ORIGINAL ARTICLE

Exposure to MRI-related magnetic fields and vertigo in MRI workers

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ABSTRACT

Objectives Vertigo has been reported by people working around magnetic resonance imaging (MRI) scanners and was found to increase with increasing strength of scanner magnets. This suggests an association with exposure to static magnetic fields (SMF) and/or motion-induced time-varying magnetic fields (TVMF). This study assessed the association between various metrics of shift-long exposure to SMF and TVMF and self-reported vertigo among MRI workers.
Methods We analysed 358 shifts from 234 employees at 14 MRI facilities in the Netherlands. Participants used logbooks to report vertigo experienced during the work day at the MRI facility. In addition, personal exposure to SMF and TVMF was measured during the same shifts, using portable magnetic field dosimeters.
Results Vertigo was reported during 22 shifts by 20 participants and was significantly associated with peak and time-weighted average (TWA) metrics of SMF as well as TVMF exposure. Associations were most evident with full-shift TWA TVMF exposure. The probability of vertigo occurrence during a work shift exceeded 5% at peak exposure levels of 409 mT and 477 mT/s and at full-shift TWA levels of 3 mT and 0.6 mT/s.
Conclusions These results confirm the hypothesis that vertigo is associated with exposure to MRI-related SMF and TVMF. Strong correlations between various metrics of shift-long exposure make it difficult to disentangle the effects of SMF and TVMF exposure, or identify the most relevant exposure metric. On the other hand, this also implies that several metrics of shift-long exposure to SMF and TVMF should perform similarly in epidemiological studies on MRI-related vertigo.

What this paper adds

- Vertigo has been reported by people working around magnetic resonance imaging (MRI) scanners and has been suggested to be associated with exposure to static magnetic fields (SMF) and/or motion-induced time-varying magnetic fields (TVMF).
- This study assessed the association between reporting of vertigo among clinical and research MRI workers and measured personal exposure to SMF and TVMF during a work shift. Vertigo was significantly associated with peak and time-weighted average metrics of SMF as well as TVMF exposure.
- This study confirms previous hypotheses that occurrence of vertigo is positively associated with levels of personal exposure to static and TVMF from magnetic resonance imaging scanners.
- In addition, the models enabled estimation of occupational exposure levels at which vertigo occurrence exceeds a prespecified level, for example 5%, which will be relevant information for policymakers and for deriving exposure limit values.

INTRODUCTION

While working in a spatially non-uniform static magnetic stray field around an MRI scanner, workers are exposed to a static magnetic field (SMF, expressed by the magnetic flux density B, in tesla (T)) as well as a motion-induced time-varying magnetic field (TVMF, expressed by the time-derivative of the magnetic flux density dB/dt, in T/s).[1 2] In an earlier publication, we investigated subjectively reported symptoms experienced by MRI staff and CT radiographers and found a positive association between scanner strength (ie, the magnetic flux density in the isocenter of the magnet, measured in T) of closed-bore MRI scanners and the incidence of one or more symptoms out of a list of 13 'SMF target' symptoms.[3] Other studies also observed a positive association between scanner strength and symptom prevalence among people working with MRI in healthcare and research MRI facilities, as well as those working in MRI system development.[4 5] In our previous study, the observed association was most evident for the specific symptoms vertigo and metallic taste, of which vertigo was the most prevalent symptom. Scanner strength was assumed to be a proxy for exposure to the static magnetic stray field of the MRI scanner, but no information was available to distinguish between effects of the static field and the motion induced low-frequency TVMF. Based on the observed associations we could therefore only conclude that symptom incidence could be associated with personal exposure to either SMF or TVMF or both.[3]

The physiological mechanism and relevant exposure metric underlying MRI-related vertigo are not yet fully understood. MRI-related vertigo is thought to be caused by an effect of the magnetic field on the vestibular system.[6–8] Several studies have shown that vertigo was more often reported during movement through a SMF, as opposed to lying inside an MRI scanner or standing still next to it.[6 9–13] These findings suggest an association with the TVMF. In

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contrast, experimental studies with healthy volunteers who were placed with their heads inside the isocenter of a 3 T and a 7 T scanner, found that vertigo was induced in a motionless body by exposure to a homogeneous SMF. The researchers hypothesise that vertigo can be induced by a Lorentz force on resting state ionic currents in the vestibular endolymph fluid and hair cells, as a result of exposure to a strong SMF, which suggests that (additional) TVMF exposure is not required to induce vertigo.[7 8] Considering these conflicting findings, it is well possible that MRI-related vertigo can be induced by multiple pathways, requiring different types of exposure.

De Vocht *et al*[4] showed that speed of movement around an MRI scanner was associated with an increased prevalence of reported symptoms among MRI system testers. Although this association did not reach statistical significance for vertigo, this sensation was reported twice as often by fast movers compared to slow movers.[4] The effect of movement speed could be the result of either a higher level of TVMF (dB/dt) exposure in fast movers, or avoidance of exposure by participants with a personal predisposition towards developing symptoms, although other explanations cannot be ruled out.

For 57% of the work shifts for which symptom information had been assessed in our study on MRI-related symptoms,[3] additional full-shift measurements of personal exposure to B and dB/dt were available. Measured exposure levels have been reported elsewhere.[14] The current paper assesses the exposure–response association between six different metrics of personal exposure to SMF and TVMF during shift-long work around an MRI scanner and self-reported vertigo. We tested the hypothesis that vertigo is significantly associated with (measured levels of) personal exposure to MRI-related stray fields. In addition, we aimed to (1) identify the (shape of the) exposure–response curve, (2) identify the exposure metric most relevant for these symptoms, (3) quantify exposure levels at which vertigo becomes manifest and (4) assess whether individual speed of movement through stray fields of an MRI scanner modifies the exposure response curve.

METHODS

Fifteen clinical and research MRI facilities in the Netherlands where patients, volunteers or live animals were scanned were visited for either 1 or 2 weeks between March 2011 and February 2012. All employees who worked at the MRI facility during the days of the visit were invited to volunteer as participants in an SMF exposure measurement survey for at least one work shift when they were working with MRI. Employees included MRI radiographers, but also other clinical staff, researchers and technical support staff. After giving personal consent for their participation, participants completed a general questionnaire, which included questions about gender, age, job title and years of MRI experience. The study was approved by the Medical Research Ethics Committee of the Utrecht University Medical Center.

Participants agreed to wear a portable magnetic field dosimeter (Magnetic Field Dosimeter, University of Queensland)[15] during at least one work shift at the MRI facility. The dosimeters registered exposure to SMFs (B, in mT) and motion-induced TVMFs (dB/dt, in mT/s). Summary exposure metrics of B and dB/dt that were estimated from each work shift included instantaneous peak exposure (peak), time-weighted average exposure based on the total duration of the shift ('full-shift TWA') and time-weighted average exposure for the time exposed to the SMF ('SMF-exposed TWA'). These metrics correlated strongly, with Pearson correlations of approximately 0.9 between B and dB/dt metrics, and somewhat less strong (approximately 0.7) between various metrics (peak, TWA) of the same type of exposure (B or dB/dt).[14]

In addition, participants were requested to fill in a logbook during each measured shift. The questions in the logbook referred to the full work shift of the participant. The logbook included exposure-related questions, such as questions about their presence in the MRI scanner room and the MRI scanners they had worked with. Participants also reported any symptoms they had experienced during their work shift. The logbook included a list of 21 symptoms that participants could check if they had experienced these during their work shift, including dizziness/vertigo. Information on potential confounding or effect modifying covariates was also collected by the logbook. These included the use of cleaning agents and solvents during the working day, alcohol consumption during the previous 24 h and the subjects' perception of the shift's workload.

Symptom information was collected in a different way at one of the 15 study locations, a veterinary clinic which was used as a pilot location for the study. Therefore, data from this location were excluded. Further details about the symptom assessment procedures and data handling are described in Schaap *et al*.[3] Further details about the exposure measurement strategy, the measurement devices and the handling and clean-up of the exposure measurement files are described in Schaap *et al*.[14] Linking the exposure measurements to the shifts with symptom data from the logbooks resulted in 358 observations with complete shift-long symptom and exposure data from 234 participants.

Statistical analyses

Associations between reporting of vertigo and six different metrics of SMF or TVMF exposure were analysed at the work-shift level, which means that shift-based exposures were linked to vertigo reported over the same work shift.

The data included repeated measurements, with 100 of the 234 participants contributing data from more than one shift. Initial analyses showed clustering of symptom reporting within subjects (ie, high between-subjects heterogeneity in reporting of symptoms), assuming a non-normal distribution of the data. Therefore, a finite mixture (FM) model was used to analyse associations between exposure levels and reporting of vertigo, with participants (study participants) incorporated as random effects in the model. As stated in our earlier publication,[3] "FM models are similar to generalised linear mixed models (GLMM), but with random effects assumed to be from a discrete distribution (instead of a normal distribution as in GLMMs). Conceptually, these models may be derived from the assumption that each subject belongs to one of several (latent) classes, and that the multiple responses for a subject are generated according to a class-specific model."[16–18] The models were fitted using the FlexMix package (V.2.3–8) in R (V.2.15.2, R Foundation for Statistical Computing, Vienna, Austria) and allowed for two classes of participants as this was found to fit the data best in our earlier analysis of the association between symptoms and scanner category.[3] These two latent classes were labelled as the 'symptom-reporting' class of participants and the 'non-symptom-reporting' class of participants, because the probability of reporting symptoms (adjusted for effect of exposure) was much higher in the first than in the latter group. Gender and age were used to predict class membership, while workload during the shift, use of solvents during the shift and alcohol consumption in the 24 h prior to the shift were included as potential confounders of the exposure–outcome relation.

All exposure metrics were log-normally distributed and were log-transformed before inclusion in the finite mixture models. The binomial logistic models assume a linear relationship between log-transformed exposure level and the logit function (ie, log-odds) of reporting vertigo, and are further referred to in this paper as 'linear models'. To assess the shape of the exposure–response association and to check for potential non-linear effects of magnetic field exposure, we fitted additional models with a natural regression spline as implemented in the R packages *splines*. Because of the low number of participants reporting symptoms, we used splines with a single (interior) knot at the median exposure for the 'symptom-reporting' class.

In addition, we classified participants as either fast or slow movers when working around the MRI scanner, by estimating the ratio between SMF-exposed TWA dB/dt and SMF-exposed TWA B. Analyses of variance indicated more variability in this ratio between individuals (69%) than between shifts (31%), and could therefore be regarded a 'personal' characteristic. Participants were either attributed to the 'slow' group or to the 'fast' group when their average ratio was below or above the median value of all personal average ratio's, respectively.

Models were compared using Akaike's Information Criterion (AIC).[19] Differences in AIC of at least 2 points were interpreted as indicating a significant difference in model fit.[20]

RESULTS

We analysed 358 shifts from 234 participants. Vertigo was reported by 20 different participants, during 67% of the work shifts of these participants (22 out of 33 shifts). The results of the fully adjusted finite mixture models for vertigo and six different (log-transformed) exposure metrics are presented in table 1. The results of the unadjusted models can be found in the online supplementary table S1. Vertigo reporting was significantly associated with all six exposure metrics ($p<0.01$). Comparison of model fit by means of the AIC suggested that reporting of vertigo was better predicted by time-weighted average exposure metrics of TVMF (dB/dt) than by time-weighted average exposure metrics of SMF (B), while model fit for peak exposure metrics of both SMF and TVMF was not significantly different. The exposure metric that showed the best overall model fit was full-shift TWA TVMF (dB/dt).

The estimated exposure–response curves are presented per metric in figure 1, for both classes in the finite mixture model. The graphs show a steep increase in probability of vertigo for participants in the 'symptom-reporting' class over a relatively short range of exposure levels for all six exposure metrics. Spline models fitted slightly better than linear models for peak B and SMF-exposed TWA dB/dt (table 1). However, as apparent from the graphs (figure 1), these spline models resulted in exposure–response curves that were very similar to those obtained under the assumption of a linear relation.

For each model we calculated the posterior probability of a worker to be member of the latent 'symptom-reporting' class. This was >99% for workers who had reported vertigo during at least one of their shifts, but only 16–22% (depending on the model/exposure metric) for workers who had not reported any vertigo.

In order to provide information on exposure levels at which sensations of vertigo become manifest, we estimated exposure levels at which the probability of reporting vertigo reached 5% in the 'symptom-reporting' class. These exposure levels are reported in table 2, and were estimated at 409 mT and 477 mT/s for peak exposure, 48 mT and 6 mT/s for SMF-exposed TWA exposure, and 3 mT and 0.6 mT/s for full-shift TWA exposure.

Separate exposure–response curves for 'fast' and 'slow' movers are presented for vertigo and full-shift TWA dB/dt exposure in figure 2. This graph suggests that symptom onset occurred at lower magnetic field exposure for 'fast' movers (5% probability level for reporting vertigo approximately 0.5 mT/s for 'fast' movers vs 0.9 mT/s for 'slow' movers), but the increase in probability of reporting vertigo with increasing exposure was much stronger in 'slow' movers than in 'fast' movers (slope for the log-odds=7.12 vs 2.98 per unit of log-transformed exposure). The interaction between individual moving speed and magnetic field exposure was (borderline) significant for two metrics only, and the effect on intercept and slope not entirely consistent across exposure metrics (data not shown).

DISCUSSION

The association between magnetic field exposure and self-reported symptoms of vertigo was investigated using six different shift-based metrics for exposure to SMF and TVMF exposure. Reporting of vertigo was positively and significantly associated with all six exposure metrics. Models based on full-shift TWA TVMF exposure showed the best model fit compared to models based on other metrics. Full-shift TWA exposure is determined by a combination of exposure intensity, frequency and duration of exposure events and the amount of unexposed time. This finding might therefore imply that, in addition to the exposure intensity, the total time a worker is exposed to motion-induced TVMF during a full workday also plays a role in the underlying physiological mechanism of MRI-induced vertigo. Studies on rats exposed to a 14.1 T superconducting magnet revealed that magnetic-field-induced circling behaviour was only displayed after at least 5 min of exposure and not at shorter durations.[21 22] This suggests a potential effect of duration of magnetic field exposure on vestibular effects among rats. Associations between MRI-related vertigo and the start,

Table 1 Log-odds per unit (mT or mT/s) of log-transformed exposure level in the 'symptom-reporting' class for six different models adjusted for gender, age, workload, use of solvents and alcohol ingestion

Exposure type	Exposure metric	β	p Value	SE	Linear model fit (AIC)	Cubic spline model fit (AIC)
SMF (B; mT)	ln(peak B)	4.11	0.001	1.27	135.71	133.74
	ln(SMF-exposed TWA B)	2.79	0.002	0.96	142.13	144.13
	ln(full-shift TWA B)	3.33	0.001	1.07	131.51	131.91
TVMF (dB/dt; mT/s)	ln(peak dB/dt)	4.16	0.002	1.46	135.81	135.84
	ln(SMF-exposed TWA dB/dt)	2.58	0.004	0.96	140.09	137.90
	ln(full-shift TWA dB/dt)	4.59	0.003	1.67	125.80	124.17

AIC, Akaike Information Criterion; ln, natural logarithm; β, log-odds; p, one-sided p value; SMF, static magnetic field; TVMF, time-varying magnetic field; TWA, time-weighted average.

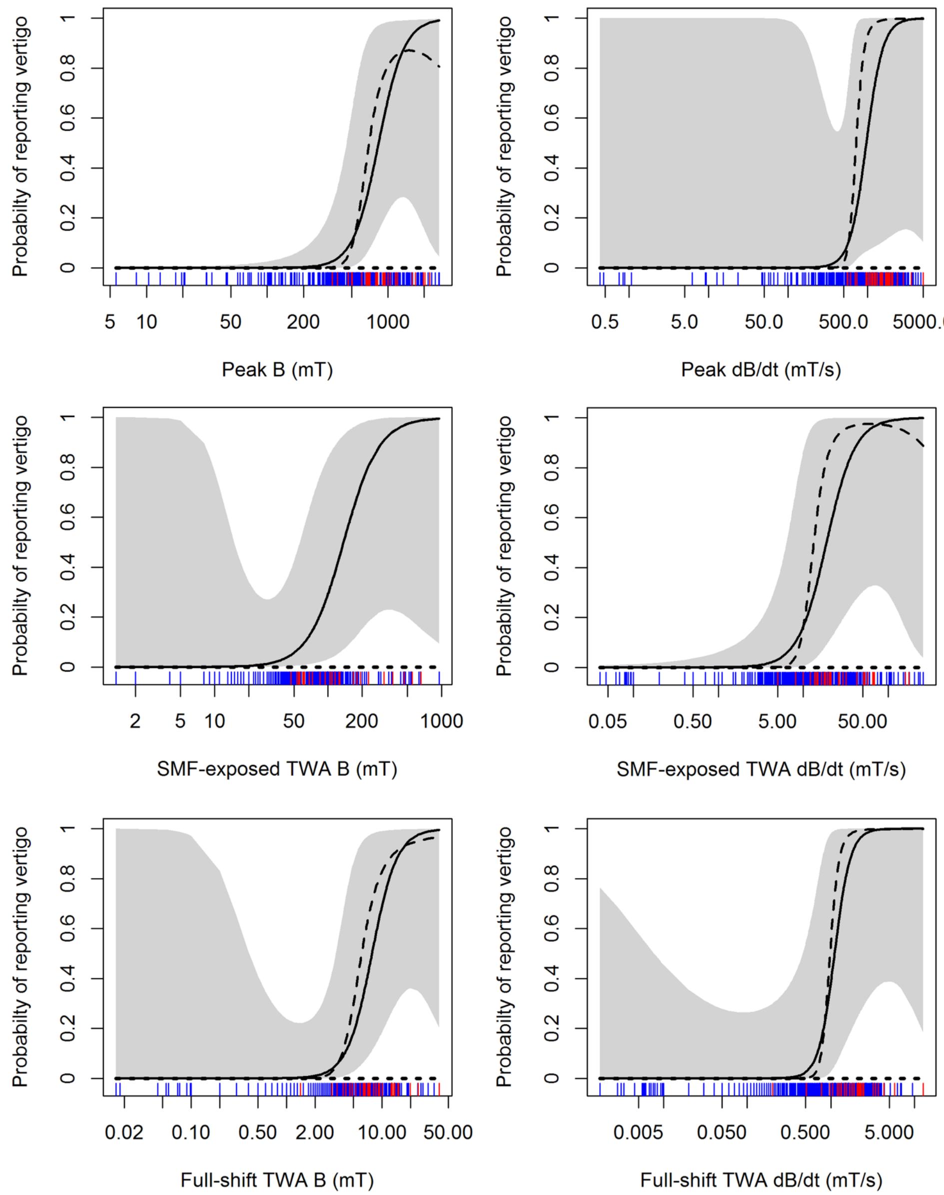

Figure 1 Exposure–response curves for vertigo per exposure metric. Dotted line: spline function for the 'non-symptom-reporting' class; dashed line: spline function for the 'symptom-reporting' class; solid line: linear function for the 'symptom-reporting' class; grey area: 95% CIs of the spline function for the 'symptom-reporting' class; blue stripes: observations from the 'non-symptom-reporting' class; red stripes: observations from the 'symptom-reporting' class. The graph of the spline function for SMF-exposed TWA B is not visible because it coincides with the linear function of the 'symptom-reporting' class. SMF, static magnetic field; TWA, time-weighted average.

end and duration of exposure events have not been studied systematically in human subjects. Unfortunately, the design of our study did not enable us to assess this into more detail.

The included shift-based exposure metrics were all strongly correlated.[14] This correlation is also reflected by the finding that vertigo was positively associated with all six exposure metrics. Therefore, even though the best fitting model was obtained using full-shift TWA TVMF exposure, it is not possible to conclude with certainty that it is also the best exposure metric to explain underlying biological mechanisms of MRI-related vertigo.[23]

Differences in model fit between SMF and TVMF exposure metrics were most prominent for the time-weighted average (TWA) metrics and nearly absent for peak exposures. TWA metrics of exposure to TVMF better predicted vertigo than TWA metrics of exposure to SMF. Although the results are based on strongly correlated exposure metrics and a relatively low proportion of participants (approximately 9%) reporting vertigo, these findings might point towards a (stronger) role of the TVMF in the emergence of vertigo, as was also suggested by previous associations of vertigo with body movement through a static magnetic stray field.[6 9–13]

The quite similar exposure–response curves that were obtained using linear and regression spline models imply that the association between log-transformed exposure levels and log-odds of vertigo can be adequately described using a linear model. However, the number of participants that reported vertigo (n=20) allowed only relatively low-dimensional spline models and not more complex curve shapes.

Table 2 Back-transformed exposure levels where probability of vertigo in 'symptom-reporting' class is estimated to be 5%

Exposure type	Exposure metric	5% level
SMF (B; mT)	peak B	409 mT
	SMF-exposed TWA B	48 mT
	full-shift TWA B	3 mT
TVMF (dB/dt; mT/s)	peak dB/dt	477 mT/s
	SMF-exposed TWA dB/dt	6 mT/s
	full-shift TWA dB/dt	0.6 mT/s

SMF, static magnetic field; TVMF, time-varying magnetic field; TWA, time-weighted average.

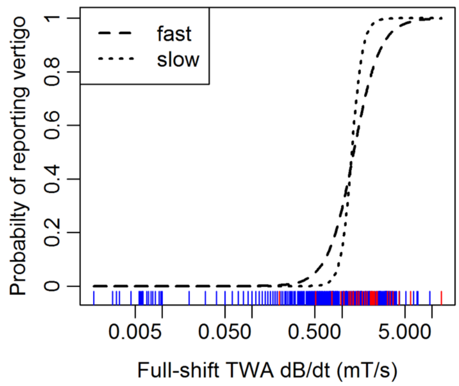

Figure 2 Exposure–response curves of the linear model for full-shift TWA dB/dt based on the 'symptom-reporting' class, stratified by speed group. TWA, time-weighted average.

The exposure–response curve was steepest for the metric with the best fitting model (full-shift TWA TVMF exposure). Based on the exposure–response curve for this metric it is estimated that above a full-shift TWA of 0.6 mT/s the sensitive individuals of the exposed population (at least 9% of the current study population) will report vertigo with a probability higher than 5%. This and the other 5% threshold-levels were derived under the assumption of a linear model, and should be interpreted as best point estimates only.

The ratio between TWA dB/dt and B in SMF exposed situations was assumed to be a proxy for the movement speed of the study participants. Based on this ratio study participants were determined to be either 'slow' or 'fast' movers. As in De Vocht *et al*[4] our models suggest that slow and fast movers may react differently when exposed to the same levels of exposure. The 5% vertigo level of full-shift TWA exposure to TVMF appeared to be lower for fast movers, but the probability of vertigo increased faster for slow movers with increasing exposure. However, interpretation is not straightforward and findings were not completely consistent across exposure metrics. On one hand, speed differences could be the result of personal adjustments in work behaviour near the MRI scanner in reaction to symptoms previously experienced during the MRI work, in order to reduce the chance of recurring symptoms. On the other hand, speed differences could also be related to specific work practices near the scanner.

Our analyses were based on a two-class finite mixture model, in which study participants are implicitly assigned to either a 'symptom-reporting' or a 'non-symptom-reporting' latent class. The increased probability of reporting vertigo with increasing levels of SMF and motion-induced TVMF exposure was only evident in the 'symptom-reporting' class, and was therefore to a large extent determined by workers who reported vertigo during at least one of their shifts. Owing to the cross-sectional nature of our survey and because not every individual was exposed over the full range of exposures (ie, some subjects only worked near low-field scanners, while others worked only near high-field scanners) it is possible that some of the low exposed individuals not reporting symptoms in this study would actually experience vertigo when exposed to higher exposure levels.

CONCLUSIONS

Among MRI workers in our study a strong association existed between reporting of vertigo and quantitative estimates of exposure to SMF and TVMF due to working in the static magnetic stray field of MRI scanners. The resulting exposure–response associations enabled estimation of shift-long exposure levels associated with a prespecified occurrence of vertigo, for example, 5%. Although associations of vertigo were best described by full-shift time-weighted average exposure to motion-induced TVMFs, vertigo was significantly associated with all peak and time-weighted average metrics of SMF and TVMF exposure, showing a strong increase in symptom prevalence over a relatively short exposure range. Our results suggest that it is very hard to disentangle the effects of the SMF and the TVMF on vertigo in a non-experimental setting, or to identify one single relevant exposure metric, when these exposure metrics are based on full-shift measurements. On the other hand, the strong correlation between different shift-based exposure metrics suggests that epidemiological studies and control measures for MRI-related vertigo could be based on any of these metrics.

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Contributors KS designed the study protocol and data collection tools, organised, monitored and conducted the data collection process, cleaned and analysed the data, contributed to the interpretation of the data, drafted and revised the paper, and is guarantor. LP conducted the statistical analyses, contributed to the interpretation of the data, drafted and revised the paper, and is guarantor. HK initiated the project, designed the study outline, co-designed the study protocol and data collection tools, contributed to the interpretation of the data, drafted and revised the paper, and is guarantor.

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Patient consent Obtained.

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