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Original Article

Temporal trends in neurosurgical volume and length of stay in a public healthcare system: A decade in review with a focus on the COVID-19 pandemic

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ABSTRACT

Background: Over the past decade, neurosurgical interventions have experienced changes in operative frequency and postoperative length of stay (LOS), with the recent COVID-19 pandemic significantly impacting these metrics. Evaluating these trends in a tertiary National Health Service center provides insights into the impact of surgical practices and health policy on LOS and is essential for optimizing healthcare management decisions.

Methods: This was a single tertiary center retrospective case series analysis of neurosurgical procedures from 2012 to 2022. Factors including procedure type, admission urgency, and LOS were extracted from a prospectively maintained database. Six subspecialties were analyzed: *Spine, Neuro-oncology, Skull base* (*SB*), *Functional, Cerebrospinal fluid* (*CSF*), and *Peripheral nerve* (*PN*). Mann-Kendall temporal trend test and exploratory data analysis were performed.

Results: 19,237 elective and day case operations were analyzed. Of the 6 sub-specialties, *spine, neuro-oncology, SB,* and *CSF* procedures all showed a significant trend toward decreasing frequency. A shift toward day case over elective procedures was evident, especially in *spine* ($P < 0.001$), *SB* (tau = 0.733, $P = 0.0042$), *functional* (tau = 0.156, $P = 0.0016$), and *PN* surgeries ($P < 0.005$). Over the last decade, decreasing LOS was observed for *neuro-oncology* (tau = −0.648, $P = 0.0077$), *SB* (tau = −0.382, $P = 0.012$), and *functional* operations, a trend which remained consistent during the COVID-19 pandemic ($P = 0.01$). *Spine* remained constant across the decade while *PN* demonstrated a trend toward increasing LOS.

Conclusion: Most subspecialties demonstrate a decreasing LOS coupled with a shift toward day case procedures, potentially attributable to improvements in surgical techniques, less invasive approaches, and increased pressure on beds. Setting up extra dedicated day case theaters could help deal with the backlog of procedures, particularly with regard to the impact of COVID-19.

Keywords: COVID-19, Length of stay, National Health Service, Neurosurgical operations, Temporal trend analysis

INTRODUCTION

There are huge pressures on healthcare systems to deliver high-quality and efficient patient care. The volume of surgical procedures and the length of time patients spend in hospital are of vital importance for hospital administrators and clinicians. It allows for the identification of areas of improvement and allows for more efficient resource allocation.[3,22]

Due to changing demographics and advances in treatment, there have been noticeable changes in the field of neurosurgery.[21] Improvements in surgical techniques, better management of comorbidities, rehabilitation, and the widespread implementation of advanced technologies have resulted in a shift in the delivery of neurosurgical care, seeing an increase in the number of day case operations and a decrease in the length of time patients spend in hospital.[5,14,17] While these factors have seen an improvement in length of stay (LOS), the increasing elderly population and the shortage of social care provision have negatively impacted LOS.[7] LOS is often used as a reflection of surgical performance and hospital management benchmarking, and while this may not be accurate, analyzing the changes in LOS could allow hospitals to identify where costs could be reduced, allowing for improved quality of life for patients and increasing hospital patient flow.[19,31] Prolonged LOS is also associated with increased mortality and disease burden, as well increasing the risk of re-admission.[2,6] As such, a common goal is to decrease the LOS following surgery without compromising patient care.

Therefore, we aimed to analyze the frequency of the most common neurosurgical procedures and the associated LOS following these surgeries over a 10-year period at a tertiary neurosurgical center in the UK. Our study investigates current practice with respect to historic volumes and LOS and also examines whether the surgical volumes have reached pre-COVID levels.

MATERIALS AND METHODS

Data source and grouping

This study was a single-center retrospective analysis of all neurosurgical operations performed at a tertiary neurosurgical center, from December 2012 to November 2022. Data on all neurosurgical cases performed during this time were exported from the trust's database and anonymized for analysis, and therefore, the institutional review board waived the necessity for individual patient consent. A total of 33,483 procedures were identified. Data on six routinely collected variables for each operation recorded: date and time of admission, age of the patient (continuous), LOS from the start of admission to discharge in hours (continuous), type of operation (day-case, elective or non-elective), OPCS4 code (operation identifier number), and description of the procedure (the operation that was performed). A total of 631 distinct operation types were observed across all subspecialties, which were condensed into the most common operations for each subspecialty. Further, subgroup analysis was then conducted for the most common umbrella operations in each subspecialty. Elective operations were classified as operations conducted during an inpatient admission for a patient, while non-elective operations were classified as any trauma or emergency operations. Day cases were elective procedures without an overnight stay.

Exclusion criteria

For subspecialty analysis, all epidural injection procedures (which are routinely done as day cases in our institution) were removed as the short LOS would skew the analysis. Second, with the aim of removing the outliers caused by those with a long LOS, as defined by Zhao *et al.*, 2018, we removed those with an LOS >30 days.[31] Similarly, all non-elective procedures were excluded due to most having a long and variable LOS, rendering temporal analysis less accurate for the sample size present. Finally, any operation type with <20 surgical procedures across the 10-year study period or those noted to have only been performed in only 4/10 study years were removed due to their insufficient sample size.

Statistical analysis

Statistical analysis was performed in the R coding language (R Foundation for Statistical Computing, Vienna, Austria). Mann-Kendall (MK) analysis was used to determine if there was a statistically significant increase or decrease in either the frequency or LOS over time. Despite our observation period of 10 years, frequency analysis of each operation subtype from the initial year 2012 was removed (on a subspecialty basis) due to sparse data. For LOS analysis, median LOS was analyzed as it is less likely to be affected by outliers than the mean. Analysis of the relationship between LOS and age was assessed using Pearson's correlation to estimate the degree of linear association between the age of patients and LOS, alongside a one-way analysis of variance and *post hoc* Tukey's test when the age was split into distinct groups (<30, 31–50, 51–70, 71+). The mean rate of change of procedure frequency was compared to the change seen during COVID-19 between 2019 and 2020, using an Independent samples *t*-test. For all statistical analyses, $P < 0.05$ was considered statistically significant.

RESULTS

Total neurosurgery – including epidural injections

There were a total of 33,483 neurosurgical operations performed between 2012 and 2022. Of this, 16,355 were day case surgeries, 15,902 were elective, and 1226 were emergency/non-elective. The mean patient age was 54.60 (±15.59), with a median of 55 (43–67) and a range of 18–100. Temporal distribution analysis demonstrated no overall statistically significant change in the frequency of operations performed annually (MK: tau = −0.06, $P = 0.85$) [Figure 1a]. However, we observed a statistically significant difference in the rate of change of year-to-year operation frequency pre-pandemic versus during the COVID-19 pandemic (+9.45% vs. −52.7%, $P < 0.04$). Temporal stratification by operation type further revealed an overall significant rise in the number of day cases compared to elective cases, with the average percentage of day case procedures rising from 31.8% in 2013–2015 to 55.70% in 2016–2022 ($P < 0.05$). Overall, analysis of LOS demonstrated a decreasing yet non-significant trend in the median LOS over the study period (MK: tau = −0.37, $P = 0.149$) [Figure 1b]. In addition, as a result of the COVID-19 pandemic, the LOS increased by 268.8% between 2019 and 2020 before returning to the pre-pandemic levels of an average annual decrease of −75.8% ($P < 0.03$).

Total neurosurgery – excluding epidural injections

Within the total procedures performed, the largest subset of procedures was day-case spinal injections (13,409 cases, accounting for nearly 40% of all cases), which included epidural injections, nerve root blocks, and facet joint injections. Exclusion of these cases revealed significant changes in the distribution of operation types with 15,802 elective cases, 3435-day case procedures, and 837 emergency/non-elective cases. Temporal distribution analysis demonstrated an overall statistically significant decrease in the frequency of operations performed annually (MK: tau = −0.51, $P = 0.04$) [Figure 1c]. This phenomenon was further exacerbated by the onset of the COVID-19 pandemic, which resulted in a 42.3% drop in the number of procedures compared to the preceding years, that had an aggregate annual change of 3.8% ($P < 0.05$). Overall, analysis of LOS demonstrated an increasing yet non-significant trend in the median LOS across the study period (MK: tau = 0.28, $P = 0.27$) [Figure 1d]. However, comparative analysis of the aggregate change in median LOS pre-pandemic versus during the pandemic revealed a significant increase in LOS as a result of COVID-19, with a 62.9% increase in LOS compared to the pre-pandemic drop of −2.8% annually ($P < 0.03$). There were comparatively fewer injections performed after the onset of COVID.

After removing all non-elective cases, a total of 19,237 operations were identified. Trends in operative frequency and postoperative median LOS for each neurosurgical subspecialty and the associated common procedure types were subsequently analyzed.

Spinal surgery

Cohort demographics

A total of 11,046 spinal neurosurgery operations were performed between 2012 and 2022, with 8986 elective and 2060-day case procedures. The mean patient age was 52 (±15.08) years, with a median of 52 (41–64) and a range of 18–99. Of the 21 distinct spinal operations, only the four most common umbrella spinal operations underwent further subgroup analysis: "*Excision of lumbar intervertebral disc,*" "*decompression of lumbar spine,*" "*anterior cervical discectomy and fusion,*" and "*lumbar fusion.*"

Frequency analysis

The most frequent operation type undertaken was "*excision of lumbar intervertebral disc*" at 3750, followed by "*decompression of lumbar spine*" at 3668. Figure 2a summarizes the frequency of spinal operations over time. There was a general trend of decreasing frequency of spinal surgeries between 2013 and 2022 (MK: tau = −0.911, $P = 0.00035$). The ratio of elective to day cases also underwent a statistically significant shift ($P < 0.001$) between the years 2015 and 2016, with the average percentage of day case procedures rising from 1.37% in 2013–2015 to 31.15% in 2016–2022 as shown in Figure 2a. Analysis of the effect of the COVID-19 pandemic also demonstrated a statistically significant decrease ($P < 0.001$) in the operation frequency, with the mean frequency change rising from −81.7 pre-pandemic to −618 during the onset of the pandemic [Supplementary Figure 1].

LOS analysis

Overall, the analysis showed a fairly constant LOS over time between 2012 and 2022, with no significant change in the median LOS (MK: tau = −0.103, $P = 0.74$), as shown in Figure 2b. Analysis of the LOS relative to age revealed a statistically significant increase in the median LOS with advancing age ($P \leq 0.001$). ANOVA with *post hoc* Tukey analysis based on age groups (<30, 31–50, 51–70, 71+) also showed a statistically significant change in the median LOS between all age groups except the <30 and 31–50 groups [Figure 2c]. Overall, analysis of the LOS pre-COVID-19 and during the years most affected by COVID-19 showed no significant difference ($P = 0.1134$) in the median LOS as a result of the pandemic [Supplementary Figure 1].

Analysis of the most common umbrella operation types revealed that there was a statistically significant reduction in the frequency of "*excision of lumbar intervertebral disc,*" "*decompression of*

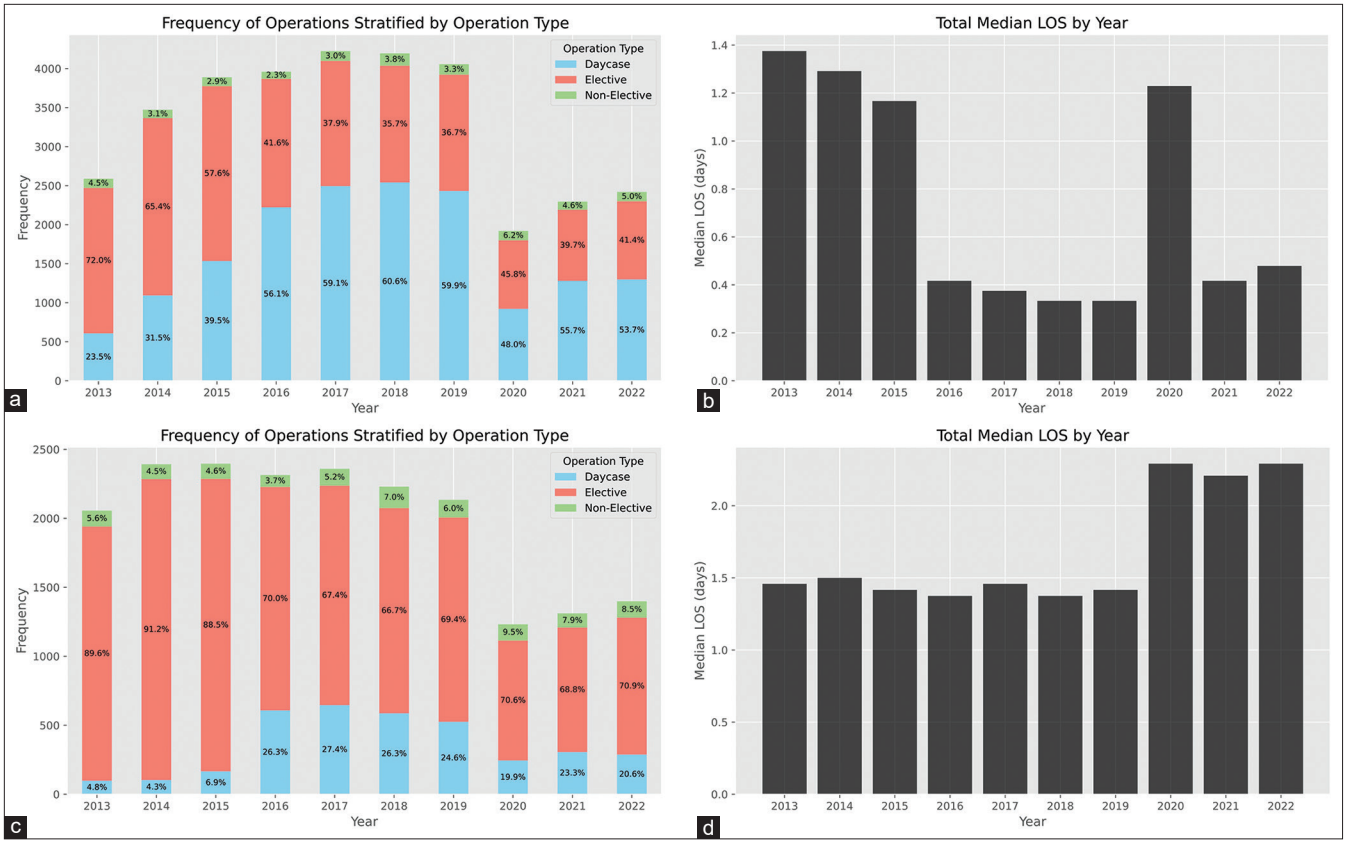

Figure 1: Bar plots representing the temporal trends in operative frequency and postoperative length of stay (LOS) from 2013 to 2022: (a) frequency of all neurosurgical operations, (b) median LOS for all neurosurgical operations, (c) frequency of all neurosurgical operations excluding spinal injections, and (d) median LOS for all neurosurgical operations excluding spinal injections.

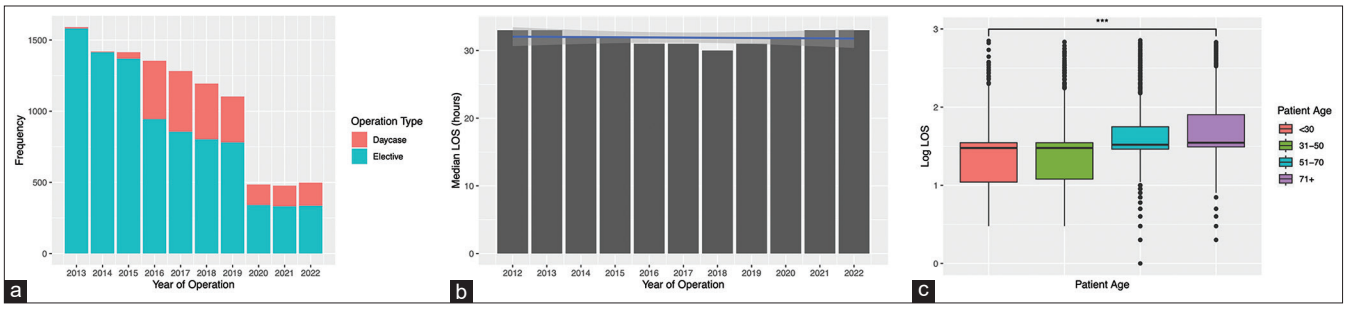

Figure 2: Plots representing the temporal trends in operative frequency and post-operative length of stay (LOS) from 2012-2022 for all spinal operations: a) Frequency of all spinal operations split by elective and day case, b) Median LOS for all spinal operations, c) Comparing LOS and age, *** = P <0.001.

lumbar spine," and "*anterior cervical discectomy and fusion.*" ($P < 0.05$), a phenomenon further exacerbated by COVID-19. "*Lumbar fusion,*" however, showed no reliable trend in frequency due to drastic alterations in frequency in some years. In terms of LOS, both "*lumbar decompression*" and "*anterior cervical discectomy and fusion*" maintained a relatively static median LOS (though the latter was noted to have a slightly increasing trend), while "*excision of lumbar intervertebral disc*" and "*lumbar fusion*" demonstrated a decreasing median LOS, with the former showing a drastic drop between the years 2015 and 2016 which was accompanied by a shift to performing >50% of these as day case surgeries [Supplementary Figure 2].

Neuro-oncology

Cohort demographics

A total of 4088 neuro-oncology operations were performed between 2012 and 2022, with 3911 elective and 177-day case

procedures. The mean patient age was 53 (±15.63), with a median of 55 (42–65) and a range of 18–89 years. Of the 19 distinct neuro-oncology operations, only the three most common umbrella neuro-oncology operations underwent further subgroup analysis: "*Excision of lesion of tissue of brain,*" "*excision of lesion of meninges of brain,*" and "*biopsy of lesion of nervous system.*"

Frequency analysis

The most frequent operation type undertaken was "*excision of lesion of tissue of brain*" in 1927, followed by "*excision of lesion of meninges of brain*" in 464. Figure 3a demonstrates a general trend of decreasing frequency of neuro-oncology surgeries between 2013 and 2022 (MK: tau = −0.822, P = 0.0013). The ratio of elective day cases, however, remained fairly constant throughout the years with no significant shift of procedure type from elective to day cases [Figure 3a]. Analysis of the effect of the COVID-19 pandemic also demonstrated a statistically significant decrease (P = 0.025) in the operation frequency, with the mean drop in procedures being −1 pre-pandemic and rising to −64 between 2019 and 2020 [Supplementary Figure 1].

LOS analysis

Overall, the analysis revealed a decrease in the median LOS over time between 2012 and 2022 (MK: tau = −0.648, P = 0.0077), as shown in Figure 3b. Further, analysis of the LOS relative to age via ANOVA and *post hoc* Tukey showed a statistically significant difference in the postoperative LOS between age groups <30 and 71+ (P = 0.041) and <30 and 51–70 (P < 0.001), as shown in Figure 3c. Interestingly, comparative analysis of the LOS pre-COVID and during COVID-19 demonstrated a statistically significant decrease (P < 0.001) in the median LOS during the pandemic [Supplementary Figure 1].

Analysis of the most common umbrella operation types revealed that there was a decreasing yet non-significant trend in operative frequency across the study period for all three classifications. In terms of the effect of the pandemic, the analysis revealed no reliable change in frequency in "*biopsy of lesion of nervous system*" or "*excision of lesion of meninges of brain*" due to high year-to-year variation in the years prior. "*Excision of lesion of tissue of brain*" operations, however, demonstrated an increasing trend up until the 2020 COVID-19 pandemic, where the frequency decreased and has remained lower than the pre-pandemic 2019 levels. Similar to operative frequency, "*excision of lesion of meninges of brain*" and "*excision of lesion of tissue of brain*" demonstrated a decreasing trend in postoperative LOS across the study period, the latter of which decreased only in the past four years. "*Biopsy of lesion of nervous system*" demonstrated a stable median LOS over the decade [Supplementary Figure 3].

Skull base (SB)

Cohort demographics

A total of 2029 SB procedures were performed between 2012 and 2022, with 1870 elective and 59-day case procedures. The mean patient age was 53 (±16.18) years, with a median of 54 (41–65) and a range of 18–92. Of the 14 distinct SB operations, only the four most common umbrella SB operations underwent further subgroup analysis: "*Excision of lesion of pituitary gland,*" "*excision of lesion of cranial nerve,*" "*excision of lesion of meninges of SB,*" and "*microvascular decompression of cranial nerve.*"

Frequency analysis

The most frequent operation type undertaken was "*excision of lesion of pituitary gland*" at 392, followed by "*excision of lesion of cranial nerve*" at 339. Figure 4a summarizes the frequency of SB operations over time. There was a general trend of decreasing frequency of SB surgeries between 2013 and 2022 (MK: tau = −0.733, P = 0.0042). The ratio of elective:

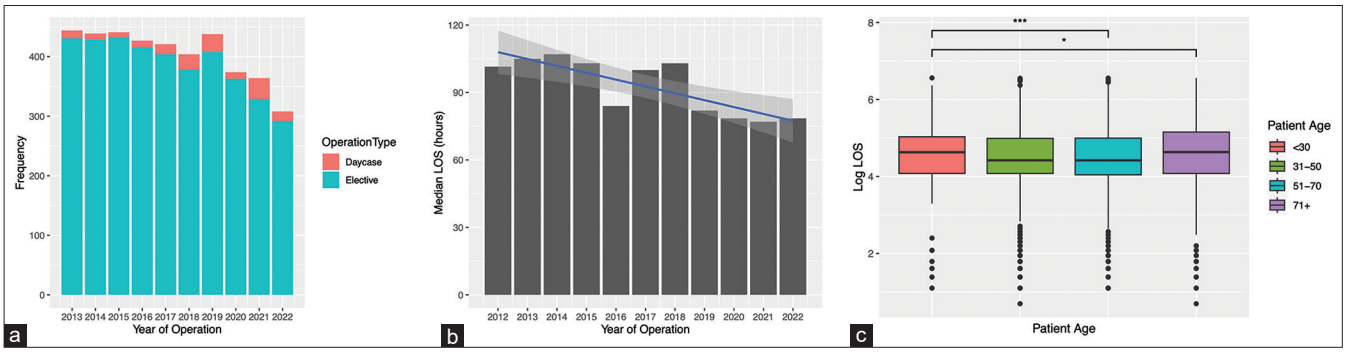

Figure 3: Plots representing the temporal trends in operative frequency and postoperative length of stay (LOS) from 2012 to 2022 for all neuro-oncological (NO) operations: (a) frequency of all NO operations split by elective and day case, (b) median LOS for all NO operations, and (c) comparing LOS and age, ***P < 0.001, *P < 0.05.

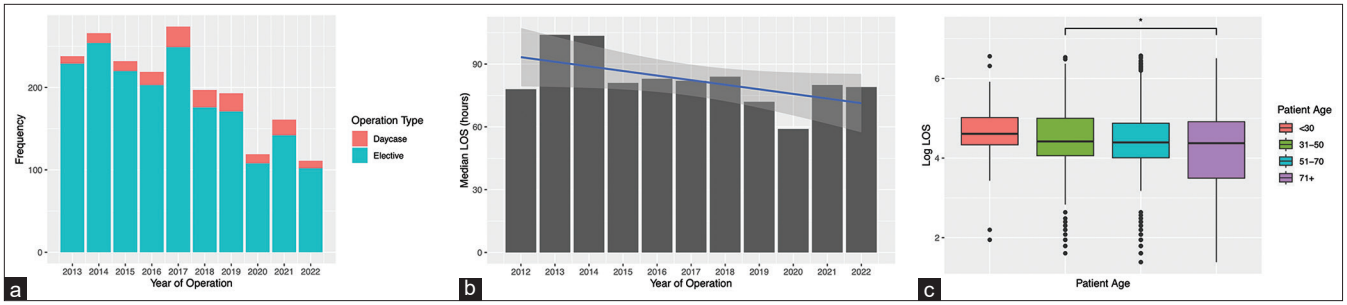

Figure 4: Plots representing the temporal trends in operative frequency and post-operative length of stay (LOS) from 2012-2022 for all skull base (SB) operations: a) Frequency of all SB operations split by elective and day case, b) Median LOS for all SB operations, c) Comparing LOS and age, * = P <0.05.

day case remained fairly constant throughout the years with no significant shift of procedure type from elective to day case in a particular year, but rather, there is a statistically significant trend toward a gradually increasing percentage of day case procedures over the years (MK: tau = 0.733, P = 0.0042), as shown in Figure 4a. Analysis of the effect of the COVID-19 pandemic further revealed that there was no statistically significant difference in procedure frequency as a result of the pandemic (P = 0.24), with the mean rate of change prior being −8 compared to −74 between 2019 and 2020 [Supplementary Figure 1].

LOS analysis

Overall, analysis showed a decrease in the median LOS between 2012 and 2022. (MK: tau = −0.382, P = 0.012), as shown in Figure 4b. Analysis of the LOS relative to age revealed a statistically significant decrease in the median LOS as age increased (P < 0.001), as shown in Figure 4c. ANOVA with *post hoc* Tukey analysis based on age groups showed a statistically significant change in the median LOS between the age groups 31–50 and 71+ only (P < 0.05). Overall, analysis of the LOS pre-pandemic and during the years most affected by COVID-19 showed a statistically significant decrease (P = 0.0027) in the median LOS as a result of the pandemic [Supplementary Figure 1].

Analysis of the most common umbrella operation types revealed that "*excision of lesion of cranial nerve*" and "*microvascular decompression of cranial nerve*" procedures demonstrated a decreasing trend in annual operative frequency, while "*excision of lesion of pituitary gland*" demonstrated an overall increasing trend in operative frequency. No reliable trend could be observed in the "*excision of lesion of meninges of SB*" group. "*Excision of lesion of pituitary gland*" and "*microvascular decompression of cranial nerve*" demonstrated a drop in procedure frequency due to COVID-19, with the former being the most pronounced. All four classifications demonstrated a trend toward decreasing LOS, with two of these being significant (P < 0.02). These were "*excision of lesion of pituitary gland*" and "*excision of lesion of cranial nerve*" [Supplementary Figure 4].

Functional neurosurgery

Cohort demographics

A total of 786 functional neurosurgery procedures were performed between 2012 and 2022, with 410 elective and 376 day case procedures. The mean patient age was 48.7 (±14.89) years, with a median of 50 (37–63) and a range of 18–87 years. Of the seven distinct functional operations, only the two most common umbrella classifications underwent further subgroup analysis: "*Deep brain stimulation*" and "*vagus nerve stimulation.*"

Frequency analysis

The most frequent operation type undertaken was "*implantation/insertion of neurostimulator*" at 393, followed by "*maintenance of neurostimulator*" at 332. Figure 5a summarizes the frequency of functional neurosurgery operations over time. We observed an increasing yet non-significant trend in the overall frequency of all functional neurosurgery procedures over ten years (MK: tau = 0.156, P = 0.59). There was, however, a significant shift (P = 0.0016) in the percentage of procedures performed as day cases between the years 2015 and 2016, with the mean percentage of day case operations rising from 11.59% in 2013–2015 to 61.95% in 2016–2022, as shown in Figure 5a. Analysis of the rate of change of frequency of operations performed pre-COVID-19 compared to the change from 2019 to 2020 revealed that there was a significant decrease in the operative frequency as a result of the pandemic (P = 0.0033). Pre-pandemic, there was a trend toward increasing frequency with an average rate of change of +1.8 procedures per annum compared to the start of the pandemic, where the rate of change was - 32 procedures [Supplementary Figure 1].

LOS analysis

Overall, analysis of the LOS showed a significant decreasing trend in the median LOS over the last decade (MK: tau = −0.648, $P = 0.0077$), as shown in Figure 5b. Analysis of the LOS relative to age revealed a statistically significant increase in median LOS with advancing age ($P < 0.001$). ANOVA with *post hoc* analysis demonstrated a significant difference between age groups <31 and <71 ($P < 0.001$), <31 and 71+ ($P = 0.0039$), and <51 and <71 ($P = 0.0013$), as shown by Figure 5c. Comparative analysis of LOS pre-COVID-19 and during COVID-19 showed no significant difference in the median LOS as a result of the pandemic, but rather, a large drop in median LOS was observed between the years 2014 and 2015 coordinating with the shift of procedure type from mostly elective to day case [Supplementary Figure 1].

When classified by the most common procedure types, "*deep brain stimulation*" and "*vagus nerve stimulation,*" neither showed a trend toward increasing or decreasing frequency, with great intra-year variation being observed instead. "*Vagus nerve stimulation*" was, however, noted to have a sudden decline in frequency between the years 2015 and 2016, with a steady rise again in the years that followed. There was no observed difference in procedure frequency as a result of the pandemic. With regard to LOS, both "*deep brain stimulation*" and "*vagus nerve stimulation*" showed a decrease. "*Deep brain stimulation*" was observed to have a relatively stable LOS until the COVID-19 pandemic, where a rapid decline was seen, whereas "*vagus nerve stimulation*" had a markedly higher LOS in 2013 with the remainder of the decade maintaining a stable lower median LOS [Supplementary Figure 5].

Cerebrospinal fluid (CSF)

Cohort demographics

A total of 548 CSF operations were performed between 2012 and 2022, with 530 elective and 18-day case procedures. The mean patient age was 52.79 (±19.04), with a median of 53 years (36–71) and a range of 18–86 years. Of the six distinct CSF operations, only the most common umbrella CSF operation, "*creation of shunt,*" underwent further subgroup analysis.

Frequency analysis

The most frequent operation type undertaken was "*creation of shunt*" at 185, followed by "*monitoring of tissue pressure in the brain*" at 112. Figure 6a demonstrates the frequency of CSF operations over time. There was a general trend of decreasing frequency of CSF surgeries carried out between 2013 and 2022 (MK: tau = −0.629, $P = 0.015$), with no significant shift of procedure type from elective to day case. Analysis of the

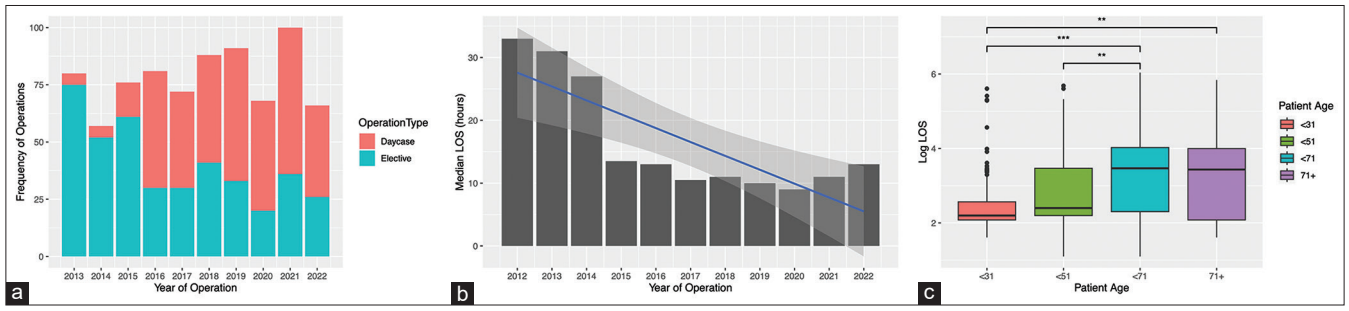

Figure 5: Plots representing the temporal trends in operative frequency and postoperative length of stay (LOS) from 2012 to 2022 for all functional operations: (a) frequency of all functional operations split by elective and day case, (b) median LOS for all functional operations, and (c) comparing LOS and age, $^{**}P < 0.01$, $^{***}P < 0.001$.

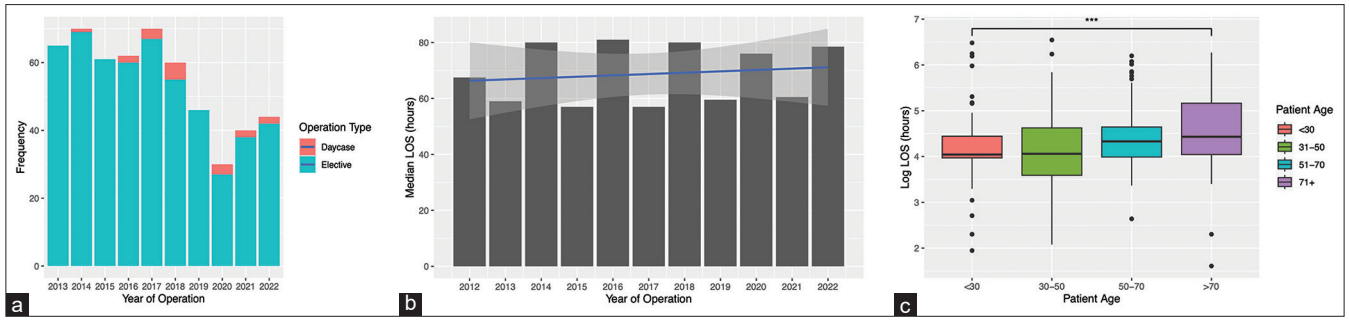

Figure 6: Plots representing the temporal trends in operative frequency and post-operative length of stay (LOS) from 2012-2022 for all cerebrospinal fluid (CSF) operations: a) Frequency of all CSF operations split by elective and day case, b) Median LOS for all CSF operations, c) Comparing LOS and age, *** = P <0.001.

effect of the COVID-19 pandemic also demonstrated no significant difference in the rate of change of the operation frequency, with the average change in procedure frequency being -3 pre-pandemic and rising to −13 between 2019 and 2020 [Supplementary Figure 1].

LOS analysis

Overall, the analysis showed a fairly constant LOS over time, with no significant change in the median LOS over the period of 10 years (MK: tau = 0.147, $P = 0.59$), as shown in Figure 6b. Analysis of the LOS relative to age revealed a statistically significant increase in the median LOS with advancing age (p <0.001). ANOVA with *post hoc* Tukey based on age groups (<30, 31–50, 51–70, 70+) highlighted a significantly higher LOS for both the 50–70 and >70 year age groups in comparison to both the 30–50 and <30 year age groups ($P = 0.0012$), as shown in Figure 6c. Analysis of the change in LOS due to COVID-19 revealed no significant difference in the median LOS from the years before the years most affected by the pandemic ($P = 0.89$) [Supplementary Figure 1].

Analysis of the most common operation type, "*creation of shunt,*" showed no clear trends in frequency, though it was noted that the frequency in the COVID-19 years 2020 and 2021 was significantly lower than observed previously, with an unprecedented rapid decline between 2019 and 2020. The median LOS in this procedure group also remained stable, though there was a minor increasing trend. This was largely a result of the year 2021, and as there was such a relatively small sample size in the pandemic years, it is hard to comment on the effect of COVID-19 on LOS for the "*creation of shunts*" [Supplementary Figure 6].

Peripheral nerve (PN)

Cohort demographics

A total of 840 PN operations were performed between 2012 and 2022, with 95 elective and 745-day case procedures. The mean patient age was 53 (±16.00) years, with a median of 54 (42–64) and a range of 18–91. Of the seven distinct PN operations, only the most common umbrella PN operation, "*carpal tunnel release,*" underwent further subgroup analysis.

Frequency analysis

The most frequent operation type undertaken was "*carpal tunnel release*" at 307, followed by "*maintenance of neurostimulator in PN*" at 144. Figure 7a summarizes the frequency of PN operations over time. There was a general but insignificant trend of decreasing frequency of PN surgeries between 2013 and 2022 (MK: tau = −0.156, $P = 0.5915$). There was no significant shift in procedure type observed, with a consistently high percentage of day case operations, reaching a high of 95.7% in 2017 and a low of 69.66% in 2015, as shown in Figure 7a. Analysis of the effect of the COVID pandemic also demonstrated a statistically significant decrease ($P = 0.009$) in the operation frequency, with the average change in procedure frequency being +5 pre-pandemic and rising to −75 between 2019 and 2020 [Supplementary Figure 1].

LOS analysis

Overall, the analysis showed a fairly constant LOS over time between 2013 and 2022, with no significant change in the median LOS (MK: tau = 0.479, $P = 0.089$), as shown in Figure 7b. Analysis of the LOS relative to age revealed no significant alteration in the median LOS relative to advancing age ($P = 0.92$). ANOVA with *post hoc* Tukey analysis based on age groups (<30, 31–50, 51–70, 71+) also showed no statistically significant change in the median LOS between any age group, as shown in Figure 7c. Overall, analysis of the LOS pre-COVID-19 and during the years most affected by COVID-19 showed no significant difference ($P = 0.12$) in the median LOS as a result of the pandemic [Supplementary Figure 1].

Analysis of the most common procedure type, "*carpal tunnel release,*" revealed a slight trend toward decreasing frequency, though this was not significant. The frequency

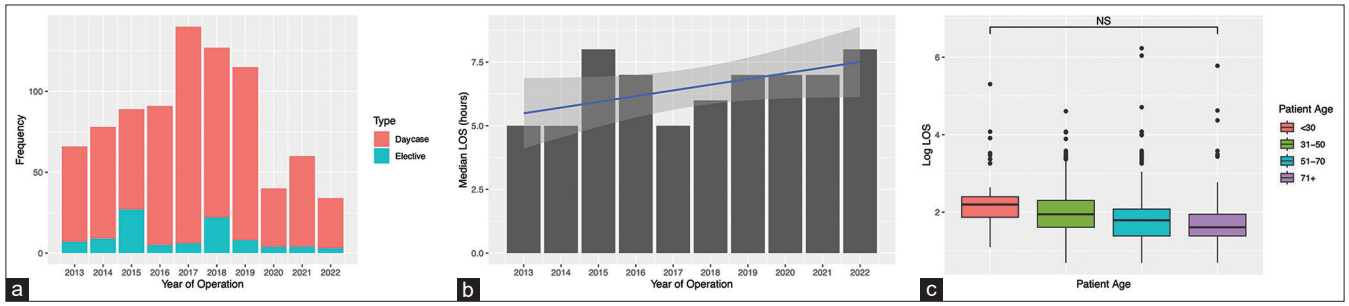

Figure 7: Plots representing the temporal trends in operative frequency and postoperative length of stay (LOS) from 2013 to 2022 for all peripheral nerve (PN) operations: (a) frequency of all PN operations split by elective and day case, (b) median LOS for all PN operations, and (c) comparing LOS and age, NS: Not significant.

was at its lowest during the initial wave of the pandemic in 2020, with a slow increase observed in the years that followed. Similarly, there was a non-significant trend toward decreasing seen in the median LOS. For this procedure group, no effect on LOS as a result of COVID-19 was observed [Supplementary Figure 6].

DISCUSSION

Over the course of the last decade, the field of neurosurgery has undergone substantial evolution due to a culmination of factors that can have multi-faceted influences on the specialty. Positive intraoperative factors have included the acquisition of new surgical methods and the refinement of previous surgical techniques, with some subspecialties, such as spine and functional, exhibiting greater leaps in interventional improvement.[24] This advancement is coupled with the improved management of patient comorbidities and neurosurgical complications and increased preoperative rehabilitation.[24] Opposing factors include the rapidly aging population combined with a shortage of hospital beds and, most notably, the recent COVID-19 pandemic. These challenges have manifested sharp declines in operating capacity and neurosurgical referrals, with a further pronounced decrease in bed availability and a concerning trend of patients avoiding healthcare services.[28] Each of these factors plays a role in altering the LOS, and given the link between prolonged LOS and increased mortality rates, disease burden, and hospital expenditure, identifying temporal trends in the LOS can allow better management of hospital resources and improve patient outcomes.[10] The importance of understanding such trends is more pertinent than ever following the pandemic, as neurosurgical centers continue to tackle increased waiting lists as well as higher referral volumes and operative procedures, thus working at a higher capacity than usual.[28] Our present study analyzed how the frequency of neurosurgical operations (day case and elective) and LOS has changed over a 10-year period from 2012 to 2022 at a tertiary neurosurgical center in the UK. It is the first-ever study from a public healthcare system such as the UK to have analyzed how operative neurosurgery has evolved over a 10-year period in a high-volume tertiary center and how COVID-19 has affected this over the past three years.

Our results show that, overall, the majority of subspecialties had a decrease in the frequency of procedures over the 10-year period, with a sudden decline during COVID-19 and a slow recovery since. The subspecialties "*Spinal,*" "*Neuro-oncology,*" "*CSF,*" and "*Skull-base*" all had a significant decrease in the frequency of procedures over time. The "*Peripheral nerve*" subspecialty had a significant overall increase during this 10-year period, though a decrease was noted between 2018 and 2020. Our frequency analysis on spinal surgery demonstrated a reduction in procedures leading up to COVID-19, particularly in lumbar discectomies, contrasting with earlier findings that showed an increase between 2001 and 2011, attributed to an increased incidence of spine degeneration within an elderly population.[10] This correlates with one survey on neurosurgical workloads in Canada where 100% of neurosurgeons involved reported performing lumbar discectomies in 2017 compared to only 87.8% a decade prior [1] and thus, our paper highlights a new trend seen in this decade with regard to spinal surgery. This may be explained by an improved emphasis on conservative measures along with the implementation of the national back pain pathway.[16,26] The less significant decrease in frequency within the other subspecialties likely highlights the more complex nature of surgery with the use of equipment such as intraoperative ultrasound, endoscopes, intraoperative neurophysiology, fluorescence imaging, and dual surgeon operating. Due to fixed capacities of operative lists, more complex procedures combined with increasing patient comorbidities mean fewer procedures can be performed in the same timeframe. Conversely, the rise seen in the "*Peripheral nerve*" subspecialty may be reflective of better pathways streamlining the decision-making process.[20] The significant drop in operative volumes in this institution during COVID-19 is recognized to be from infection control measures, which led to less efficient operative pathways initially and then subsequently due to a lack of theater staff, leading to the cancellation of many operative lists.

Notably, "*Functional*," "*Neuro-oncology*," and "*Skull base*" subspecialties all had a rise in the frequency of day case procedures, with the "*Spinal*" subspecialty having a significant rise after 2015. This rise across these subspecialties is perhaps not unsurprising when considering how advancements have been made with regard to the use of more minimally invasive surgeries with improved anesthetic techniques, such as awake spinal surgery and a heavier focus on minimizing total time to recovery postoperatively. In our center, we have observed the appearance of dedicated day case theaters and staffing teams over the study period, correlating with the increased incidence demonstrated by our results. This, alongside fewer complications and an associated reduction in postoperative pain, inherently lends itself to a proportional increase in day-case procedures.[25] In light of these trends, we tentatively predict that in future years, day-case procedures may continue to rise in number and extend to other neurosurgical subspecialties. More prominent after the COVID-19 pandemic, the mismatch between surgical referrals and operative capabilities inevitably leads to long waiting lists in the National Health Service (NHS). The drop in procedure frequency observed during the pandemic, a result of both cancellation of non-urgent elective procedures and patient avoidance of services, has increased the backlog of patients requiring surgical intervention. As such, the shift to a more

day-case-heavy surgical list could help reduce the hospital's financial burden while increasing patient and bed turnover.

The effect of increasing day case procedures has understandably had a large effect on postoperative LOS. Overall, "*Neuro-oncology*," "*CSF*," and "*Functional*" subspecialties had a statistically significant decrease in the median LOS over time, with "*Skull Base*" showing a trend toward decreasing though insignificant. No notable changes were noted in the "*Spinal*" subspecialty, while "*Peripheral nerve*" did show a trend toward an increasing LOS, though once again, this was not significant. The trends observed toward reducing LOS across most subspecialties could be attributed to a variety of factors outside the shift from elective to day cases. The understanding of how reducing inpatient stay enhances patient recovery has led to many campaigns to encourage faster discharges either at home or to alternate care facilities, with many studies attributing extended LOS to higher mortality rates.[31] This can be further explained by the recent shift in our department toward optimized rehabilitation protocols and streamlined postoperative planning under the guidance of a multi-disciplinary team consisting of neurosurgeons, advanced nurse practitioners, occupational therapists, physical therapists, speech and language therapists, and social care workers. This allows for efficient and holistic assessment of patients in the preoperative period to facilitate easier and reliable patient-centered postoperative recovery and discharge. Similarly, improvement in a multitude of pre- and perioperative factors has allowed for faster recovery from surgery. Such examples include better fluid management, which has been directly linked to shorter LOS, and advancements in anesthetics to reduce the occurrence of postoperative complications such as delirium, which, therefore, allows faster discharge.[13,27] With regard to the operations themselves, neurosurgical approaches continue to become less invasive and more precise with improved technology, a factor that has been linked to shortening LOS due to decreased risk of adverse events.[19] Our results regarding median LOS within the "*Neuro-oncology*" subspecialty specifically are likely attributed to the NICE-recommended reconfiguration in 2006 away from emergency (non-elective) procedures toward urgent elective procedures. Results from an earlier study support this trend, which has been directly linked to a reduction in hospital burden and patient satisfaction and is undoubtedly a great success within the field of neurosurgery over the last decade.[23]

With regard to trends between LOS and differing age groups, "*Spinal*," "*Functional*," "*CSF*," and "*Neuro-oncology*" subspecialties had a statistically significant increase in median LOS with age, while "*Skull* base" showed the opposite trend. Our results for "*Neuro-oncology*" contradict an earlier study showing a negative correlation between the age of patients presenting with a tumor and the hospital LOS.[9] However, controversy exists as evidence also shows that older patients are the patient cohort with the greatest likelihood of having an unnecessarily extended LOS when they were otherwise fit for discharge.[11] In addition, elderly patients are also the age-group with the greatest number of comorbidities, which significantly fluctuates on a patient-to-patient basis. Moreover, extended LOS is influenced by capacity at discharge locations and other socioeconomic factors, such as family circumstances and transportation availability. In this light, shorter LOS for elderly patients could be expected due to higher proportions of patients returning to facilities such as nursing homes where additional care can be provided, meaning a reduced hospital stay is required. Thus, clearly, it is difficult for us to accurately conclude the exact effect of old age on median LOS compared with younger age groups.

With respect to the impact of the pandemic on LOS, we reported a statistically significant reduction in median LOS within the subspecialties of "*Neuro-oncology*" and "*Skull base*." This is not unexpected, as reducing hospital LOS was a strategy adopted in clinical practice in an attempt to deal with the increased pressures seen during the pandemic.[26] Thus, the pandemic provided neurosurgery with a unique opportunity to determine whether favoring shorter hospital LOSs is a sustainable future method for the NHS to tackle the many negative connotations linked to a longer LOS. Nevertheless, the impact of shortened LOS on future re-admission rates, long-term outcomes, and patient-reported quality of care provision remains to be evaluated, and as such, monitoring prospective trends on these topics is of great clinical significance.

Overall, when comparing the impact of the pandemic on the frequency of procedures, with the exception of "*Skull base*" and "*Peripheral nerve*" subspecialties, our results showed that COVID-19 led to a statistically significant decline in operation frequency above the normal trend in years prior. In the past three years, this impact has been the equivalent of not having done any surgery for more than a whole year. However, the impact of the pandemic in a private healthcare system such as the USA showed opposing results, whereby no significant change in procedure frequency was reported due to COVID-19.[29] Similar trends have been found in other studies within the field, with a clear pattern seen in which non-elective procedures were prioritized at the expense of substantial cancellations of elective procedures.[4] With regard to the reductions seen in the "*Neuro-Oncology*" and "*Functional*" subspecialties, we suggest that this may be due to a decline in the number of craniotomies, occipital nerve, deep brain, and spinal cord stimulation. A reduced incidence of more chronic conditions, including spine conditions, hydrocephalus, and chronic subdural hematomas,[18] perhaps as a result of patient reluctance to present clinically, may have

also contributed to our trends. However, uncertainty remains as we are unable to elicit whether the reductions seen across these three subspecialties are merely attributed to outliers seen between 2019 and 2020 and unrelated to the pandemic. The fact that the frequency of SB procedures was unaffected during the pandemic is surprising, especially in light of the findings reported in another study.[4] This observation can potentially be attributed to the enhanced levels of support allocated to the SB team within our department, due to the inherent life-threatening nature and critical complications associated with these cases/procedures. As a result of this, no discernible decline in operative frequency was noted. Similarly, when analyzing the effect of the pandemic on SB frequency, given that each year varies drastically, this may explain why there was no significant reduction seen during the pandemic, and thus, it is possible that our data exploring the impact of COVID-19 on the frequency of skull-base procedures is not an accurate predictor of trends that may be seen across other tertiary centers.

The consequence of numerous neurosurgical cancellations seen in the face of the pandemic is an expected rise in the number of referrals and an augmented post-pandemic waiting list.[30]

Interestingly, across many subspecialties, our post-pandemic findings from 2021 and 2022 generally do not reflect a substantial rise in the frequency of procedures as would be predicted, with no change or a decrease from pandemic levels being the predominant trend. Only the subspecialties of "*Neuro-oncology*" and "*CSF*" depicted a postpandemic rise. The hypothesized rise following the pandemic may have been hindered by a multitude of factors, including a shortage of hospital beds, stricter theater regulations, and self-isolation due to invalid swab results and COVID-related staff illness.[8] In our institution, due to a shortage of theater staff, we had fewer operating lists available than pre-COVID for nearly three years. The efficiency of lists has also decreased due to a variety of reasons, including a huge influx of new staff to replace those who left. The backlog of cancellations caused by the pandemic will unlikely be cleared by simply catching up to a pre-COVID level of operating and increasing theater efficiency by marginal amounts. One strategy to effectively prevent this backlog from severely straining NHS neurosurgical services could be by bringing online extra day case theaters for neurosurgery. This can take advantage of the increased trend for day-case surgery in neurosurgery and will be less expensive than increasing the number of beds, and when combined with dynamic bed management and patient data-driven decision-making, this can help optimize resource allocation. In addition, utilization of telemedicine and similar technologies, whose efficacy was proven during the COVID-19 pandemic, can enable further improvement in neurosurgical care provision. In support, the previous literature has suggested a reduction in hospital appointments by 75.6% through the utilization of telemedicine and virtual consults.[15]

At present, we do not know whether the reported trends seen at our tertiary center accurately depict trends that would be seen across other UK tertiary centers. This is especially pertinent when considering socioeconomic and ethnic differences that differ between tertiary centers serving different regions, which is in part demonstrated by our results correlating increased age with prolonged LOS. Thus, our data serve to provide a "glimpse" into neurosurgical trends within the UK that may be extrapolatable within other cohorts. Nevertheless, these results are unlikely to generalize to other private or hybrid healthcare systems due to different treatment incentives, both economic and operational, reduced financial constraints, and greater access to state-of-the-art novel technologies. Moreover, an element of uncertainty remains regarding future trends as it is difficult to pre-empt how advancing technologies, including radiomics and artificial intelligence, will alter the field of neurosurgery.[12]

Limitations

Despite these results, there are a few limitations in this study. First, the sample size varied throughout the course of the ten years, resulting in an imbalance dataset with some procedures having a markedly lower number of patients in some years than others. Despite our exclusion criteria largely mitigating the effects of this, it is still likely that these variations have somewhat skewed our results. Second, we were unable to determine the number of comorbidities for each individual patient, as this may have influenced LOS trends seen in this study. In addition, the impact of intraoperative and immediate postoperative complications on the LOS for patients after surgery was not explored, and the temporal trends in these factors can further elucidate/explain the changes observed. Finally, this being a single-center retrospective analysis poses questions of the generalizability and extrapolation of these results in geographically and financially distinct healthcare systems with clinically and demographically different patient populations and surgical preferences.

CONCLUSION

This study details the temporal trends observed in operative neurosurgery over a decade in a high-volume tertiary center in a public healthcare system. We observed a significant decline in postoperative LOS across most neurosurgical subspecialties, coupled with a shift toward day-case surgeries. These changes may be attributed to improved neurosurgical techniques, the pressure on inpatient beds, and perhaps the desire of patients to avoid staying in hospitals. However,

the decline in overall surgical volume across subspecialties indicates the growing role of non-surgical treatments, evolving more complex (and hence longer) surgical practices, and stringent patient selection criteria. In addition, it highlights the challenges, both logistical and financial, that the NHS faces – challenges further exacerbated by the COVID-19 pandemic. COVID-19 has had a significant impact on the volume of neurosurgical procedures, and the volumes continue to be less than the pre-COVID era. Utilizing the shift away from elective and setting up extra dedicated day case neurosurgery theaters would be a practical way of dealing with the backlog of procedures.

Ethical approval

The author(s) declare that they have taken the ethical approval from IRB, Reference number: 22HIP32.

Declaration of patient consent

Patients' consent not required as patients' identities were not disclosed or compromised.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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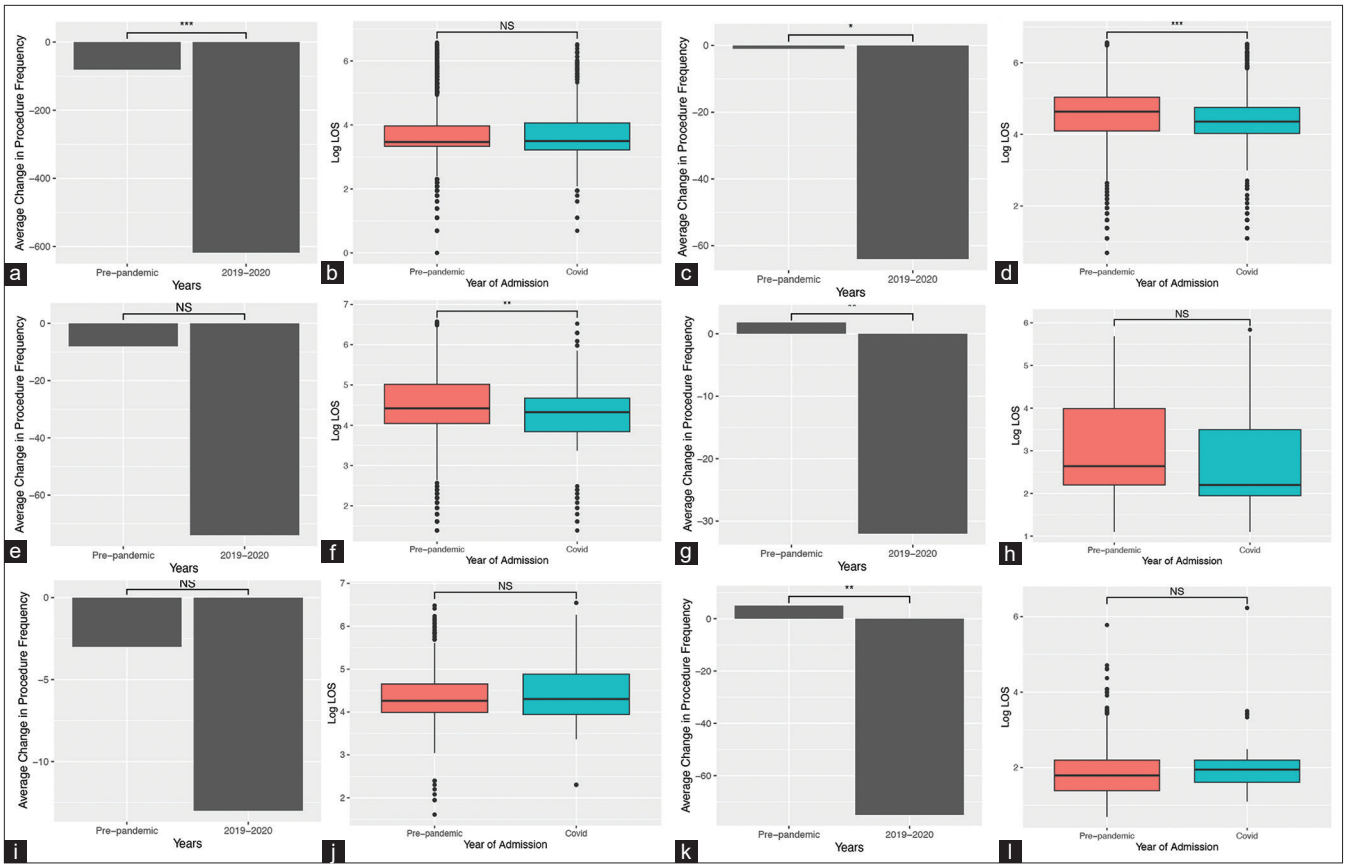
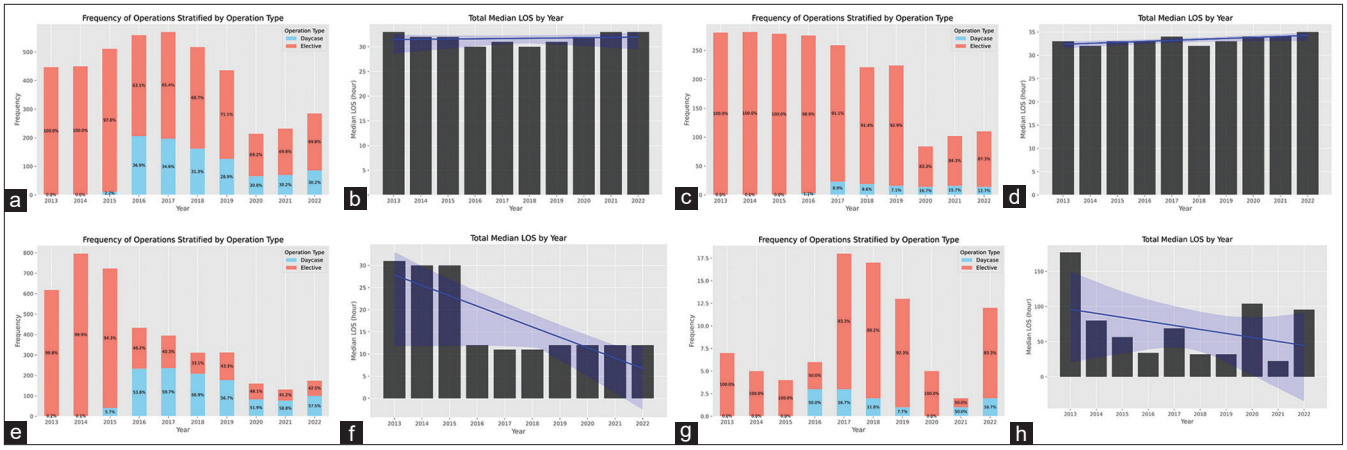
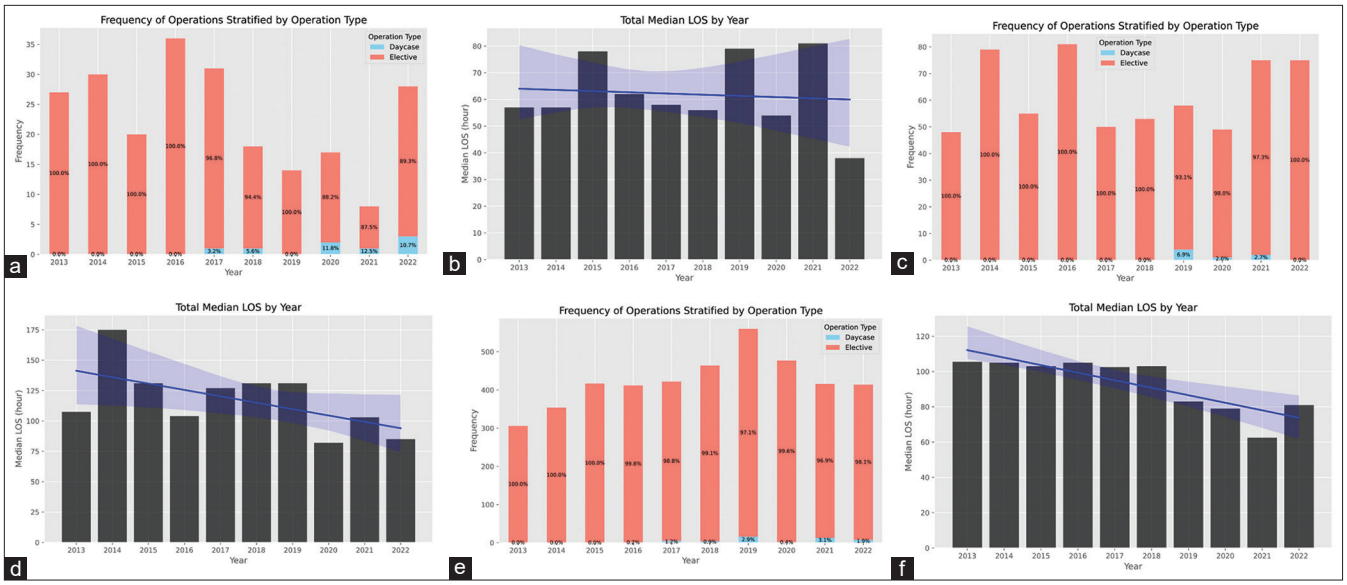
SUPPLEMENTARY FIGURES



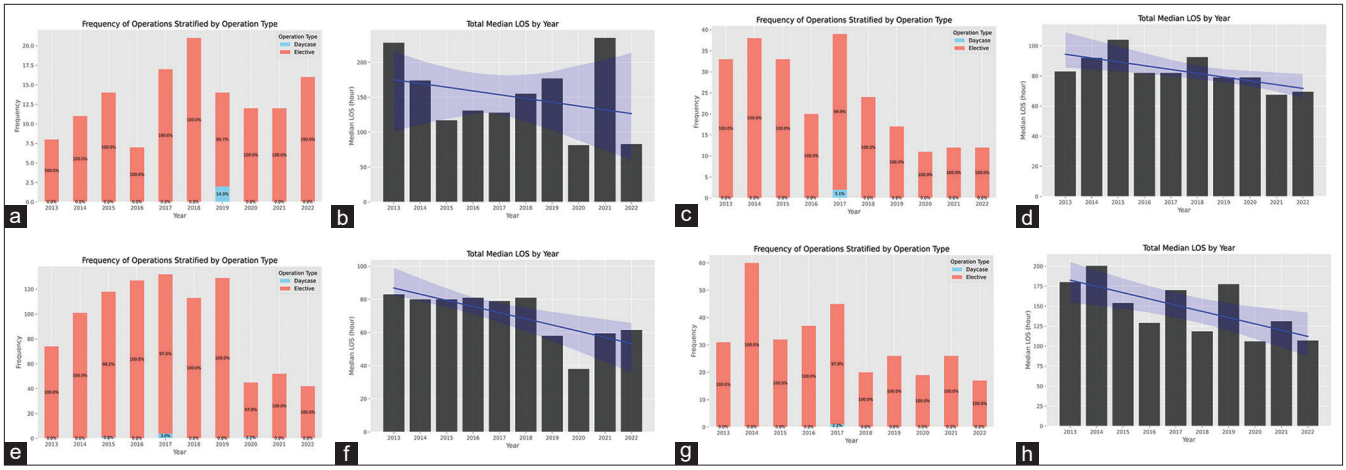
Supplementary Figure 1: Plots representing the change observed in Frequency and post-operative length of stay (LOS) due to the COVID-19 pandemic in 6 neurosurgical subspecialties, (a) Average change in frequency of spinal procedures, *** = $P < 0.001$. (b) Box plot of the log LOS for spinal surgery pre-pandemic compared to the years most affected by COVID-19 (2020 and 2021), NS = not significant. (c) Average change in frequency of neuro-oncological procedures, * = $P < 0.05$. (d) Box plot of the log LOS for neuro-oncological surgery pre-pandemic compared to the years most affected by COVID-19, *** = $P < 0.001$. (e) Average change in frequency of skull base procedures, NS = not significant. (f) Box plot of the log LOS for skull base surgery pre-pandemic compared to the years most affected by COVID-19, ** = $P < 0.005$. (g) Average change in frequency of functional procedures, ** = $P < 0.005$. (h) Box plot of the log LOS for functional neurosurgery pre-pandemic compared to the years most affected by COVID-19, NS = not significant. (i) Average change in frequency of CSF procedures, NS = not significant. (j) Box plot of the log LOS for CSF surgery pre-pandemic compared to the years most affected by COVID-19, NS = not significant. (k) Average change in frequency of peripheral nerve procedures, ** = $P < 0.005$. (l) Box plot of the log LOS for peripheral nerve surgery pre-pandemic compared to the years most affected by COVID-19, NS = not significant.



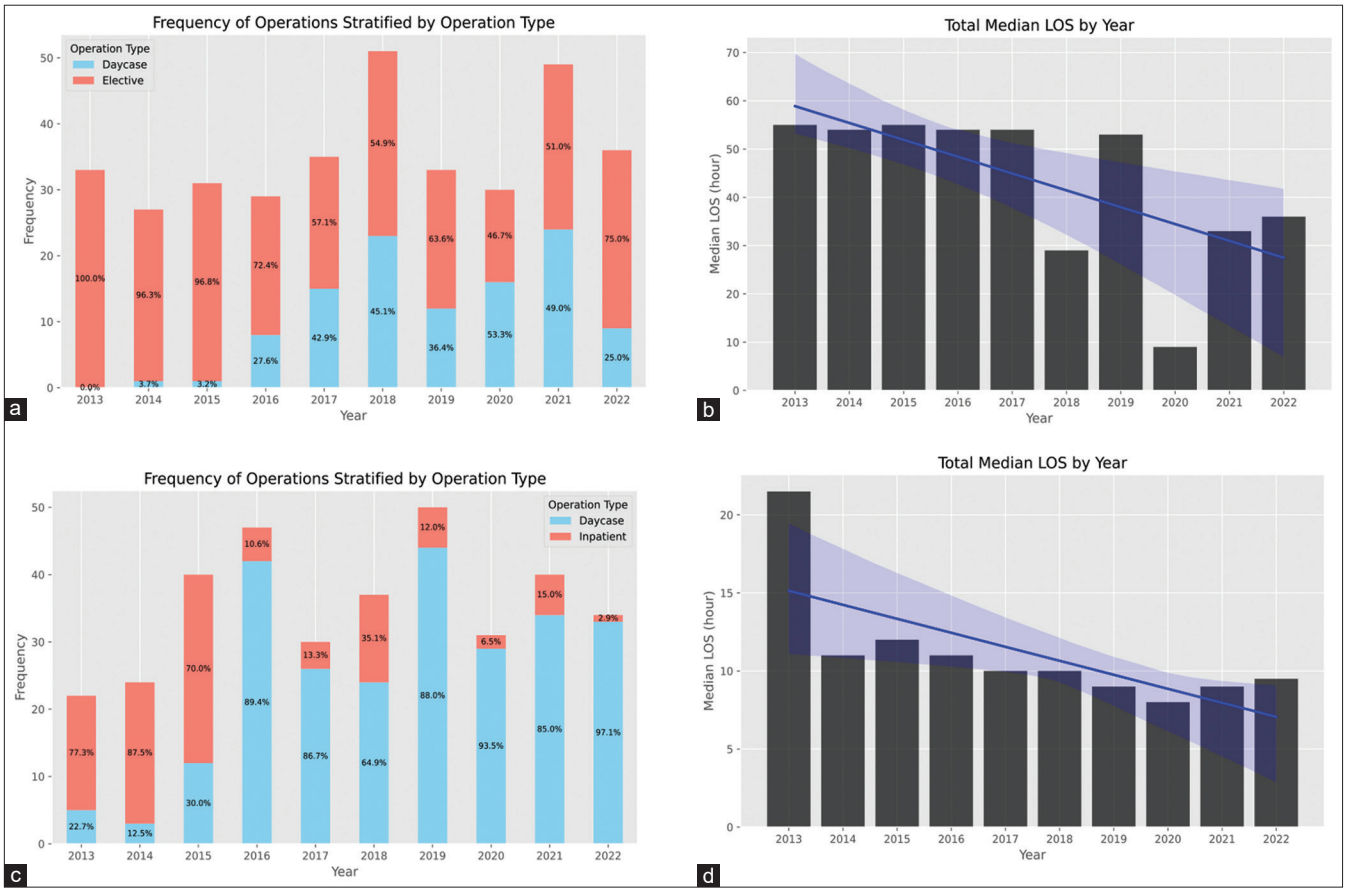
Supplementary Figure 2: Bar plots representing the temporal trends in operative frequency and postoperative length of stay (LOS) from 2013 to 2022: (a) frequency of all "*decompression of lumbar spine*" operations, (b) median LOS for all "*decompression of lumbar spine*" operations, (c) frequency of all "*anterior cervical discectomy and fusion*" operations, (d) median LOS for all "*anterior cervical discectomy and fusion*" operations, (e) frequency of all "*excision of lumbar intervertebral disc*" operations, (f) median LOS for all "*excision of lumbar intervertebral disc*" operations, (g) frequency of all "*lumbar fusion*" operations, and (h) median LOS for all "*lumbar fusion*" operations.



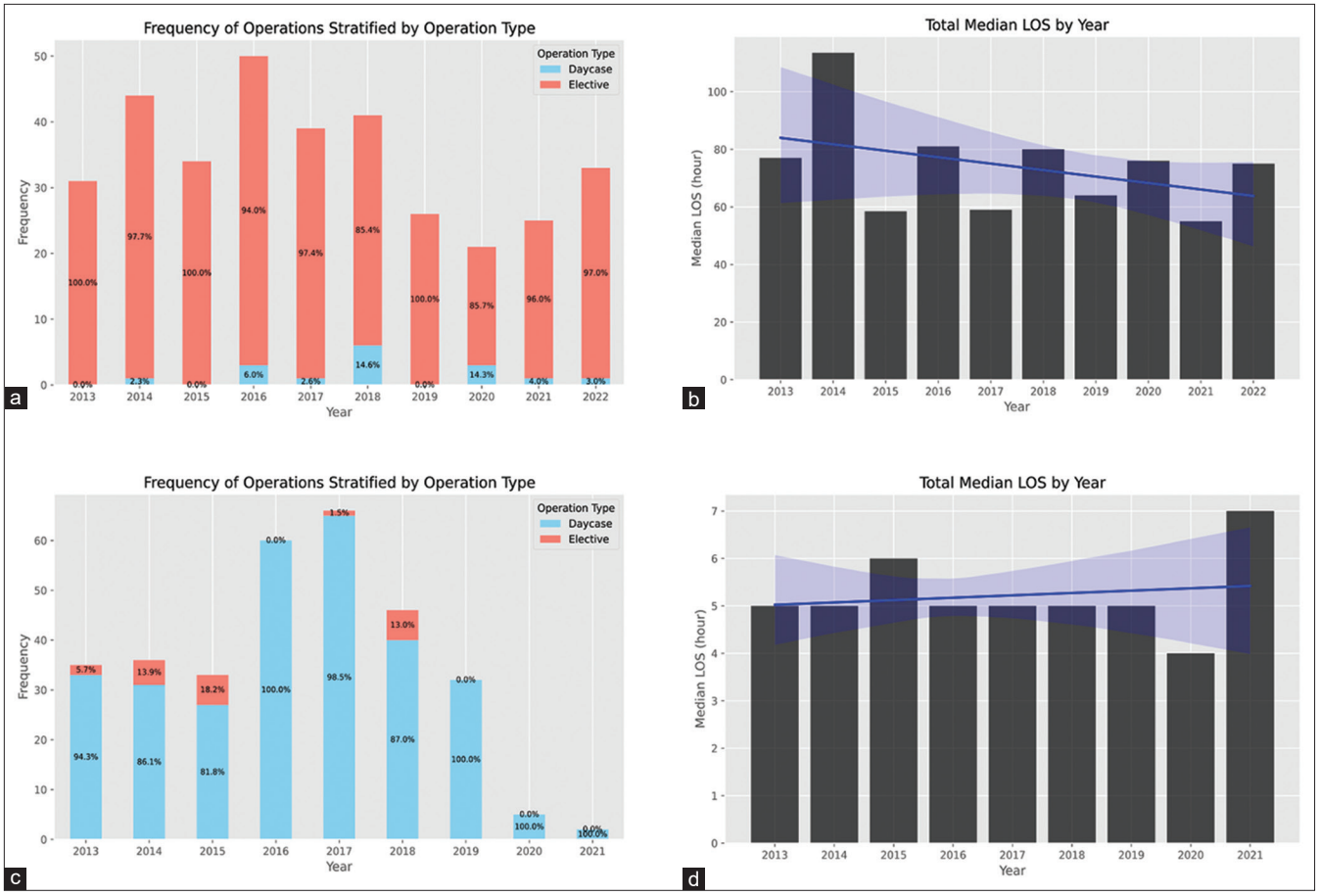
Supplementary Figure 3: Bar plots representing the temporal trends in operative frequency and postoperative length of stay (LOS) from 2013 to 2022: (a) frequency of all "*biopsy of lesion of nervous system*" operations, (b) median LOS for all "*biopsy of lesion of nervous system*" operations, (c) frequency of all "*excision of lesion of meninges of brain*" operations, (d) median LOS for all "*excision of lesion of meninges of brain*" operations, (e) frequency of all "*excision of lesion of tissue of brain*" operations, and (f) median LOS for all "*excision of lesion of tissue of brain*" operations.



Supplementary Figure 4: Bar plots representing the temporal trends in operative frequency and postoperative length of stay (LOS) from 2013 to 2022: (a) frequency of all "*excision of lesion of meninges of skull base*" operations, (b) median LOS for all "*excision of lesion of meninges of skull base*" operations, (c) frequency of all "*microvascular decompression of cranial nerve*" operations, (d) median LOS for all "*microvascular decompression of cranial nerve*" operations, (e) frequency of all "*excision of lesion of pituitary gland*" operations, (f) median LOS for all "*excision of lesion of pituitary gland*" operations, (g) frequency of all "*excision of lesion of cranial nerve*" operations, and (h) median LOS for all "*excision of lesion of cranial nerve*" operations.



Supplementary Figure 5: Bar plots representing the temporal trends in operative frequency and postoperative length of stay (LOS) from 2013 to 2022: (a) frequency of all "*deep brain stimulation*" operations, (b) median LOS for all "*deep brain stimulation*" operations, (c) frequency of all "*vagus nerve stimulation*" operations, and (d) median LOS for all "*vagus nerve stimulation*" operations.



Supplementary Figure 6: Bar plots representing the temporal trends in operative frequency and postoperative length of stay (LOS) from 2013 to 2022 for CSF and peripheral subspecialties: (a) frequency of all "*creation of shunt*" operations, (b) median LOS for all "*creation of shunt*" operations, (c) frequency of all "*carpal tunnel release*" operations, and (d) median LOS for all "*carpal tunnel release*" operations.