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ORIGINAL PAPER

Plastic Changes in the White Matter Induced by Templestay, a 4-Day Intensive Mindfulness Meditation Program

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Abstract

Objectives Further explorations are needed to determine how behavioral-lifestyle changes of various types influence neural plasticity in the white matter (WM); in particular, little is known about the influence of one's self-discipline on changes in WM. A retreat program called Templestay follows the self-discipline practices used by Buddhist monks for 3 nights and 4 days; this program mainly involves meditation and other forms of behavioral-lifestyle modifications. In this study, we explored how neural plasticity occurs in WM structures in response to a relatively short retreat program.

Methods We designed a longitudinal study that investigates WM neural plasticity over the course of Templestay. The Templestay group experienced the daily life of Buddhist practitioners, whereas the control group only participated in a retreat program at the same temple. Diffusion tensor imaging data were acquired before and after the Templestay program to investigate neural plasticity in the WM. We examined changes in the fractional anisotropy maps.

Results We observed significant changes in the fractional anisotropy maps at the left superior longitudinal fasciculus, left posterior corona radiata, and splenium of the corpus callosum after 4 days of Templestay. Based on the results of our study, a 4-day meditation period in combination with behavioral-lifestyle modifications facilitates WM myelination in regions important for cognitive functions.

Conclusions These results provide evidence of very rapid structural remodeling of the WM, suggesting that activity-dependent changes in myelination are induced by Templestay, a relatively understudied self-discipline program that includes behavioral-lifestyle modifications.

Keywords Mindfulness training · Meditation · Neural plasticity · Templestay · Diffusion tensor imaging · Fractional anisotropy

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The importance of individuals' behavioral patterns has been emphasized in studies investigating the influence of behavioral changes on mood or cognitive functions (Butler et al. 2006; Driessen and Hollon 2010). Mood or cognitive functions have been determined to be related to the brain, and the question of whether changes in our behavioral patterns influence neural plasticity has been raised (Yoon et al. 2017; Yoon et al. 2019). Studies indicate that neural plasticity may occur during behavioral changes or training (Klimecki et al. 2013; Zatorre et al. 2012). Neural plasticity induced by behavioral modifications has been considered to occur mainly in synapses (Caroni et al. 2014). However, conduction velocity, which is associated with neural plasticity in the white matter (WM), has recently been suggested to be influenced by behavioral modifications (Fields 2015). WM integrity is assessed using diffusion tensor imaging (DTI), a magnetic resonance method that provides a fractional anisotropy (FA) value representing the microstructural integrity of the WM (Basser and Pierpaoli 1996). Changes in FA values have been reported in studies that found

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changes in WM myelination secondary to behavioral changes or training (Engvig et al. 2012; Tang et al. 2010).

Previous reports have observed changes in neural plasticity following meditation, a form of behavioral change or training (Fox et al. 2014; Tang et al. 2015). Meditation is conceptualized as a family of training practices that self-regulate the body and mind by engaging a specific attentional set (Cahn and Polich 2006). Various kinds of meditation practices share common origins in Buddhist traditions, including Vipassana meditation, Zen meditation, and mindfulness-based approaches, such as integrative body-mind training and mindfulness-based stress reduction (Tang et al. 2015). Despite the differences between these practices, meditation has been shown to modify the neuronal functions underlying emotional regulation, attentional processing, and self-awareness (Kang et al. 2013; Tang et al. 2009). Although reports have examined the influence of various forms of Buddhist-related training on neural plasticity, no studies have assessed the influence of self-discipline practices adopted by Buddhist practitioners on neural plasticity. Templestay is a 3-night and 4-day retreat program in which participants experience the life of Buddhist practitioners by staying at a Buddhist temple. This program includes 19 h of meditation training and other activities involving behavioral-lifestyle modifications, including but not limited to the ceremonial service; 108 bows, a ritual to remove worldly desires; and the tea ceremony (Hwang et al. 2018). In an earlier study, Hwang et al. (2018) reported that this 4-day program has benefits of increased resilience, thus rendering participants less vulnerable to stress. Therefore, it is likely that the combination of this meditation training with comprehensive behavioral-lifestyle modifications might have an effect on neural plasticity.

Previous magnetic resonance imaging (MRI) studies on meditation have provided evidence that various gray matter (GM) areas in the frontal region are involved in meditation, particularly the rostrolateral prefrontal cortex (Kang et al. 2013; Lazar et al. 2005), anterior cingulate cortex (Chetelat et al. 2017; Kyeong et al. 2017), and anterior insula (Cotier et al. 2017; Lutz et al. 2013). The WM connecting the GM should also be more robust to allow more efficient communication among the increased activity or volume of the GM. In fact, according to a systematic review of neuroimaging studies on meditation (Fox et al. 2014), meditation-associated WM structures include the corpus callosum (CC), which connects both hemispheres (Zarei et al. 2006) and the superior longitudinal fasciculus (sLF), which connects frontal structures to the posterior regions of the brain (Makris et al. 2005). These WM structures not only connect the frontal region of the brain but also reportedly play crucial roles in higher cognitive functions (Hofer and Frahm 2006; Lehéricy et al. 2004). Therefore, meditation may improve cognitive functions related to the functions of specific brain regions, and these improvements are associated with enhanced microstructural integrity of the WM. Similar to other meditation studies, the Hwang et al. (2018) study on Templestay suggested improvements in cognitive functions. Therefore, it can be speculated that the WM might exhibit changes in areas similar to the changes reported in other meditation studies with Templestay.

In this study, we tested whether Templestay, a meditation retreat program associated with behavioral-lifestyle modifications, would induce WM plasticity. We hypothesized that behavioral-lifestyle modifications would have a synergetic influence on WM plasticity induced by meditation training; thus, we would be able to observe changes within 4 days. To eliminate the effects of environmental and dietary factors, all of the participants stayed at the same temple for 3 nights and 4 days and were also fed the same diet. While the individuals in the control group maintained their usual lifestyle at the temple, the experimental group participated in the Templestay program, which includes 19 h of meditation training and associated behavioral-lifestyle modifications. Hence, we investigated WM plasticity, as measured by changes in FA, in brain structures that are associated with meditation over 4 days of intensive meditation training and accompanying behavioral-lifestyle modifications under controlled environmental and dietary conditions.

Method

Participants

Sixty-eight healthy office workers, aged 20 years and older, were recruited via an Internet advertisement and randomly assigned to either the Templestay or the Control group in a 2:1 ratio using a mixed block randomization method. The randomization was managed by a blind agent independent from the researchers. None of the participants had participated in meditation training or psychotherapy within the 3 months prior to the start of the study. All participants were required to be free of medical, neurological, and psychiatric illness; psychoactive medications for at least 1 month; and contraindications for MRI scanning. Forty-four participants were enrolled in the Templestay group, and twenty-four participants were enrolled in the control group. After completing the study, one participant from the control group was excluded because the participant was involved in long-term meditation training. It was clearly explained to all participants that if anyone had any difficulties participating in the program, they could stop the program at any time. Furthermore, as soon as new information came to light that could affect an individual's willingness to continue participating in the program, we would notify the individual immediately. Older adults exhibit a smaller degree of experience-dependent neuronal plasticity (Bloss et al. 2011), and age-related decreases in WM volume have been reported to obscure the effect of short-term meditation training

(Basser and Pierpaoli 1996; Stadlbauer et al. 2008). Therefore, we only included participants who were 40 years of age or younger in the DTI analysis (N = 33 and N = 17 in the Templestay and control groups, respectively). All participants fully understood the study procedure and provided written informed consent. The study was conducted in accordance with the Declaration of Helsinki, and the Institutional Review Board of Seoul National University Hospital approved this study. All methods were performed in accordance with relevant guidelines and regulations.

Procedure

All Templestay and active control sessions were conducted during a single 3-night, 4-day retreat at Daewonsa Temple in Korea to control the environment and diet. The Templestay sessions involved all the basic elements of Templestay, such as meditation, conversation time with monks, and Ulryeok (working together). The 19 h of meditation training completed by the Templestay group focused on mindfulness meditation, including bowing meditation (108 prostrations, which empties 108 kinds of affliction arising from individual's vulnerability), Zen meditation and mental imagery (achieving calmness and mindfulness by clearing all rambling thoughts). The control group stayed at the same temple for the same period of time and was provided the same meals and tea as the Templestay group; however, they maintained their own lifestyle without completing any meditation training. The control group was thoroughly separated from any elements related to meditation during the experiment. They were banned from contact with any monks and were not even allowed to enter the Buddhist sanctuary. Detailed information regarding the structure of the Templestay is provided in the Supplementary Material (Fig. S1 and S2). This experiment was divided into 12 sessions (7 Templestay and 5 control sessions) between July 2014 and July 2015. Each session lasted 3 nights and 4 days, and each session included between 2 and 9 participants.

Measures

T1-weighted (T1) and DWI data were acquired in the sagittal plane using a Siemens 3 T Trio MRI scanner (Siemens Magnetom Trio, Erlangen, Germany) with a 32-channel head coil. T1 images were acquired using a 3D magnetization-prepared rapid-acquisition gradient echo (MPRAGE) sequence with the following parameters: repetition time (TR), 1670 ms; echo time (TE), 1.89 ms; voxel size, 1 × 1 × 1 mm^3; field of view (FOV), 250 mm; 9-degree flip angle; and 208 slices. Two sets of diffusion-weighted images were collected for each participant during each scanning session (pre- and posttraining) using opposite phase-encoding directions (anterior > posterior (A > P) and posterior > anterior (P > A)) to correct geometric distortions and eddy currents. The first set was acquired with a TR of 9000 ms, a TE of 82 ms, a 112 × 112 matrix, an FOV of 224 mm and a voxel size of 2 × 2 × 2 mm^3. Diffusion-sensitizing gradient echo encoding was applied in 72 directions using a diffusion-weighting factor b of 1000 s/mm^2. The second DTI set was identical to the first set except that a diffusion-weighting factor b of 0 s/mm^2 was used for six volumes. The total acquisition time for the two scans was 12 min and 47 s. Compared with the pre-Templestay imaging data acquisition, which measured the individuals' baselines, the timing of the post-Templestay imaging data acquisition could be critical for the present study. We attempted to strictly control the time gap to no more than 3 days between the termination of Templestay and the post-Templestay imaging data acquisition to accurately assess WM changes that occurred after Templestay.

Data Analyses

The DTI data were processed with the FMRIB Software Library (FSL, http://www.fmrib.ox.ac.uk/fsl). The DWI data were preprocessed using corrections for susceptibility (TOPUP, FSL) and eddy current distortions as well as skull removal and motion corrections. The preprocessed images were fitted to the tensor model at each voxel, and an FA map was also calculated. Voxelwise analysis of the FA maps was carried out using tract-based spatial statistics (TBSS) (Smith et al. 2006). Individual FA maps were aligned to the FMRIB58_FA standard-space image for voxelwise nonlinear registration. The registered FA maps were resampled to 1 × 1 × 1-mm^3 resolution. The skeleton was thresholded at an FA value of 0.2. For the longitudinal analysis, subtractions of pre- to postskeletonized maps were conducted for each subject. These difference maps were merged and then used as input for randomization using 5000 permutations and threshold-free cluster enhancement (TFCE). The TFCE-corrected p-maps were thresholded at $p < 0.01$ (familywise error (FWE)-corrected). The cluster above this level is reported, and the regions of the cluster were identified from the "JHU ICBM-DTI-81 White-Matter Labels" atlas (Mori et al. 2005). To analyze the demographic characteristics, chi-squared test and independent t tests were conducted. For the interaction effects, time (pre/post; within-subject factor) × group (between-subject factor) mixed-design ANOVA was conducted. The statistical tool used in this study was SPSS version 25 (SPSS Inc.; Chicago, IL).

Results

The demographic characteristics of the participants included in the DTI analysis are summarized in Table 1. No significant differences in age, gender, handedness, years of education, marital status, religion, or participant or parental socioeconomic status were observed between the Templestay group (N = 33) and the active control group,

Table 1 Participants' demographic characteristics

	Templestay	Control	Statistical analysis	
	(N = 33)	(N = 17)	χ^2, F, or T	P
Age (years, ± SD)	30.758 ± 4.829	31.588 ± 5.185	0.562	0.577
Sex (male/female)	7/26	6/11	1.156	0.282
Handedness (right/left)	29/4	17/0	2.240	0.134
Education (years, ± SD)	16.545 ± 1.548	17.382 ± 1.596	1.792	0.079
Sociodemographic status[a]				
Participants	2.606 ± 0.556	2.588 ± 0.618	-0.103	0.918
Participants' parents	2.606 ± 0.827	2.765 ± 0.903	0.623	0.536
Marital status (single/married)	29/4	12/5	2.273	0.132
Religion			1.702	0.637
None	24	11		
Buddhism	5	2		
Catholic	2	3		
Presbyterian	2	1		

The values are presented as the means ± SD

[a] Socioeconomic status was assessed using the Hollingshead scale

the control group (N = 17). There was no significant group difference (T = 0.072, P = 0.943) in the time interval between the termination of Templestay and post-Templestay imaging data acquisition between the Templestay group (M = 1.576, SD = 0.614) and the control group (M = 1.588, SD = 0.507). There was a group difference (T = -3.120, P = 0.003) in the time interval between the starting time of Templestay and the image acquisition between the Templestay group (M = 2.636, SD = 2.261) and the Control group (M = 1.353, SD = 0.493). Figure 1 shows the results from the whole-brain analysis of FA changes across the groups (Templestay and control). In voxelwise brain WM tracts, significant differences at TFCE-corrected maps (at level of P < 0.01) were found between the Templestay group and the control group. The detailed results of post hoc analyses of ROIs (splenium of CC, left posterior corona radiata, and left sLF) are presented in the Supplementary Material (Tables S1 and S2).

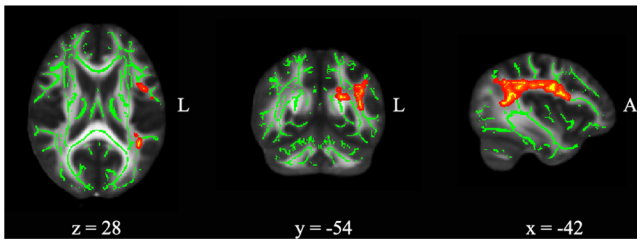

Fig. 1 Increased FA in the Templestay group (N = 33) compared with that in the Control group (N = 17). The results are FWE-corrected and projected on a red-yellow color scale, for which the range is shown for p < 0.01. Regions colored in red-yellow show the left superior longitudinal fasciculus, left posterior corona radiata, and splenium of the corpus callosum. The green lines indicate the mean FA skeletons obtained from the Templestay group and the Control group.

Discussion

This study was conducted to investigate the influence of Templestay, a behavioral-lifestyle modification program in which participants adhere to the practices of Buddhist monks, on WM neural plasticity. We demonstrated that individuals who completed 19 h of various forms of meditation training over 4 days had a significant group by session interaction in WM microstructural integrity. Compared to control participants who maintained their usual lifestyle in the same environment, the Templestay group showed a greater posttraining increase in FA values in the left sLF, which connects the prefrontal region to other regions in the brain. We propose that activity-dependent changes in myelination are induced by 4 days of meditation training along with the synergetic influence of behavioral-lifestyle modifications.

In a previous review study on meditation, a number of challenges in meditation research were indicated (Tang et al. 2015): (i) in cross-sectional studies, the effect of meditation could be overemphasized due to pre-existing differences between groups; (ii) the effects in those who have meditated before and those who have not meditated are mediated through different mechanisms; and (iii) the influence of meditation training can be confounded by other variables, such as lifestyle factors and diet. To investigate the pure effect of behavioral-lifestyle modifying training on WM neural plasticity, the present study was designed to control the challenges mentioned in the review study. First, our study is a within-subject longitudinal study in which WM structural differences between pre- and posttraining were measured. Second, we recruited participants from the community, and only participants without meditation experience within the past 3 months

were included. Once included in the study pool, the participants were randomly assigned to either the Templestay group or the control group. This approach made it possible to control the attribution of changes in the different brain regions between the experts and beginners. Third, while most of the previous studies only controlled for the length of the training time, we controlled for all other factors related to behavioral-lifestyle modifications. The control group stayed in the same temple and was fed the same meals during the experiment.

During brain maturation, the development of certain cognitive functions coincides with the maturation of appropriate brain regions (Nagy et al. 2004). The CC plays an important role in connecting the left and right hemispheres of the brain (Chung et al. 2004; Schulte et al. 2005), and our results showing increased FA values in the CC may indicate that Templestay enhances the communication between the left and right hemispheres of the brain. An interhemispheric imbalance has been reported in various mental disorders (Herrington et al. 2010; Oertel-Knochel et al. 2012), and interhemispheric interactions have been reported to be associated with cognitive processing and mood (Borod 1992; Sack et al. 2005). The most prominent changes that occurred among CC regions were in the splenium of the CC, which is regionally adjacent to and has a close functional relationship with the posterior cingulate cortex, the core region of the default-mode network (Taylor and Forsyth 2016). The default-mode network has been associated with mind-wandering (Mason et al. 2007), and our mindfulness meditation mainly involves simplifying individuals' thoughts. Therefore, we speculate that mindfulness meditation prominently enhanced WM integrity in regions closely associated with mind-wandering. Incorporating functional imaging approaches to assess the influence of mindfulness meditation on neural plasticity is an interesting future research topic.

In the present study, the left sLF showed a significant group by session interaction, demonstrating a greater increase in the FA value in the Templestay group than in the control group. The results from the present study are consistent with the results of our previous cross-sectional study reporting increased FA values in the left sLF of a meditation practitioner (Kang et al. 2013). The sLF is one of the core pathways linking the frontal-parietal network, which plays a critical role in working memory (Karlsgodt et al. 2008). Interestingly, our results suggest that the Templestay has an asymmetric effect on the improvement of microstructure integrity in the sLF, with no significant improvement in the right sLF. In a previous meditation study, a similar finding revealed that only the left side of the sLF showed an FA increment after meditation (Kang et al. 2013). The executive control network connected to the sLF has been found to have stronger functional connectivity on the left than on the right side (Kucyi et al. 2012). We speculate that the difference in the functional network strength between the left and right sides could have differentially affected the enhancement of microstructural integrity in the sLF during the Templestay. In addition, Templestay (19 h and 50 min) consists of 820 min of mindfulness meditation and 370 min of activities mainly involving linguistic activities such as participating in Buddhist services or conversations with monks. We speculate that 31% (370/1,190) of activities involving linguistic activities would have influenced more prominent changes in the left hemisphere of the brain, which is reported to be involved in linguistic activities (Vigneau et al. 2006; Yoon et al. 2015). Our findings of microstructural integrity enhancement in the left sLF suggest the potential positive influence of Templestay on linguistic and/or task-related activities in our daily life.

Notably, the neural plasticity observed in our participants occurred within 4 days of intensive training. To date, training-induced WM neural plasticity has been shown to require a longer duration of training than GM neural plasticity. Although increased GM plasticity was observed after 7 days of juggling training (Driemeyer et al. 2008), changes in WM plasticity were only reported after 6 weeks of similar juggling training (Scholz et al. 2009). Four weeks of training were required to observe changes in the FA in previous longitudinal meditation-related studies (Tang et al. 2010, 2012a, b). Although Tang et al. 2012a) claimed that the FA values tended to change more gradually than other scalar measures, our results suggest that the FA can also change within 4 days of training. Our findings support the existence of rapid structural remodeling, which was claimed by the authors of a study reporting changes in WM following only two hours of video game training (Hofstetter et al. 2013). We speculate that we were able to present these results since our study included other forms of behavioral-lifestyle modifications in addition to meditation. In fact, according to animal studies, neural plasticity is heavily influenced by environmental factors (Chourbaji et al. 2011; Juraska and Kopcik 1988). Taken together, these results suggest that the behavioral-lifestyle modifications associated with the Templestay program may have enhanced the WM plasticity induced by meditation, leading to a rapid increase in FA. The environment-meditation interaction would be an intriguing question for further research.

Significant increases in FA values were observed following Templestay. An increase in FA is known to be associated with changes in myelination and other factors, such as changes in axon diameter or axon permeability (Zatorre et al. 2012). Myelination has been regarded as relatively static, with changes in myelination occurring only under specific conditions, such as neurodevelopment or injury (Cho et al. 2016; Cho et al. 2019). However, recent studies have provided insight into the mechanisms that underlie activity-dependent changes in myelination. As noted by Wake et al. (2011), neuronal action potential-dependent changes in myelination occur via changes in oligodendrocyte signaling, which cause increases

in the local synthesis of the major proteins of the myelin sheath. Learning new skills has been demonstrated to increase the production of oligodendrocyte progenitor cells, and modulation of oligodendrocytes is critical for learning in adult mice (Sampaio-Baptista et al. 2013). Oligodendrocytes switch from an activity-independent mode of myelination to an activity-dependent mode in the presence of brain-derived neurotrophic factor (BDNF) (Lundgaard et al. 2013). Because BDNF levels change in response to meditation (Xiong and Doraiswamy 2009), researchers have attempted to treat mental illness by modifying BDNF levels (Russo-Neustadt 2003). These findings serve as a rational basis for the current movement to prevent mental disorders, such as recurrent depression, via meditation-related training (van der Velden and Roepstorff 2015). Templestay provides a favorable environment that is associated with increased BDNF levels (Chourbaji et al. 2011) and induces neural plasticity in the WM in a relatively short period, suggesting that it may be a possible option among the different types of meditation-related training for enhancing mental health. Notably, Hwang et al. (2018) showed that the influence of Templestay on resilience to stress was more prominent when assessed over a long-term period where the Templestay group showed more sustained improvements in the group × time effect from baseline to 3 months postintervention analysis. The results of the present study revealed a group × time effect on neural plasticity from baseline to postintervention, suggesting that neural plasticity is required to sustain the long-term maintenance of symptom improvements.

Limitations and Future Research

The present study has several limitations. First, only participants who were 40 years of age or less were included in the DTI analysis because we have hypothesized that the decrease in WM volume that occurs with age might obscure the effect of short-term meditation training (Ota et al. 2006; Stadlbauer et al. 2008). The effect of the Templestay program on older participants and the interaction between meditation training and the aging process should be further explored in future studies. Second, since the effect of Templestay is not well understood, the implications of the FA changes are unclear. Both our Templestay program and the meditations conducted in other studies are forms of meditation that stem from Buddhism; thus, we expected similar trends in the changes in the FA values. In fact, in the study by Fox et al. (2014), sLF in the left hemisphere is consistently reported to be associated with meditation, but robust findings in the sLF in the right hemisphere have not been reported. Within 4 days of training, the left sLF, but not the right sLF, were significantly influenced by Templestay. Thus, Templestay mediates WM plasticity via a similar mechanism as other forms of meditation training. In our study, we observed changes in the FA after 4 days of training, whereas 4 weeks were required to observe FA changes in previous longitudinal studies (Tang et al. 2012a, b). We concluded that along with meditation, other behavioral-lifestyle modifying factors may have synergetic effects on WM plasticity, which is consistent with our hypothesis.

Our study was conducted to investigate the mechanism by which modifications of behavioral-lifestyle factors, particularly modifications induced by following the Buddhist monks' 1700-year tradition of self-discipline, affects WM neural plasticity. Consistent with the results of previous meditation studies, a significant group by session interaction was observed in the FA of the left sLF, left posterior corona radiata, and splenium of the CC after 4 days, which is a shorter period than the duration of meditation-related training employed in previous longitudinal studies investigating WM neural plasticity. We propose that an interaction between meditation training and the modification of behavioral-lifestyle factors may have enhanced the effect of meditation training on human WM plasticity. Studies investigating whether Templestay affects brain function or GM plasticity would be interesting topics of future research. As was observed in our study, approaching human traditions scientifically will expand our understanding of humanity.

Data Availability Statement All data are available at the Open Science Framework (https://osf.io/2x5wg/).

Author Contributions YBY and DB: analyzed the data and wrote the manuscript. SK, WJH, and KKC: acquired the MRI data. TYL and SNK: collaborated in recruitment and study procedures. KYL and HYP: participated in theoretical development. JSK: collaborated in the writing and editing of the final manuscript. YBY and DB contributed equally to this work. All authors approved the final version of the manuscript for submission.

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Compliance with Ethical Standards

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The present study was approved by the Institutional Review Board of Seoul National University Hospital.

Informed consent Informed consent was obtained from all individual participants included in the study.

Conflict of interest The authors declare that they have no conflict of interest.

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