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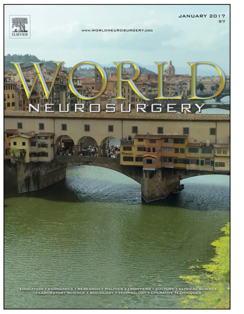

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2D-HD versus 3D endoscopy in endonasal skull base surgery: a comparative pre-clinical study

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Abstract

Background: Three-dimensional (3D) endoscopy has been recently introduced in endonasal skull base surgery. Only a relatively limited number of studies have compared it to two-dimensional, high definition (2D-HD) technology.

Objective: To analyze, in a preclinical setting for endonasal endoscopic surgery, surgical maneuverability comparing 2D-HD and 3D endoscopy.

Methods: A group of 68 volunteers, both novice and experienced surgeons, were asked to perform two tasks, namely simulating grasping and dissection surgical maneuvers, in a model of the nasal cavities. Time to complete the tasks was recorded. A questionnaire to investigate subjective feelings during tasks was filled by each participant. In 25 subjects, the surgeons' movements were continuously tracked by a magnetic based neuronavigator coupled with dedicated software (ApproachViewer – part of GTx-UHN) and the recorded trajectories were analyzed by comparing "jitter", "sum of square differences", and "funnel index".

Results: Total execution time was significantly lower with 3D technology ($p<0.05$) in both beginners and experts. Questionnaires showed that beginners preferred 3D endoscopy more frequently than experts. A minority (14%) of beginners experienced discomfort with 3D endoscopy. Analysis of *jitter* showed a trend towards increased effectiveness of surgical maneuvers with 3D endoscopy. Sum of square differences and funnel index analyses documented better values with 3D endoscopy in experts.

Conclusions: In a pre-clinical setting for endonasal skull base surgery, 3D technology appears to confer an advantage in terms of time of execution and precision of surgical maneuvers.

Running title: 3D vs 2D-HD endoscopy

Keywords: endoscopic surgery; skull base; three-dimensional endoscopy; neuronavigation; preclinical; surgical maneuverability.

Abbreviations: 2D: two-dimensional; 3D: three-dimensional; CT: Computed Tomography; GTx-UHN: Guided-Therapeutics software developed at University Health Network – Toronto, Canada; HD: high definition; SD: standard definition; S.I.M.O.N.T. - SInus Model Othorino-Neuro Trainer.

INTRODUCTION

Three-dimensional (3D) technology has been recently introduced in endoscopic surgery. To date, only a relatively small number of studies have compared two-dimensional, high definition (2D-HD) with 3D technologies in skull base surgery; the majority mostly explored the efficacy of 3D endoscopy in clinical practice[1-14] and cadaveric dissection,[13,15-17] reporting on qualitative and subjective data. Although almost all authors agree on the benefits of 3D technology, the available data are not entirely conclusive: the main limits of descriptive clinical studies and questionnaires are their subjectivity and strong variability of the data collected. A number of confounders, such as experience of the surgical team, uniqueness of the treated lesion, and other uncontrolled biases, may influence the results.[18]

Only a few preclinical studies have performed quantitative, comparative analysis of 3D versus 2D-HD endoscopy in a controlled preclinical setting for endoscopic endonasal[8,11,19-22] and laparoscopic surgery.[23-25] These investigations are characterized by the execution of simulated surgical maneuvers in stylized models of body cavities. Execution time and number of errors were the most frequently analyzed outcomes.

In this study, we performed a preclinical, controlled, quantitative comparison of 2D-HD versus 3D endoscopy for endonasal skull base surgery. In addition to “classic” outcomes, i.e. time to perform the tasks and subjective surgeons’ impressions, we objectively analyzed the trajectories of the instruments, traced by a magnetic neuronavigation system, and introduced new mathematical parameters for their evaluation.

MATERIALS AND METHODS

Subjects

Two groups of subjects were enrolled: experts and non-experts in nasal endoscopic surgery. The expert group included surgeons from the Units of Otorhinolaryngology and Neurosurgery of the University of Brescia who had performed at least 200 endoscopic endonasal procedures. Non-experts were enrolled among medical students and physicians without any experience in endoscopic endonasal, endoscopic ventricular, or laparoscopic surgery.

Phantom and endoscopes

Subjects were asked to perform surgical tasks in a dry anatomical model of the nasal cavities and upper airways (S.I.M.O.N.T. - SInus Model Othorino-Neuro Trainer, ProDelphus®, Olinda, Brasil) (Figure 1). Two different endoscopes were compared: the SD (Standard Definition) 3D endoscope by Visionsense Ltd Petach (Tikva, Israel) and the 2D-HD endoscope by Karl Störz (Tuttlingen, Germany). The 0° optics were fixed using a holder in the upper part of the left nasal cavity throughout the tasks (Figure 1). The field of view was therefore constant for each participant, task, and endoscope.

Tasks

Participants were asked to perform two different tasks (video 1):

- Task 1: simulation of the "grasping" movement. This consisted in grabbing and removing from the nasal fossa, with Weil-Blakesley forceps, three spherical targets positioned in different sites of the nasal cavity: the first in the upper border of nasal choana, the second in the posterior wall of the nasopharynx (midline), and the third in the posterior part of the inferior meatus (Figure 2, A-C);
- Task 2: simulation of the "dissection" movement. This consisted in positioning the tip of an angled Seeker dissector through a metal circle 5 mm in diameter, located on the posterior wall of the nasopharynx and sagittally oriented (Figure 2, D-F). Participants were asked not to touch the border of the circle with the dissector; if touched, a new attempt was allowed until the task was performed correctly.

Both tasks were designed to test depth perception during surgical maneuvers.

Randomization

Experts and non-experts were randomized into two subgroups (Figure 3). Subgroup A used 3D first and then 2D-HD endoscopy; subgroup B performed the tasks with 2D-HD first and then with 3D. Each task was repeated twice in each session. An interval of at least 2 days between the two sessions was set to avoid any possible bias in the second session due to expertise acquired in the first (Figure 3).[20,25]

Outcome measures

The main outcome measured was the time needed to complete each task. All participants also completed a questionnaire to record subjective feelings during the tasks, i.e. preference for 2D or 3D technology, and possible sense of discomfort or dizziness.

In a subpopulation of subjects the Aurora® magnetic navigation system (Northern Digital Inc.) and "*Approach viewer"* software (part of Gtx-UHN) were used to record and trace the trajectories of the instruments used by each participant during the tasks (Figure 4 – video 2). A CT scan of the phantom was performed using a 1x1 frame with contiguous slices, at 0.4 mm. CT was performed at a gantry of 0° with a scan window diameter of 225 mm and a pixel size of more than 0.44 x 0.44. Images were recorded on a CD in DICOM format and imported in the navigation system.

Three mathematical parameters were used to elaborate tracking data: "jitter", "sum of square differences" and "funnel index".

- Jitter

This index derives from the third derivative of the trajectory curve function. The value has a geometric meaning and aims at summarizing uncertainty, tremor, and number of attempts of the subject (the lower the value, the better the performance). It is a well-recognized index for analysis of complex data, such as sound and oscillations.[26,27]

- Sum of square differences

This index was applied only to analyses of task 2, obtained with both 3D and 2D-HD. It represents the distance between the trajectory of the tip of the instrument and the curve that is considered ideal, which is obtained from the average of all the trajectories (the lower the value, the better the performance) (Figure 5, A).

- The funnel index or ideal path

This was applied only to the analyses of task 2. It represents the proportion of a single trajectory that transits in the ideal area that leads to the target. The area has a triangular shape with the apex corresponding to the circumference of the target (the higher the value, the better the performance) (Figure 5, B).

Statistical analyses

The differences between the two groups and demographic features at baseline were tested using Student's t and chi-squared tests for mean and proportion comparisons, respectively. We evaluated the associations of execution time, jitter, sum of square differences, and funnel index with group and endoscopic vision in the total trial, task 1 (only for execution time and jitter), and task 2, and the associations of data improvement between the two repetitions of the task with group and endoscopic vision were assessed using a Student's t-test. At multivariate analyses, we fit linear mixed data with random intercepts for subjects. A log transformed for the indices was considered where appropriate.

For statistical tests, P values <0.05 were considered significant in two-tailed tests. All computations were carried out using the STATA program for personal computers, version 12.0 (STATA Statistics/Data Analysis 12.0 - STATA Corporation, College Station, TX, USA).

RESULTS

A total of 68 subjects were enrolled, including 18 experts and 50 non-experts. All subjects completed the trial. The magnetic tracking system was used by 25 (36.8%) participants (6 [33.3%] experts and by 19 [38%] non-experts).

No expert surgeon experienced physical discomfort using 3D endoscopy, while 7 (14%) non-experts reported it. Beginners preferred 3D endoscopy more frequently than experts (72% and 44.4%, respectively). Half of the experts expressed no preference, while only 18% of beginners preferred 2D-HD endoscopy.

Sensitivity analyses showed no difference between subgroups A and B, confirming that randomization was effective.

All execution times are reported in Table 1. Experts had a lower execution time compared to non-experts in 3D and 2D visions, considering the tasks both together and separately. In the expert group, mean total execution times (task 1 + task 2) were 84.1 and 69.9 seconds in 2D-HD and 3D endoscopy, respectively; instead, non-experts took 114.9 and 110.0 seconds, respectively. The advantage in execution time related to 3D vision was more evident in experts (p= 0.005).

Reduction in execution time between the first and second repetitions are detailed in Table 2. In task 1, the improvement between the two repetitions reached statistical significance in both groups and both endoscopic views ($p < 0.002$). These data were confirmed in multivariate analysis (Table 3).

Values of jitter are reported in Tables 1 and 2.

In multivariate analysis, overall jitter (task 1+ task 2) was significantly lower among experts ($p=0.029$, Table 3), while 3D vision did not give any remarkable advantage over 2D-HD ($p > 0.05$; Tables 1 and 3). There was no difference in jitter between the two repetitions in either univariate (Table 2) or multivariate analyses (Table 3).

Table 4 compares the values of sum of square differences and funnel index according to groups and endoscopic visions. Experts had lower values of sum of square differences and higher of funnel index in 3D endoscopy, while non-experts showed an opposite trend.

A considerable reduction of the sum of square differences between the two repetitions was documented only with 3D endoscopy for both experts and beginners (106.6 vs 66.56, Table 5). The funnel index variation between the two repetitions was not significant for either 3D or 2D-HD endoscopy (Table 5).

DISCUSSION

The aim of this preclinical study was to compare 2D-HD and 3D technology when applied in endonasal endoscopy. We created a controlled set-up in which different variables (e.g. type of task, field of view) were uniform and constant. In particular, an endoscope holder was used to create a constant field of view and avoid possible biases related to endoscope handling.[19] S.I.M.O.N.T faithfully reproduces the anatomy of the nasal cavities and paranasal sinuses, making the results more applicable to clinical practice.[28] Randomization eliminated possible biases due to unbalanced division of participants into groups A and B. The enrollment of both experts and non-experts allowed investigation of the effectiveness of 3D and 2D-HD endoscopy separately in each subgroup. The repetition of each task enabled exploration of possible differences in the learning curve according to the endoscope adopted. Finally, both subjective and objective outcomes were analyzed. In particular, a tracking system was used to study the trajectories of the instruments, and mathematical parameters were applied for the first time to objectively quantify the advantage provided by each endoscopic view. Continuous and highly informative variables allowed for detailed statistical analysis.

A recent systematic literature review by Zaidi *et al*[29] has provided an overview of both clinical and preclinical studies on 3D endoscopy for ventral skull base surgery. Subjective judgments are usually favorable to 3D endoscopy, although dizziness and non-optimal color perception were sometimes reported.[3] In our study, a small proportion of participants (all non-experts) reported some degree of physical discomfort with 3D. The questionnaire also assessed personal preferences: interestingly, beginners chose 3D endoscopy more frequently than experts. This could be interpreted as evidence that 3D endoscopy is more intuitive and easier to get accustomed to, but significant biases (e.g. willingness to accept the newest technology by beginners and difficulty in adapting to a new technology by experts) cannot be excluded.

All currently-available clinical reports are deeply biased by the small number of patients and other uncontrolled factors (i.e., type of disease, type of resection, surgeon's experience, patient's anatomy, etc.).[18] To eliminate this variability, some authors designed preclinical studies in which participants had to perform specific tasks in a controlled setting. [8,11,19,20,22,29] In this study, we designed two tasks with the aim of simulating two different surgical maneuvers (grasping, dissecting) to emphasize the importance of depth perception. In both tasks the perception of the spatial orientation of the instrument was essential, but in the second exercise a more accurate estimation of the depth of the instrument in the surgical field was required (video 1).

Three-dimensional endoscopy was significantly related to a shorter execution time, a finding that is in agreement with previous studies.[8,20,21]

When analyzing the difference between the first and second execution of each task, we documented a learning process, whatever the task (1 and 2) or endoscope adopted (3D and 2D-HD). However, different from other reports,[22] we could not demonstrate any advantage of 3D endoscopy in terms of a steeper learning curve when analyzing execution times.

As expected, the advantage conferred by 3D endoscopy was more evident in task 2 (video 1). In fact, the use of 3D endoscopy lowered the margin of error, as documented by the decrease in execution time. This is in agreement with the lower error rate reported by other authors when 3D endoscopy is used.[11,20,21]

The analysis of instrument trajectories in a preclinical research setting for endonasal surgery was firstly introduced by Inoue et al., who used an optic tracking system to study the length of each route. They demonstrated a shorter trajectory in beginners when 3D endoscopy was used ($p< 0.05$).[8]

In our study, we further developed the analysis of surgeons' movements. The Aurora® system, coupled with dedicated software developed at the University of Toronto (ApproachViewer – part of GTx-UHN), allowed the recording of surgeon's movements in the surgical field. The data were investigated by comparing the mathematical parameters of "jitter", "sum of square differences", and "funnel index".

The total value of jitter was lower in experts when using 3D technology. However, we could not demonstrate any significant advantage conferred by 3D technology *per se*, when compared to 2D-HD.

The sum of square differences and funnel index gave controversial results. Experts showed better values of sum of square differences with 3D technology, while the beginners showed the opposite. Moreover, beginners showed a trend toward a steeper learning curve, even if with worse absolute values. The tendency of funnel index values was similar as for the previous parameter, but no remarkable differences were observed between the two repetitions of the task.

These data can be difficult to interpret. One could think that experts better capitalized on the advantages conferred by 3D technology, which resulted in more effective and direct trajectories of the instruments (lower jitter and sum of square differences, higher funnel index). Conversely, beginners felt more confident with 3D endoscopy, which is corroborated by their subjective preference and better execution time. However, the analysis of their trajectories did not reveal any significant advantage of 3D endoscopy, probably because the uncertainty of the surgical maneuvers due to their inexperience marred the possible benefit of the new technology. We did document a possible advantage in terms of the learning process, albeit not significant, that may possibly due to the relatively small sample size.

To summarize, these preclinical data add evidence to clinical impressions and other preclinical data on the possible advantage of 3D technology in terms of a shorter learning curve and increased surgical efficiency.

Limitations

Some limitations of our study should be expressed. First, 3D endoscopy was not HD, which could have reduced the potential advantage of 3D due to lower image quality compared to 2D-HD. The mathematical parameters we used to analyze surgical trajectories are novel, need further validation, and, possibly, a larger population study. Finally, the low number of experts could lead to a low statistical power and low-precision estimates. However, we selected a ratio of 1:2.7 between "experts" and non-experts to increase the power of statistical tests for group comparisons.

CONCLUSIONS

In a preclinical model of endonasal endoscopic skull base surgery, three-dimensional, standard definition endoscopy offered an advantage in terms of lower execution time both for both experts and beginners compared with 2D-HD technology. A statistically significant, more direct, and efficient trajectory with 3D among experts was also documented. We recorded a trend towards a shorter learning curve only for beginners, who generally preferred 3D technology.

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FIGURE LEGENDS

Figure 1. Laboratory setup. The Phantom S.I.M.O.N.T. (SInus Model Othorino-Neuro Trainer, ProDelphus®, Olinda, Brasil) lies in front of the operator. A 0° endoscope is fixed by a holder in the upper part of the left nasal cavity. In the screen, the field of view (unchanged for every task) is evident.

Figure 2. Tasks. (A-C) Task 1: simulation of "grasping" movement. This consisted in grabbing three spherical targets positioned in different sites of the nasal cavity with Weil-Blakesley forceps: the first in the upper border of nasal choana (A), the second in the posterior wall of the nasopharynx (B), and the third in the posterior part of the inferior meatus (C). Each target had to be carried out in the nasal fossa.
(D-F) Task 2: simulation of the "dissection" movement. This consisted in positioning the tip of an angled Seeker dissector through a metal circle 5 mm in diameter, located on the posterior wall of the nasopharynx and sagittally oriented.

Figure 3. Study flow diagram (see text for further details).

Figure 4. Examples of recorded trajectories. A, correct execution of task 1 is shown; B, a double attempt for completing task 2 can be observed (see also video 2).

Figure 5. A, "sum of square differences" (yellow dotted area). This expresses how much the trajectory of the instrument (blue line) is distant from the ideal one (red line), obtained by the average of all the trajectories. B, " funnel index". This expresses the percentage of trajectory (green area) that runs in the region that is considered ideal to reach the target in task 2 (identified by red dotted lines).

TABLE LEGENDS

Table 1. Execution time and jitter according to groups and endoscopic visions.

NS: not statistically significant; SD: standard deviation.

Table 2. Execution time and jitter in first repetition, second repetition, and difference between repetitions according to groups and endoscopic visions.

*No difference between 1st repetition and 2nd repetition, and between endoscopic vision (2D vs. 3D).

NS: not statistically significant; SD: standard deviation.

Table 3. Multivariate linear mixed models: associations of execution time and jitter with endoscopic vision, groups, and repetition of exercise.

NS: not statistically significant; CI: confidence interval.

Coefficients and confidence intervals were log transformed.

Table 4. Values of sum of square differences and ideal path, according to groups and endoscopic visions.

NS: not statistically significant

Table 5. Sum of square differences and ideal path values, according to task repetition, expertise, and endoscopic vision.

SD: standard deviation.

VIDEO LEGENDS

Video 1. Tasks performed by study participants

00:00-00:18 grasping task

00:19-00:30 dissection task

(see text for further details)

This video shows the two tasks performed in the study. In the first, participants were asked to retrieve, with Weil-Blakesley forceps, three spherical targets positioned at different levels of the simulated nasal cavity.

In the second task, participants were asked to go through a metal circle, located deep in the nasopharynx, with the tip of an angled Seeker dissector without touching the ring.

Video 2. Retrieval of data with magnetic navigation system in ApproachViewer – part of GTx-UHN

00:00-00:17 retrieval and visualization of recorded trajectories from one session

00:18-00:32 visualization of a trajectory recorded for task one (grasping task)

00:19-00:39 visualization of a trajectory recorded for task one (grasping task): an incorrect attempt was recorded before the task was correctly completed

(see text for further details)

This video shows the retrieval and visualization of recorded trajectories in Guided-Therapeutics software developed at University Health Network – Toronto, Canada. Once all recorded trajectories are retrieved, a single one can be visualized. The first was recorded during task one, clearly showing the retrieval of the spheres at different levels, while the last was recorded during task 2, with the participant clearly performing an incorrect attempt before completing the task.

	Execution time (seconds)				Jitter			
	2D Mean (SD)	**3D Mean (SD)**	**P value** *2D vs 3D*	**P value** *Experts vs Beginners*	**2D Mean (SD)**	**3D Mean (SD)**	**P value** *2D vs 3D*	**P value** *Experts vs Beginners*
Total	106.7 (49.4)	99.4 (49.0)	NS		7.48 (3.45)	6.95 (3.85)	NS	
Experts	84.1 (29.4)	69.9 (29.9)	0.005	2D 0.035	6.16 (2.71)	3.95 (0.6)	NS	2D NS
Beginners	114.9 (52.7)	110.0 (50.4)	NS	3D<0.001	7.94 (3.63)	7.95 (3.96)	NS	3D 0.016
Total 1°task	58.4 (33.4)	54.3 (29.2)	NS		4.43 (2.85)	4.34 (2.91)	NS	
Experts	42.9 (17.7)	38.9 (21.0)	0.070	2D 0.023	3.53 (1.99)	2.23 (0.41)	NS	2D NS
Beginners	64.0 (36.0)	59.8 (29.9)	NS	3D 0.003	4.72 (3.08)	5 (3.05)	NS	3D 0.015
Total 2° task	48.3 (20.5)	45.1 (27.7)	0.045		2.86 (1.13)	2.59 (1.3)	NS	
Experts	41.2 (15.7)	31.0 (14.6)	0.002	2D 0.099	2.63 (1.05)	1.72 (0.4)	NS	2D NS
Beginners	50.9 (21.5)	50.2 (29.6)	NS	3D 0.001	2.94 (1.17)	2.88 (1.39)	NS	3D 0.046

Table 1. Execution time and jitter according to groups and endoscopic visions.

NS: not statistically significant; SD: standard deviation.

		Execution time (seconds)					**Jitter**		
		1° repetition Mean (SD)	**2° repetition Mean (SD)**	**Mean difference**	**P value** 1° repetition vs 2° repetition	**P value** *2D vs 3D*	**1° repetition Mean (SD)**	**2° repetition Mean (SD)**	**Mean difference***
1° task	**Total 2D**	34.1 (22.0)	24.4 (13.4)	9.7 (14.6)	<0.001	NS	2.21 (1.45)	2.22 (1.46)	0.01 (0.58)
	Total 3D	30.3 (16.6)	23.9 (14.2)	6.4 (10.3)	<0.001		2.17 (1.57)	1.17 (1.42)	1.00 (0.71)
	Experts 2D	24.6 (10.3)	18.3 (8.5)	6.3 (6.4)	<0.001	NS	1.77 (1.03)	1.75 (1.06)	0.03 (0.66)
	Experts 3D	23.1 (15.4)	15.8 (6.9)	7.3 (11.3)	0.002		1.14 (0.4)	1.08 (0.05)	0.05 (0.40)
	Beginners 2D	37.5 (24.2)	26.5 (14.2)	11.0 (16.5)	<0.001	0.069	2.35 (1.57)	2.37 (1.57)	-0.02 (0.57)
	Beginners 3D	32.9 (16.4)	26.9 (15)	6.0 (10.0)	<0.001		2.49 (1.66)	2.51 (1.48)	-0.01 (0.79)
2° task	**Total 2D**	26.5 (12.5)	21.8 (13.5)	4.7 (16.2)	0.002	NS	1.32 (0.61)	1.54 (0.89)	-0.22 (1.02)
	Total 3D	23.0 (12.1)	22.1 (18.6)	0.9 (14.8)	0.081		1.38 (0.94)	1.21 (0.46)	0.17 (0.70)
	Experts 2D	22.4 (11)	18.7 (9.7)	3.7 (13.5)	NS	NS	1.16 (0.40)	1.47 (0.73)	-0.31 (0.51)
	Experts 3D	16.7 (8)	14.3 (10.0)	2.4 (10.9)	NS		0.87 (0.28)	0.84 (0.15)	0.03 (0.21)
	Beginners 2D	27.9 (12.8)	22.9 (14.6)	5.0 (17.2)	0.003	NS	1.37 (0.67)	1.57 (0.96)	-0.20 (1.16)
	Beginners 3D	25.2 (12.6)	24.9 (20.2)	0.3 (16.1)	NS		1.55 (1.02)	1.32 (0.47)	0.22 (0.81)

Table 2. Execution time and jitter in first repetition, second repetition and difference between repetitions according to groups and endoscopic visions.

*No difference between 1° repetition and 2° repetition, and between endoscopic vision (2D vs 3D).

NS: not statistically significant; SD: standard deviation.

		Total			Task 1			Task 2		
		Coef	**CI95%**	**P value**	**Coef**	**CI95%**	**P value**	**Coef**	**CI95%**	**P value**
Execution time										
Model A	**3D vs 2D**	-0.20	-0.39, -0.01	0.035	-0.15	-0.38, 0.09	NS	-0.3	-0.51, -0.08	0.006
	Non-experts vs Experts	0.44	0.20, 0.67	<0.001	0.43	0.16, 0.71	0.002	0.45	0.20, 0.70	<0.001
	Interaction 2D non-experts vs 2D experts	-0.17	-0.39, 0.05	NS	-0.1	-0.37, 0.17	NS	-0.24	-0.49, 0.01	0.055
Jitter										
Model B	**3D vs 2D**	-0.36	-90, 0.18	NS	-0.33	-0.99,0.35	NS	-0.36	-0.83, 0.11	NS
	Non-experts vs Experts	0.58	0.14, 1.02	0.01	0.35	0.12,1.19	0.016	0.43	0.04, 0.82	0.029
	Interaction 2D non-experts vs 2D experts	-0.35	-0.98, 0.27	NS	-0.44	-1.20,0.31	NS	-0.32	-0.87,0.22	NS
Execution time										
Model C	**3D vs 2D**				-0.07	-0.14, 0.01	0.091	-0.1	-0.20, -0.01	0.037
	Non-experts vs Experts				0.39	0.15, 0.62	0.001	0.33	0.11, 0.55	0.003
	2° repetition vs 1° repetition				-0.27	-0.35, -0.19	<0.001	-0.17	-0.26, -0.07	0.001
Jitter										
Model D	**3D vs 2D**				0.02	-0.23,0.26	NS	-0.08	-0.26,0.09	NS
	Non-experts vs Experts				0.42	0.14,0.70	0.004	0.24	0.00,0.48	0.050
	2° repetition vs 1° repetition				0.01	-0.23,0.26	NS	0.04	-0.13,0.21	NS

Table 3. Multivariate linear mixed models: associations of execution time and jitter with endoscopic vision, groups and repetition of exercise.

NS: not statistically significant; CI: confidence interval.

Coefficients and confidence intervals were log transformed.

	Sum of square differences			Funnel index		
	2D Mean (SD)	**3D** Mean (SD)	**P value** *2D vs 3D*	**2D** Mean (SD)	**3D** Mean (SD)	**P value** *2D vs 3D*
Total 2° task	106.42 (92.2)	169.17 (189.67)	< 0.05	1.20 (0.40)	1.31 (0.59)	NS
Experts	239.63 (116.41)	42.26 (24.35)	< 0.05	0.91 (0.28)	1.87 (0.1)	< 0.05
Beginners	70.09 (39.57)	232.63 (205.3)	< 0.05	1.28 (0.4)	1.03 (0.54)	NS

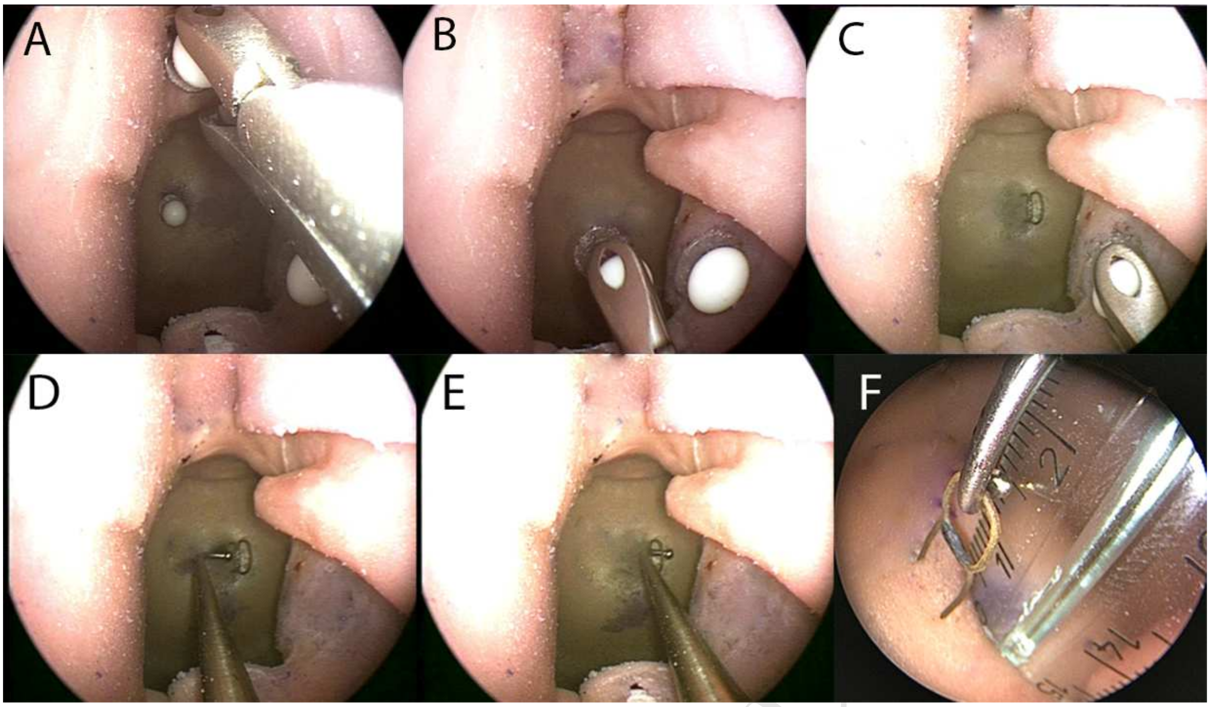
Table 4. Values of sum of square differences and ideal path, according to groups and endoscopic visions

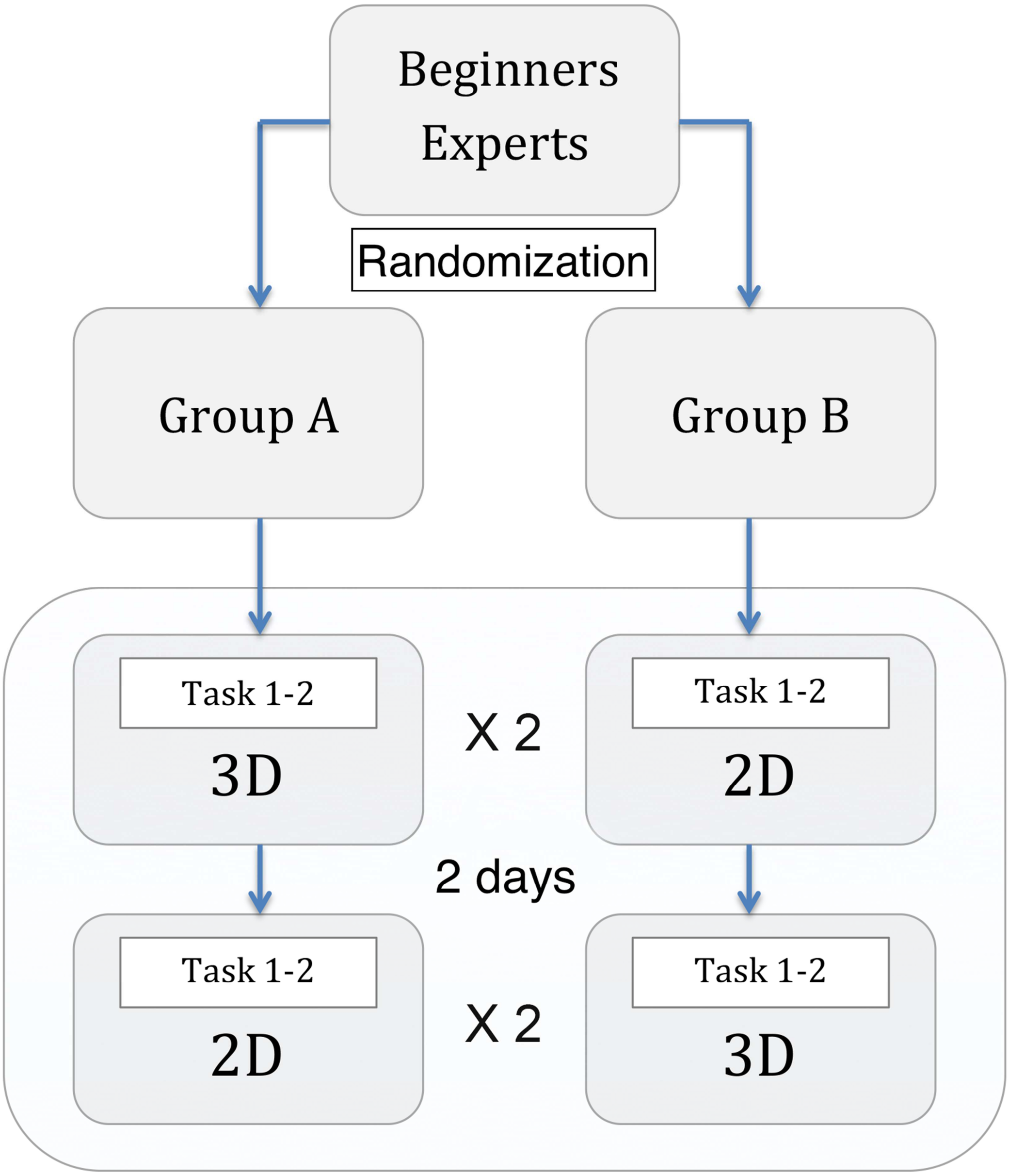
NS: not statistically significant

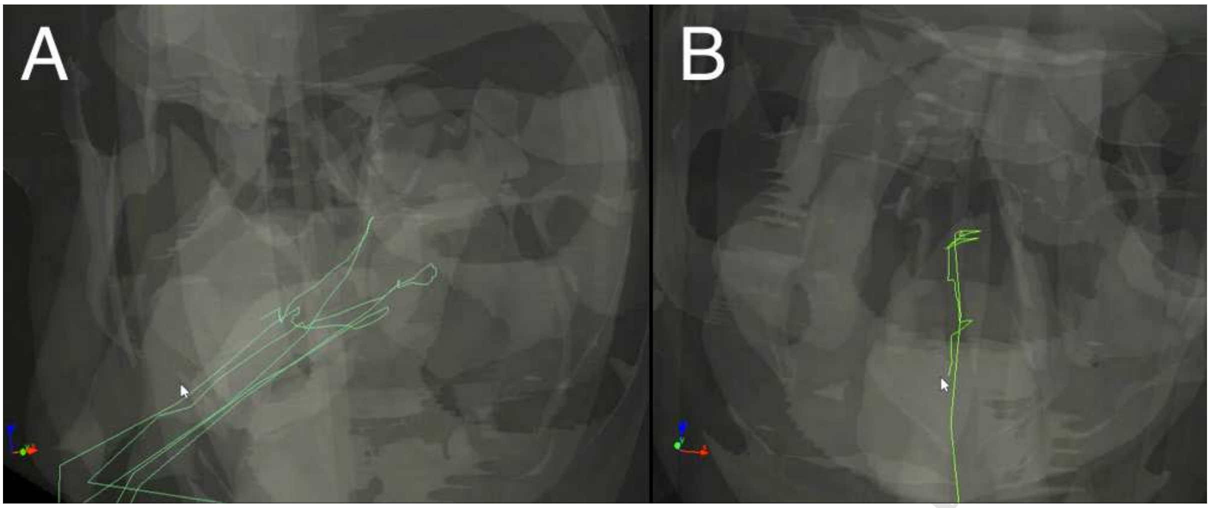
	Sum of square differences			Ideal path	
		1° repetition Mean (SD)	**2° repetition Mean (SD)**	**1° repetition Mean (SD)**	**2° repetition Mean (SD)**
2° task	**Total 2D**	44.04 (53.34)	62.57 (65.41)	0.66 (0.23)	0.51 (0.23)
	Total 3D	106.6 (136.1)	66.56 (80.1)	0.62 (0.33)	0.65 (0.31)
	Experts 2D	81.91 (87.24)	116.99 (72.4)	0.64 (0.26)	0.31 (0.04)
	Experts 3D	20.75 (11.59)	21.51 (18.26)	0.93 (0.06)	0.94 (0.06)
	Beginners 2D	30.52 (29.14)	50.01 (59.69)	0.66 (0.23)	0.56 (0.23)
	Beginners 3D	146.2 (149.5)	26.9 (15)	0.49 (0.31)	0.53 (0.29)

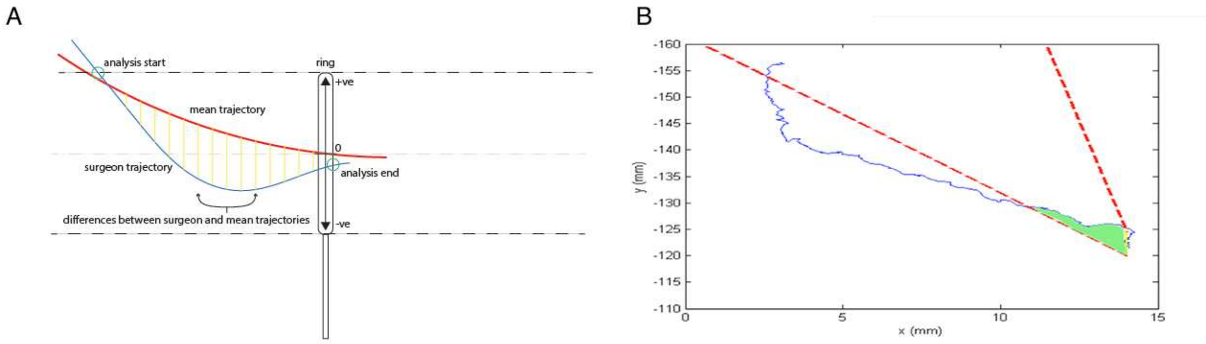
Table 5. Sum of square differences and ideal path values, according to task repetition, expertize and endoscopic vision.

SD: standard deviation.


A
B
C
D
E
F


Beginners
Experts
Randomization
Group A
Group B
Task 1-2
3D
X 2
Task 1-2
2D
2 days
Task 1-2
2D
X 2
Task 1-2
3D


A
B


A
analysis start
ring
+ve
mean trajectory
0
surgeon trajectory
analysis end
differences between surgeon and mean trajectories
-ve
B
-160
-155
-150
-145
-140
-135
-130
-125
-120
-115
-110
y (mm)
0
5
10
15
x (mm)

Highlights

- A novel, navigation based method to quantify surgical maneuverability was applied to the comparative analysis of 3D and 2D-HD endoscopy in a preclinical model for endonasal endoscopic skull base surgery
- Total execution time was significantly lower with 3D technology ($p<0.05$), in both beginners and experts.
- Analysis of *jitter* showed a trend towards increased effectiveness of surgical maneuvers with 3D endoscopy. *Sum of square differences* and *funnel index* analyses documented better values with 3D endoscopy in experts.
- The study confirms some previous papers, reporting a gain in precision and efficacy with 3D endoscopy in experts, and introduces novel mathematical analyses for surgical maneuverability

Abbreviations: 2D: two-dimensional; 3D: three-dimensional; CT: Computed Tomography; HD: high definition; SD: standard definition; S.I.M.O.N.T. - SInus Model Othorino-Neuro Trainer.