.0) versus 91.2 (±38.7) cm² (p = 0.0258). In the multivariate analysis, there was an independent association between DC size and mortality risk (p = 0.028).

Unfavorable outcome at 6 months

In univariate analysis, there was no association between DC size and functional outcome after SAH (105.0 ±46.3 vs. 98.0 ±42.3) cm² for favorable and unfavorable outcome, respectively; p = 0.2188). Congruently, the multivariate analysis also showed no significant association with outcome when assessing DC size as a continuous variable (p = 0.098).

Association between DC size (as a dichotomous variable) and SAH outcome

According to the results of the ROC curve analysis, a clinically relevant cutoff for DC size was set at 105 cm² (Figure S1). The rate of cerebral infarction in individuals with DC >105 cm² and

| TABLE 1 | Baseline and outcome characteristics of the patients in the final cohort |
|-------------------------|-----------------|------------------|------------------|------------------|------------------|
| Characteristic          | Number of patients | Mean (±SD) age, years | Women, n (%) | WFNS (grade IV–V), n (%) | ICH, n (%) | Aneurysm location, n (%) |
|-------------------------|-----------------|------------------|------------------|------------------|------------------|------------------|
| Number of patients      | 232             | 52.2 (±12.2)     | 151 (65.1)       | 154 (66.4)       | 156 (67.2)       |
| Mean (±SD) age, years   |                 |                  |                 |                 |                 |
| Women, n (%)            |                 |                  |                 |                 |                 |
| WFNS (grade IV–V), n (%)|                 |                  |                 |                 |                 |
| ICH, n (%)              |                 |                  |                 |                 |                 |
| Aneurysm location, n (%)|                 |                  |                 |                 |                 |
| Internal carotid artery |                 |                  |                 |                 |                 |
| Middle cerebral artery  |                 |                  |                 |                 |                 |
| Anterior cerebral artery|                 |                  |                 |                 |                 |
| Posterior circulation   |                 |                  |                 |                 |                 |
| Acute hydrocephalus, n (%)|             |                  |                 |                 |                 |
| Treatment modality: clipping, n (%) | 182 (78.4) |                 |                 |                 |                 |
| Cerebral infarction, n (%)   | 163 (70.3) |                  |                 |                 |                 |
| In-hospital mortality, n (%) | 69 (29.7) |                  |                 |                 |                 |
| Unfavorable outcome, n (%)  | 150 (66.7) |                 |                 |                 |                 |

Abbreviations: ICH, intracerebral hemorrhage; SD, standard deviation; WFNS, World Federation of Neurosurgical Societies.

*Seven cases were lost to follow-up at 6 months after subarachnoid hemorrhage.
DC $\leq$ 105 cm² was 55.6% (50/90) versus 79.6% (113/142), respectively (hereinafter). There was a lower rate of in-hospital mortality in individuals with DC $>$ 105 cm²: 17.8% (16/90) versus 37.3% (53/142). Fittingly, unfavorable outcome at 6-month follow-up was observed less frequently in patients with a large DC: 60.2% (53/88) versus 70.8% (97/137). When comparing only those patients who survived the initial treatment, the difference with regard to unfavorable outcome was less prominent: 49.3% (37/75) versus 54.3% (44/81).

In the multivariate analysis, adjusted for relevant outcome confounders, there was an independent association between large DC size (>105 cm²) and all primary outcome endpoints (Table 2): cerebral infarcts (adjusted odds ratio [aOR] 0.30, p < 0.0001), in-hospital mortality (aOR 0.28, p = 0.043), and unfavorable outcome (aOR 0.51, p = 0.043).

**Impact of DC size on further ICP management**

In the multivariate analysis (Table S4), DC size (as a continuous variable) showed a borderline significance for the association with the need for EMIT (p = 0.055). In the ROC curve analysis, the relevant DC size cutoff for the secondary endpoints was defined at 75 cm². The subsequent multivariate analysis showed that small DC flap size (<75 cm²) was independently associated with risk of refractory ICP after DC necessitating EMIT: aOR 2.31 (p = 0.023; Table 3, see also Table S5 for the results of the univariate analysis).

In the univariate/multivariate analyses, duration of medical ICP treatment after DC as a continuous variable did not show a significant association with DC size. However, after the dichotomization of the duration of postoperative ICP treatment at 72 h (according to the ROC curve), SAH patients with a small DC flap (<75 cm²) were more likely to require longer (>3 days) postoperative ICP treatment in the final multivariate analysis: aOR 3.60 (p = 0.009; Table 3).

**DISCUSSION**

The appropriate size of DC is essential for treatment success in patients with TBI and ischemic stroke. In patients with SAH, there is still no evidence regarding the clinical value of the extent of DC. In

### TABLE 2 Multivariable analysis for the association between decompressive craniectomy size (dichotomized at >105 cm²) and the primary study endpoints

| Parameter | aOR (95% CI) | p     |
|-----------|--------------|-------|
| Cerebral infarcts | 0.30 (0.16–0.56) | <0.0001 |
| DC size, >105 cm² | 0.81 (0.31–2.10) | 0.666 |
| DC timing, primary | 1.01 (0.99–1.04) | 0.405 |
| Age, per-year-increase | 1.42 (0.70–2.86) | 0.332 |
| WFNS, grade 4–5 | 1.44 (0.70–2.95) | 0.321 |
| Aneurysm location, ACA | 0.56 (0.26–1.20) | 0.135 |
| ICH | 0.56 (0.26–1.20) | 0.135 |
| Treatment modality, clipping | 0.32 (0.09–1.06) | 0.062 |

**In-hospital mortality**

DC size cutoff for the secondary endpoints was defined at 75 cm². The subsequent multivariate analysis showed that small DC flap size (<75 cm²) was independently associated with risk of refractory ICP after DC necessitating EMIT: aOR 2.31 (p = 0.023; Table 3, see also Table S5 for the results of the univariate analysis).

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**TABLE 3 Multivariable analysis for the association between decompressive craniectomy size (dichotomized at <75 cm²) and secondary study endpoints.**

| Parameter | aOR (95% CI) | p     |
|-----------|--------------|-------|
| The need for EMIT | 2.31 (1.12–4.74) | 0.023 |
| DC size, <75 cm² | 0.36 (0.12–1.07) | 0.065 |
| DC timing, primary | 0.97 (0.94–1.00) | 0.063 |
| Age, per-year-increase | 1.57 (0.67–3.65) | 0.301 |
| WFNS, grade 4–5 | 1.30 (0.61–2.76) | 0.503 |
| Aneurysm location, ACA | 1.90 (0.81–4.45) | 0.140 |
| ICH | 0.55 (0.19–1.58) | 0.264 |
| Treatment modality, clipping | 2.31 (1.12–4.74) | 0.023 |

**Prolonged post-DC medical ICP treatment (>3d)**

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In the univariate/multivariate analyses, duration of medical ICP treatment after DC as a continuous variable did not show a significant association with DC size. However, after the dichotomization of the duration of postoperative ICP treatment at 72 h (according to the ROC curve), SAH patients with a small DC flap (<75 cm²) were more likely to require longer (>3 days) postoperative ICP treatment in the final multivariate analysis: aOR 3.60 (p = 0.009; Table 3).

**TABLE 3 Multivariable analysis for the association between decompressive craniectomy size (dichotomized at <75 cm²) and secondary study endpoints.**

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| DC size, <75 cm² | 0.36 (0.12–1.07) | 0.065 |
| DC timing, primary | 0.97 (0.94–1.00) | 0.063 |
| Age, per-year-increase | 1.57 (0.67–3.65) | 0.301 |
| WFNS, grade 4–5 | 1.30 (0.61–2.76) | 0.503 |
| Aneurysm location, ACA | 1.90 (0.81–4.45) | 0.140 |
| ICH | 0.55 (0.19–1.58) | 0.264 |
| Treatment modality, clipping | 2.31 (1.12–4.74) | 0.023 |

Abbreviations: ACA, anterior cerebral artery; aOR, adjusted odds ratio; CI, confidence interval; DC, decompressive craniectomy; EMIT, enhanced medical intracranial pressure treatment; ICH, intracerebral hemorrhage; ICP, intracranial pressure; WFNS, World Federation of Neurosurgical Societies.
our large monocentric series, DC size had a significant impact on the risk of cerebral infarction, in-hospital mortality and unfavorable outcome, as well as on the severity of postoperative intracranial hypertension requiring further medical treatment.

Decompressive craniectomy is widely used both prophylactically and in cases of persistent ICP refractory to medical treatment [2,5]. The pathophysiologic aim of DC is to reduce ICP and minimize cerebral ischemia by increasing cerebral perfusion and tissue oxygenation [10].

The outcomes of patients with SAH requiring DC remain poor [8,9]. The major dilemma regarding the use of DC after SAH is that, although decompression might be a lifesaving measure, the long-term functional outcomes and quality of life of survivors are usually poor [25]. Several recent studies have highlighted the importance of early decompression for the achievement of more favorable functional outcomes of patients with SAH necessitating DC [2,4,5,26]. Further analysis of factors related to outcome after DC in SAH is of paramount clinical importance.

There is still no consensus on the standard surgical technique for DC, in particular, the location and the extent of bone removal [27]. A larger DC size increases the area of possible brain expansion and decreases the amount of venous congestion around the DC [15]. At the same time, higher rates of DC-related complications were reported in patients with larger craniectomies [15]. Therefore, the question of the optimal extent of DC depends on the evidence for clinical benefit from the DC size for every single primary diagnosis.

Regarding TBI and ischemic stroke, the relationship between DC size and clinical outcome has been reported in several studies [11-16]. The majority of prospective trials recommended 12 cm as the minimum diameter of DC [28,29]. The recently published Brain Trauma Foundation TBI guidelines favor large (12 cm × 15 cm or 15 cm in diameter) unilateral fronto-temporo-parietal DC [30].

With regard to SAH, the evidence for the impact of DC size on further clinical course and outcome is sparse. In 2007, Schirmer et al. [5] performed surface measurements in 16 SAH patients, but did not find any associations between DC extent and patient outcomes in this small cohort. In another small study of 19 SAH cases based on maximum DC diameter [17], the authors were also unable to identify a link between DC size and SAH outcome. The present study therefore provides the first evidence of the clinical impact of size of DC in the context of SAH using a sufficient sample size. Patients with a large DC flap (>105 cm²) were at lower risk of cerebral infarctions, in-hospital mortality and unfavorable outcome at 6 months.

Moreover, DC size was also associated with the postoperative clinical course of ICP. In particular, a small DC (<75 cm²) was related not only to poorer outcomes (Table S6), but also to the persistence of pathologic ICPs requiring further medical treatment. These associations could be confirmed in the multivariate analysis adjusted for patient age, initial clinical condition, presence of ICH, timing of DC, and treatment modality.

As compared to previously reported flap areas (77 cm² [31], 81.8 cm² [32], 84.3 cm² [33], 85.4 cm² [5], 88.7 cm² [34] and 119 cm² [35]), our data on the mean DC surface in the cohort (100.9 cm²), and particularly the above-mentioned “critical” cutoffs (<75 cm² and

**FIGURE 3** Three-dimensional reconstructions of two decompressive craniectomy (DC) cases with a similar maximal anterior-posterior diameter (~12 cm), but different DC surface areas: 88.8 cm² (Case A) and 148.9 cm² (Case B)


To address the true DC extent and its impact on the study endpoints, we evaluated the DC surface area using semiautomatic measurements with 3D modeling software. Although the majority of the recommendations on the size of DC are based on the maximal (anterior-posterior) diameter of the bone flap [28–30], the following two examples from our series underline the importance of taking the effective area of decompression into consideration when analyzing DC size. Figure 3 shows 3D reconstructions of two DC cases with comparable anterior-posterior extent, but markedly different DC surface areas. We believe that future studies addressing the clinical utility of DC size should utilize software-based surface measurements rather than use a simple mono-metric assessment or unprecise formula-based surface estimations which might not reflect the true DC extent.

A limitations of the present study is that, because of the retrospective study design, the accuracy and completeness of the data depend on the quality of documentation in the electronic medical records. Another important limitation is the presence of selection bias in the analyzed cohort because the indications and the technique used for DC were not based on a strictly predefined study protocol; there is therefore large variation in the extent of DC. Moreover, clipping was overrepresented in the analyzed cohort, as in the majority of DC cohorts [9]. These factors limit the generalizability of the study results to other SAH populations. Although we tried to account for basic outcome predictors in our analysis, the potential effect of other confounders on the study results cannot be completely excluded. In particular, it is generally acknowledged that cerebral infarcts after SAH are multifactorial in nature and, as such, we cannot conclude that there is a direct causal relationship between DC size and occurrence of infarcts in the cohort. Moreover, non-unique timepoints and the number of follow-up CT scans performed confer additional risk of information bias.

In conclusion, the results of this study provide the first evidence for the role of craniectomy flap size in the outcome of SAH patients requiring DC; specifically, a large craniectomy area of >105 cm² might lead to better SAH outcomes regardless of patient age, initial clinical and radiographic severity, craniectomy timing and treatment modality, while a small DC of <75 cm² seems to confer additional disadvantage with regard to sufficient ICP control in the postoperative course.

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CONFLICT OF INTERESTS
None declared.

AUTHOR CONTRIBUTIONS
Ramazan Jabbarli: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Writing – original draft (equal). Shi-Qing He: Data curation (equal); Writing – original draft (equal). Marvin Darkwah Oppong: Validation (equal); Writing – review and editing (equal). Annika Herten: Visualization (equal); Writing – review and editing (equal). Mehdi Chihi: Conceptualization (equal); Writing – review and editing (equal). Daniela Pierscianek: Writing – review and editing (equal). Philipp Dammann: Methodology (equal); Writing – review and editing (equal). Ulrich Sure: Supervision (equal); Writing – review and editing (equal). Karsten H Wrede: Investigation (equal); Methodology (equal); Writing – original draft (equal); Writing – review and editing (equal).

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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