

Intraoperative computed tomography registration and electromagnetic neuronavigation for transsphenoidal pituitary surgery: accuracy and time effectiveness

Clinical article

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Object. The authors assessed the feasibility, anatomical accuracy, and cost effectiveness of frameless electromagnetic (EM) neuronavigation in conjunction with portable intraoperative CT (iCT) registration for transsphenoidal adenomectomy (TSA).

Methods. A prospective database was established for data obtained in 208 consecutive patients who underwent TSA in which the iCT/EM navigation technique was used. Data were compared with those acquired in a retrospective cohort of 65 consecutive patients in whom fluoroscope-assisted TSA had been performed by the same surgeon. All patients in both groups underwent transnasal removal of pituitary adenomas or neuroepithelial cysts, using identical surgical techniques with an operating microscope. In the iCT/EM technique–treated cases, a portable iCT scan was obtained immediately prior to surgery for registration to the EM navigation system, which did not require rigid head fixation. Preexisting (nonnavigation protocol) MR imaging studies were fused with the iCT scans to enable 3D navigation based on MR imaging data. The accuracy of the navigation system was determined in the first 50 iCT/EM cases by visual concordance of the navigation probe location to 5 preselected bony landmarks. For all patients in both cohorts, total operating room time, incision-to-closure time, and relative costs of imaging and surgical procedures were determined from hospital records.

Results. In every case, iCT registration was successful and preoperative MR images were fused to iCT scans without affecting navigation accuracy. There was 100% concordance between probe tip location and predetermined bony loci in the first 50 cases involving the iCT/EM technique. Total operating room time was significantly less in the iCT/EM cases (mean 108.9 ± 24.3 minutes [208 patients]) compared with the fluoroscopy group (mean 121.1 ± 30.7 minutes [65 patients]; $p < 0.001$). Similarly, incision-to-closure time was significantly less for the iCT/EM cases (mean 61.3 ± 18.2 minutes) than for the fluoroscopy cases (mean 71.75 ± 19.0 minutes; $p < 0.001$). Relative overall costs for iCT/EM technique and intraoperative C-arm fluoroscopy were comparable; increased costs for navigation equipment were offset by savings in operating room costs for shorter procedures.

Conclusions. The use of iCT/MR imaging–guided neuronavigation for transsphenoidal surgery is a time-effective, cost-efficient, safe, and technically beneficial technique. (DOI: 10.3171/2010.5.JNS091821)

KEY WORDS • transsphenoidal approach • pituitary tumor • stereotactic navigation • intraoperative computed tomography • electromagnetic navigation • time effectiveness

TRANSSPHENOIDAL approaches to sellar and parasellar lesions enable safe, rapid, and effective surgical therapy for a variety of lesions involving the anterior skull base. The safety and efficacy for transsphenoidal procedures are largely dependent on a precise knowledge of the anatomy in the sphenoid sinus and the relationship of the surgical focus to critical juxtaseellar structures. Continuous fluoroscopy has traditionally been

used for intraoperative guidance in TSA.⁸ However, fluoroscopy provides guidance information in only 2 dimensions, does not reflect soft-tissue anatomy, is limited when bony landmarks are not present due to tumor or prior surgery, and potentially exposes the patient and operating room personnel to significant doses of ionizing radiation. Frameless stereotactic navigation can provide accurate 3D guidance data and soft-tissue resolution for

Abbreviations used in this paper: iCT = intraoperative CT; EM = electromagnetic; TSA = transsphenoidal adenomectomy.

This article contains some figures that are displayed in color online but in black and white in the print edition.

transsphenoidal surgery.^{4,9,11,12,15,29} However, frameless navigation usually adds time and cost to the procedure, necessitates an additional MR imaging study prior to surgery, requires rigid head fixation, and is limited by line-of-sight restrictions for optical tracking devices.

To address these limitations, a protocol for iCT registration and EM stereotactic navigation in transsphenoidal surgery was developed at our institution. Patients underwent iCT scanning immediately before induction of anesthesia, and preexisting nonnavigation-compatible MR images were fused to the CT studies. Registration to the iCT/MR imaging data set was rapidly accomplished using an EM registration system using skin surface fiducial technique, and continuous frameless navigation was used throughout the procedure.

We prospectively assessed the feasibility and accuracy of the iCT/EM navigation protocol in a consecutive series of patients undergoing TSA in comparison with a prior series of patients with TSA in which we used C-arm fluoroscopic guidance. For both guidance modalities, we also compared total surgical time, procedural (incision-to-closure) time, and overall costs derived from hospital financial data.

Methods

The study protocol was approved by the Swedish Medical Center Institutional Review Board. A prospective database was established for 208 patients in whom iCT/MR imaging-guided transsphenoidal surgery for pituitary adenomas was performed by a single surgeon (M.M.) between April 2007 and May 2009. For comparison, a retrospective analysis was performed in a cohort of 65 patients with the same lesion characteristics who underwent TSA between January 2006 and March 2007; the same surgeon (M.M.) performed these operations using identical surgical techniques with standard fluoroscopy-assisted navigation. For both groups, the analysis included only pituitary tumors or neuroepithelial cysts confined to the sella and immediate parasellar and suprasellar region. Patients with primarily intracranial, frontal base, or laterally situated lesions treated via transnasal transsphenoidal approach (craniopharyngioma, meningioma, chordoma) were excluded from the analysis. The prospective database included demographic, endocrinologic, tumor characteristic, and outcome data, and indices of surgical efficiency including total operating room time and incision-to-closure time. Total operating time was recorded as time in minutes between patient entry and exit from operating room; incision-to-closure time was defined as the time in minutes between the initial incision and removal of sterile drapes at the conclusion of the procedure. In the first 50 iCT/EM cases, time for iCT scan acquisition and patient registration were separately recorded. Imaging costs for C-arm fluoroscopy and iCT scanning were estimated from hospital charge data obtained from aggregate financial records. Procedural costs were derived from hospital financial records for the 2 procedures, calculated using per-minute operating room cost and disposable EM navigation equipment costs (for example, magnetic reference array and EM probes). The

comparison of capital equipment—such as C-arm fluoroscope, navigation system, portable CT scanner, and nasal speculum—were not considered in this analysis as this equipment is used in numerous other clinical settings, and it is difficult to assign specific depreciation costs to the EM/CT-guided TSA application alone. For comparison of fluoroscopy and iCT/EM navigation, dollar amounts in hospital financial records were adjusted to an arbitrary unit—the charge amount for the C-arm fluoroscopy.

All patients in both cohorts underwent identical endonasal, transseptal approaches^{5,32} in which an operating microscope was used, and a fat graft was harvested through a small abdominal incision. In some cases, adjunctive endoscopy was performed after lesion resection. In the fluoroscopy group, the patient's head was placed on a horseshoe headrest, and the fluoroscope was positioned laterally after induction of anesthesia and used intermittently throughout the procedure to identify key points of bony anatomy referable to the sphenoid sinus, clivus, anterior skull base, and sella.^{8,21} In patients in the iCT/EM navigation TSA group, a CereTom (Neurologica, Inc.) portable noncontrast head CT scanner was used in a preoperative room adjacent to the operating room (scan parameters: 140 kVp; 7 MA; 28000 MA; 1.25 × 1.25 [thickness by spacing]; 1900–2000 mGy-cm [dose length product]). The CT scans were then loaded into the AX-LEM Stealth Station navigation system (SNT/Medtronic) while the patient was transferred to the operating room and prepared for general anesthesia. In the majority of cases, the iCT data were fused to preexisting patient MR images obtained at other institutions, which were otherwise incompatible with frameless navigation. After induction of general anesthesia, the patient's head was placed on a horseshoe headrest and positioned in accordance to the surgeon's preference. The navigation device was then registered by attaching a small mobile magnetic reference array approximately 1.5 cm in diameter to the patient's forehead skin using self-adhesive tape, secured by an overlying adhesive plastic bandage (Fig. 1). The magnetic field generator was placed in an articulating arm fixed to the left side rail of the operating table and remained underneath the sterile drapes at a distance of approximately 30–40 cm from the patient's head. A 4-cm EM probe was used to trace the surface features of the face and cranial vault as fiducial points for registration to the iCT/MR imaging data set. Based on prior experience with the surface tracing procedure, we included scalp fiducial points over the vertex and posterior temporal and parietal regions to improve accuracy at the depth of the sella.²³ Standard anatomical landmarks such as the lateral and medial orbital canthi and the nasion were used to confirm initial preoperative accuracy of the registration. Once registration was accomplished, it was possible to move the patient's head or the EM generator at any time during the case without affecting accuracy, as long as the forehead emitter was not displaced.

A sterile 10-cm EM probe was used for intraoperative navigation. A nonferromagnetic (titanium) nasal speculum (Mizuho America) was guided in the proper trajectory using the navigation probe, and 3D navigation was displayed on ceiling-mounted LCDs (liquid crystal displays).



FIG. 1. Setup for EM neuronavigation. An EM localizer is attached to the forehead and an EM generator placed adjacent to the head. Note that the head and generator are not rigidly fixed and can be repositioned after the registration is completed.

In some cases, the navigating probe was attached to either suction or a ring curette to provide continuous navigation during tumor resection, or the probe tip was bent behind the EM-emitting portion (Fig. 2) to enable navigation in a nonlinear trajectory. In the first 50 cases, accuracy was determined by the surgeon using visual comparison of the navigation probe tip location through the microscope to 5 bony anatomical structures: top of sphenoid rostrum, midline floor of sella, midline junction of sella and planum sphenoidale, and carotid protuberances at the mid-sellar level bilaterally (Fig. 3). Dissection to the sella was accomplished primarily with CT navigation images to highlight bony structures, whereas sellar and parasellar navigation during tumor resection was performed using a blended image of CT and MR imaging for soft-tissue and vascular identification (Fig. 3).

Results

Intraoperative CT/MR Imaging EM Navigation Feasibility and Accuracy

Intraoperative registration to the navigation system using iCT images was successful in all 208 cases. Preoperative MR images were fused to iCT scans without affecting navigation accuracy in all cases in which suitable electronic MR imaging data sets were available. In the preoperative holding area, iCT scan acquisition required 7–12 minutes (mean 8.5 minutes). Setup of the AXIEM localizer and forehead emitter required less than 1 minute. Using the surface tracing fiducial protocol, registration of the patient required 3–7 minutes (mean 4.5 minutes). Accuracy to external reference points prior to surgery was excellent in every case. Similarly, accuracy of navigated reference points to visualized intraoperative bony loci was within 1–2 mm for all 50 cases. No ap-

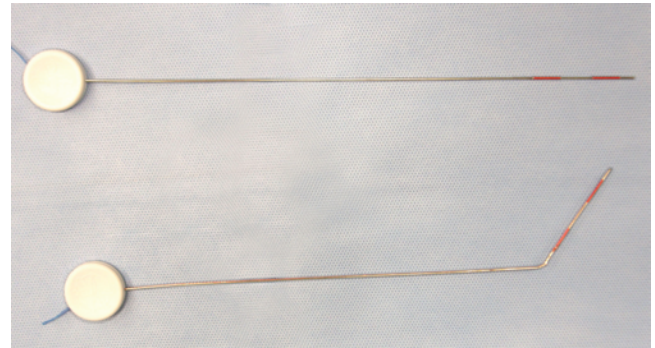


FIG. 2. Electromagnetic navigation probes. Note that the probe can be bent behind the EM transmitters (red) to provide nonlinear navigation.

parent distortion of the EM field by surgical instruments, operating table, or headholder was observed, except for transient disruption of the EM signal during electrocautery. We previously noted that EM signals from the navigation probe could not be obtained within the cylinder of a ferromagnetic nasal speculum—hence, the use of the iMR imaging-compatible titanium speculum in this series. No apparent untoward effect of the EM navigation protocol was noted. No procedural complications related to navigation or anatomical errors occurred.

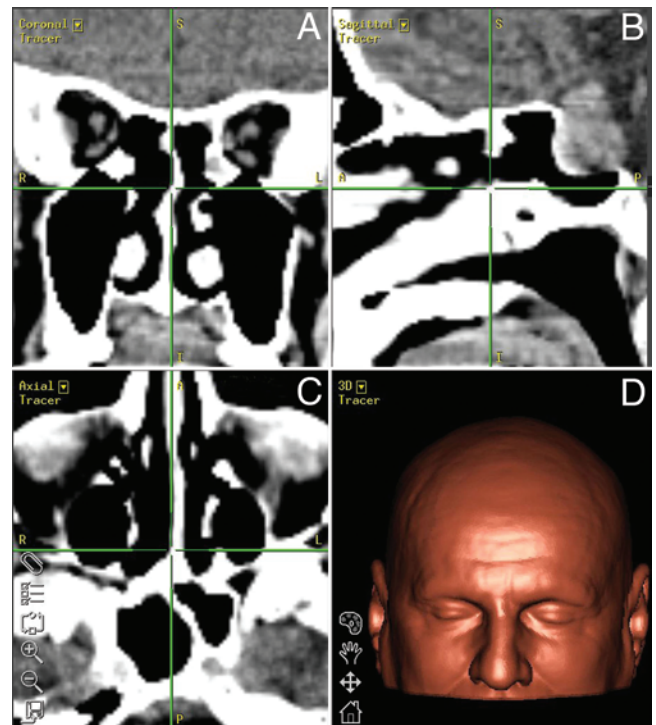


FIG. 3. Intraoperative verification of accuracy. The navigation probe tip is touching the apex of the sphenoid rostrum, which is delineated in axial (C), coronal (A), and sagittal (B) views on the navigation display derived from CT data set. The 3D rendering (D) is used for surface fiducial tracing.

Time and Cost Effectiveness of iCT/MR Imaging EM Navigation

Comparison of total surgical minutes and incision-to-closure time for the 2 patient cohorts are shown in Table 1. In the fluoroscopy group (65 patients), the mean total operating room time was 121.1 ± 30.7 minutes (range 74–225 minutes; median 115 minutes) and the incision-to-closure time was 71.75 ± 19.0 minutes (range 38–138 minutes; median 71.5 minutes). For the iCT/EM group (208 patients), the mean total operating room time was 108.19 ± 24.3 minutes (range 56–242 minutes; median 106 minutes), and incision-to-closure time was 61.1 ± 18.7 minutes (range 23–110 minutes; median 60.5 minutes). Compared with fluoroscopy-guided cases, iCT/EM times were significantly shorter for both total operating room time and incision-to-closure times ($p < 0.001$). Relative cost as reflected by hospital charges and costs for the 2 procedures is also shown in Table 1. Charges for C-arm fluoroscopy and iCT scan were nearly equivalent; disposable navigation equipment added an additional 31% to the iCT/EM costs. However, the reduction in total operating room time costs for iCT/EM offset the additional expense for disposable navigation equipment, such that the overall costs for iCT/EM were 3% less compared with fluoroscopy.

Discussion

Transsphenoidal approaches are safe and effective options for a number of lesions affecting the anterior skull base. Both microscopic^{5,24,28} and endoscopic^{2,10,13,18,24} techniques are applicable, and most lesions can be surgically treated using a minimally invasive endonasal approach. The most essential component of these procedures is the surgeon's accurate comprehension of the 3D relationships of the lesion to critical structures such as carotid arteries, optic apparatus, cavernous sinus, and brain. In this regard, many experienced neurosurgeons do not use any intraoperative guidance, except in complex cases involving extrasellar dissection or reoperation. In 1965 Hardy and Wiger⁸ described the addition of lateral fluoroscopy to TSA, and for the past 40 years most surgeons have used fluoroscopy to augment transsphenoidal navigation. However, lateral fluoroscopy has several limitations: 1) it provides only 2D data (anteroposterior and rostrocaudal), and critical information about midline and right-left lateral relationships is lacking; 2) soft tissue is not delineated, and prior surgery or bony destruction by tumor may limit accurate identification of location; 3) accuracy depends on a "true" lateral projection, and movement of the patient's head requires repositioning of the fluoroscope; and 4) the patient, surgeon, and operating room personnel are exposed to ionizing radiation, necessitating the use of cumbersome lead aprons throughout the procedure.

In 1999 Elias and colleagues⁴ published their experience with frameless CT-guided stereotaxy in which they used preoperatively acquired scans for TSA and showed that the technology could provide continuous 3D information for localization and surgical trajectory with minimal additional cost and time, compared with fluoroscopy. In a

TABLE 1: Comparison of procedure time and costs for iCT/EM navigation compared with C-arm fluoroscopic guidance for TSA*

Factor	C-Arm Fluoroscopic Guidance	iCT/EM Navigation
no. of patients	65	208
mean total OR time (mins)	121.1 ± 30.7	$108.9 \pm 24.3^\dagger$
mean incision-to-closure time (mins)	71.75 ± 19.0	$61.3 \pm 18.2^\dagger$
cost/charges‡		
imaging	1.000	1.053
disposable navigation products	0	0.307
OR	4.971	5.519
total	6.519	6.331

* OR = operating room.

† Significant difference ($p < 0.001$).

‡ Each unit equals the hospital charge amount for 90-minute fluoroscopy.

similar analysis of fluoroscopy-assisted frameless stereotaxy in TSA, real-time navigation was safe, accurate, and associated with shorter operating times and less expense, but it did not allow the surgeon to visualize neurovascular and soft-tissue structures.¹¹

As to the use of neuronavigational systems in TSA, numerous investigators have reported on the utility and accuracy of using MR imaging–based fiducial markers, primarily employing optical navigation systems with preoperative navigation-specific MR images.^{3,19,26} There are several limitations of this approach: 1) although MR imaging–based navigation provides accurate soft-tissue details, it is less precise in delineating and localizing the bony anatomy; 2) obtaining preoperative navigation MR images can be time consuming, expensive, and inconvenient for the patient; and 3) surgical navigation using optical tracking devices may be limited for transsphenoidal procedures due to the close relationship between the microscope and the nose and the diameter of the pointing devices.⁷ Registration involving face and scalp surface tracings as fiducial reference points eliminates the need for adhesive or implanted fiducial markers and speeds the registration process. Registration to face surface only may produce inaccuracies at increasing depths below the surface;²³ therefore, we included surface registration points at the vertex and posterior parietal and temporal regions and did not experience apparent diminished accuracy at the depth of the sella.

Intraoperative MR imaging combined with neuronavigation has been used in transsphenoidal surgery to obtain updated assessment of tumor volume and real-time navigation, using either low field strength^{1,6,16,22,31} or high field strength.^{16,17} Although most authors ascribed value to neuronavigation using updated intraoperative MR images, the use of intraoperative MR imaging prolonged the anesthesia and total operative times.⁶

Neuronavigation systems have also been used with the endoscopic transnasal approach to manage anterior

skull base lesions.^{13,18} The EM/CT approach can be directly adapted to endoscopic transsphenoidal surgery by incorporating the EM probe into the endoscope shaft. In addition, endoscopy-augmented real-time navigation systems allow virtual images of nearby anatomical structures (such as internal carotid arteries, sphenoid sinus, and tumors) to be superimposed to the endoscopic live images^{13,14,27,30} and may be useful in the future as virtual images are incorporated into endoscopic viewpoints.

In our experience, an iCT-based EM navigation is superior to traditional fluoroscopy in providing safe neuronavigation without subjecting the patient and others to additional radiation. The boundaries of the sella and parasellar structures can be delineated more accurately compared with traditional lateral fluoroscopy and to MR imaging-based guiding systems, particularly in cases of reoperation in which there is an absence of anatomical landmarks. Portable iCT scanning within the operating room environment improves the procedural workflow by eliminating the inconvenience of scheduling and obtaining preoperative images, while minimizing additional costs. The ability to fuse preexisting nonnavigation MR images to the iCT data set offers the advantages of high-resolution, accurate soft-tissue neuronavigation. Additionally, removal of the fluoroscopy device from the operating room and eliminating the need for the protective lead apron can make the approach significantly more comfortable for the surgeon and more accessible to the assistant. In our analysis, the time needed for iCT/EM registration and calibration was minimal and comparable to the setup time traditionally spent for fluoroscopy image guidance.

Magnetic tracking systems possess several advantages over the more traditional optical tracking neuronavigation systems.^{9,20} First, magnetic tracking obviates the need for rigid skull fixation. Alternative strategies to avoid rigid fixation include preoperative scanning with an attached fiducial system^{17,20} or using a fiducial systems directly attached to the skull.²⁵ Positioning the head on a horseshoe device is less traumatic to the patient and affords the surgeon the added benefit of increased comfort and better visualization by not having to rely on a fixed angle of approach throughout the procedure. Minor positional readjustments by changing the degrees of flexion or extension of the patient's head or side-to-side tilts can be beneficial in approaching anterior skull base lesions through the nostril. Second, magnet-based devices solve the line-of-sight problem associated with optical systems, wherein there is interruption of the infrared pathways between camera and reference fiducial or probe by the operative microscope, sterile drapes, or a variety of obstacles present in the operating room. This can be especially pronounced during TSA due to the proximity of the operative microscope and surgeon to the head and the operative field. In our experience, distortion by other EM devices in the room or ferromagnetic objects was not apparent. Third, EM tracking enables the combination of the probe with instruments in use (for example, curette, suction, or endoscope) and accurate navigation in a nonlinear trajectory by bending the probe tip to interrogate anatomical points behind other structures or out of direct line-of-sight view. Likely these attributes will be increas-

ingly important as flexible endoscopic devices are developed.

The determination of value for any new technology includes the assessment of the benefits in comparison to costs. For the iCT/EM protocol, preoperative workflow is streamlined by the obviation of additional preoperative MR imaging and fiducial placement, the removal of the C-arm fluoroscope, and a decrease in the procedural time. In our study, the significant decrease in operating room costs was primarily due to a 15% reduction in procedural (incision-to-close) time, which was likely a consequence of continuous neuronavigation that facilitated accurate direction during speculum placement, sphenoidotomy and identification of sella and parasellar structures. Although not analyzed in this study, it is our impression that the extent of bone and mucosa removal was less in iCT/EM cases due to continuous navigation, and that TSA procedures were less invasive as a result. Costs for C-arm fluoroscopy and iCT were comparable. It is notable that the largest overall expense for the procedure was charges for operating room time, such that additional costs of disposable navigation equipment were offset by cost savings derived from an average 10-minute reduction in surgical procedures with iCT/EM.

There are several limitations to this analysis. First, the 2 cohorts were derived from different time periods and potential differences in factors other than navigation may have affected operating room efficiency and costs. Although the comparison was not case matched, the demographics, standardized treatment algorithms, surgical technique, and lesion characteristics were otherwise identical in both groups, with the exception of image guidance. Cost increases between epochs due to inflation were not considered; however, in our analysis the overall costs for the later period (iCT/EM) were lower, suggesting that corrections for inflation would accentuate the cost-savings for iCT/EM. Second, capital expenditures for neuronavigation, the iCT equipment, speculum, and C-arm fluoroscope are not included in the cost analysis. However, these devices are used for a wide variety of other applications at our institution, and it is difficult to ascribe proportional depreciation costs to the TSA application alone. Third, imaging and operating room expenses were based on hospital charge data rather than hospital costs. Hospital costs were not available for these services, which encompass a broad variety of expenses including equipment depreciation, personnel, and supplies. However, because the analysis compared relative charges for the 2 guidance modalities, the ratio of charges should provide a valid comparison of costs. Fourth, accuracy was measured by nonquantitative means, through the comparison of anatomical landmarks by visual inspection to neuronavigation data. The accuracy of the EM neuronavigation system has been previously demonstrated,^{9,20} and the current report confirmed operational accuracy in the setting of the iCT/MR imaging protocol. Finally, the absence of any anatomical surgical errors with iCT/MR imaging EM navigation is not necessarily related to the navigation technique.

Conclusions

The use of an EM iCT/MR imaging-guided neuro-navigation system as part of an operative protocol is time effective and can be efficient, safe, and technically beneficial; the technology is especially beneficial in reoperative cases with distorted anatomical landmarks. The iCT/EM neuronavigation protocol reduced operating room time and incision-to-closure time significantly, in part by improving surgical trajectories and reducing the exposure needed for identification of landmarks. The key to the continuing evolution of the transsphenoidal approaches for anterior skull base lesions will be innovative applications of new and existing technologies to minimize exposures and concurrently eliminate anatomical errors and their serious associated complications. Although not documented in this analysis, an accurate 3D localization will likely reduce morbidity related to injuries to critical parasellar structures. These considerations become more pertinent as the scope of TSA procedures are expanded beyond the sella to include the entire anterior skull base.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: all authors. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: all authors. Critically revising the article: all authors. Reviewed final version of the manuscript and approved it for submission: all authors. Statistical analysis: all authors. Administrative/technical/material support: all authors. Study supervision: all authors.

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