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INTRODUCTION

The introduction of endoscopy transformed visualization of the surgical field, allowing minimally invasive surgery for previously major open procedures. Decreased post-operative morbidity and shorter recovery periods were seen thereafter. A major disadvantage of endoscopy is the loss of binocular vision, limiting depth perception and consequently the accurate recognition and management of relevant structures. Experienced surgeons combat the lack of depth perception using visual feedback, haptic feedback, and detailed knowledge of anatomy, though these methods have been shown to be misleading. Three-dimensional (3D) endoscopy has been introduced to endonasal sinus surgery (ESS) to provide real-time depth perception that could, in theory, improve surgical efficacy and thus patient outcomes. This article will evaluate 3D endoscopy in a controlled preclinical setting, objectively and subjectively comparing it to two-dimensional (2D) endoscopy. A recent article concluded that complication rates in endonasal sinus surgery have not changed since the late 1990s. We believe that 3D endoscopy has the potential to demonstrate a long-overdue improvement.

Phillip Bozzini invented the endoscope in 1806. It consisted of an eyepiece and container using a candle for light, and was used as a cystoscope. The endoscope was technically limited until Karl Storz compounded the Hopkins rod and Hirschowitz’s fiberoptics to produce the modern rigid endoscope in the 1960s. The landmark 1997 article from Jho et al. introduced endoscopic transsphenoidal pituitary surgery. More recent meta-analyses have found higher rates of total gross removal and remission for functioning pituitary tumors when using an endoscopic approach. The endoscopic approach to the pituitary is less invasive, reduces postoperative pain, and often negates the need for nasal packing. However, a difficult transition from microscopic to endoscopic approaches is widely reported in the literature, largely due to ergonomic shortcomings, training issues, and the loss of 3D visualization.

Depth perception is allowed by the interpretation of intuitive clues, and by stereopsis. Stereopsis describes the perception of depth produced by the reception of visual stimuli from both eyes in combination. 3D endoscopy has been introduced into ear, nose, and throat (ENT) surgery with the purpose of allowing stereopsis where traditional 2D endoscopes do not. Stereoscopic vision permits better visualization of curvature and texture of surfaces, which is especially important for skull base surgeons who depend on the subtleties of the ventral skull base for safe entry into the cranial vault. Images produced by the 3D system closely mimic the real world, resulting in an improved visuospatial orientation and theoretically improving surgical outcomes.

The endoscope used in this study incorporates dual chip-on-the-tip technology in which two video chips create...
two digital images that are projected onto a screen. Polarizing glasses are worn to project a different image to each eye. Current polarizing displays are relatively cheap, but the use of polarizing screens and glasses can be challenging for some surgeons, contributing to vertigo. Some displays have filtered almost 75% of light output by the time it reaches the eye, and so a dark background environment is required. These are the major ergonomic shortcomings of 3D endoscopic technology. It is likely that technological improvements will circumvent these issues in future designs.

Numerous studies evaluating the use of 3D technology in an ENT setting have suggested that it shortens the learning curve for novice surgeons, and others advocate its use in surgical training. In their landmark article, the Southern Surgeons Club group found that 90% of endoscopic surgical complications occurred in the first 30 patients of the learning curve, with the initial risk being tenfold of that after 50 operations. If 3D endoscopy can shorten the learning curve, it will follow that patient outcomes will be improved.

A recent systematic review failed to find evidence of clinical superiority of 3D endoscopy over 2D in terms of resection rates, pituitary gland preservation, and complications, although all included studies reported a subjectively improved depth perception with 3D endoscopy. Four articles found that 3D endoscopy is useful for novices, reducing their learning curve for endoscopy skills. Shah et al. found that a group of experienced surgeons disliked the initial learning curve when using 3D technology, which could explain why clinical trials with experienced surgeons are yet to demonstrate objective superiority of the 3D endoscope.

This study will evaluate the growing body of evidence advocating a reduced learning curve and increased performance in novices using 3D endoscopy. It will utilize the Karl Storz (Karl Storz GmbH & Co., Tuttingen, Germany) 3D high-definition (HD) endoscope that has not been used in previous studies. The current body of evidence on novices using 3D HD endoscopy in simulated surgical environments consists of an aggregate of just 39 subjects. This study has the statistical power to demonstrate the hypothesized superiority of 3D HD endoscopy over 2D HD in novices.

MATERIALS AND METHODS

This is a prospective, randomized crossover study. Participants were consented and randomized to two groups, 2D first (group A) and 3D first (group B), which determined the mode of visualization (2D or 3D) they used first. Each participant was required to carry out two standardized tasks in a laparoscopic box trainer. They then used the other endoscope setting to carry out the same tasks. Randomization was used to minimize carry-over bias or order bias. Participants were then asked to fill out a subjective questionnaire on baseline characteristics, endoscope preference, and depth perception (Fig. 1).

Sample

Participants were medical students from the University of Birmingham with little or no prior experience in endoscopy.

Outcomes

Time taken to complete tasks was recorded, including adjustment time (the time taken to pick up the first bead). Errors made during completion of the tasks were also recorded. Errors
RESULTS

A total of 93 participants took part in the study. Median age was 20 years, and the median year of medical study was the second. Previous experience of endoscopy was minimal; six participants had assisted in one endoscopic procedure (all described their role as holding the endoscope in position for the surgeon), and none had assisted in more than one. Only one participant was excluded because they shut one eye when using the 3D endoscope as they found it easier; unfortunately, doing this made the mode of visualization 2D rather than 3D.

Equal randomization between groups A and B allowed carryover bias to be neutralized, thus permitting direct comparison of 2D and 3D. Wilcoxon tests showed that attempts with 3D were significantly faster overall than 2D (median 78 vs. 94.5 seconds, \( P = .004 \)). Large individual variation was observed with both settings (Fig. 4). No significant difference was observed between 2D and 3D in adjustment time (\( P = .121 \)). Total errors made during task completion were significantly reduced when using 3D (3 vs. 5, \( P < .001 \)); these included errors of accuracy (1 vs. 2, \( P < .001 \)) and dexterity (2 vs. 3; \( P < .001 \)). Further comparisons between the objective outcome measurements for the two endoscopes can be seen in Table I. Subjectively, 68.5% (\( n = 63 \)) of participants preferred the 3D endoscope. Depth perception was found to be better with the 3D setting, with participants rating it median 7/10 compared to 4/10 for 2D (\( P < .001 \)).

Subgroup analysis was then carried out, comparing scores for those who used 2D first with those who used 3D first. Using a repeated task paradigm allowed us to assess the factor of learning in relation to the method of visualization.

Our results demonstrated a significant carryover of skills from the first task to the second; Mann-Whitney tests showed that participants were significantly faster using either 2D visualization (\( P = .001 \)) or 3D visualization second (\( P = .006 \)), so participants were faster on their second attempt regardless of the endoscope they used. This demonstrates a learning effect, confirming a carryover bias in our study. Interestingly, the median number of errors made was not affected by the order of sequence, and participants using 3D endoscopy made significantly fewer errors than 2D regardless of whether they had already completed the task.

The magnitude of difference between 2D and 3D attempts was much greater in the 2D-first subgroup (34 vs. 11, \( P < .001 \)), and these participants showed the lowest scores of any group on their second attempt using 3D. In other words, participants improved to a greater extent when using 3D visualization on their second attempt. Once familiar with the task, participants were more competent using 3D than 2D (70 vs. 74.5), although this difference was not statistically significant. In light of these results, we can conclude that 3D visualization aids in shortening the learning curve of novices.

The Fisher exact test demonstrated that endoscope preference was significantly affected by the order of endoscope used (Fig. 5), with 82.6% of those who used 2D first preferring 3D, and 54.3% of those who used 3D first preferring 3D (\( P = .007 \)).

DISCUSSION

We evaluated the novice use of a 3D HD endoscope in a controlled preclinical environment, comparing it to 2D HD visualization. We found that participants mostly preferred the 3D HD endoscope, performing tasks significantly faster and making significantly fewer errors than when using 2D HD. This confirmed the hypothesized superiority of 3D technology in our novice sample.

Similar results of a reduced time taken have been shown in previous preclinical studies using 3D endoscopy,\(^{21,29,30,38}\) but none to this level of significance. Our finding of a reduced error rate is also in agreement with preceding studies.\(^{21,28,30}\) The clinical benefits of a reduced error rate are clear. Furthermore, our results reinforce those found in many laparoscopic studies on 3D endoscopy.\(^{39}\) It is important to consider that lower error rates during 3D attempts may have played a large part in the reduction in time taken with 3D. If a participant made an error, they generally had to go back and correct it, so it is unsurprising they both showed the same trend.

The evidence of improvement with 3D technology can be attributed solely to the form of visualization; differences between endoscope maneuverability, field of...
view, and image resolution were all negated by using the same endoscope with 2D or 3D settings.

On the Likert scale responses, we found that depth perception was significantly higher with 3D than with 2D. This provides a simple explanation for our results; with better depth perception, participants are likely to be more accurate and confident completing tasks, resulting in faster completion times alongside lower error rates. Depth perception in turn improves spatial awareness, which is an important cognitive factor for coordinating movements in a given environment. Egi et al. found that those with a low space perception ability performed endoscopic tasks better with 3D visualization than with 2D ($P = .0085$). Studies have identified other relevant cognitive factors that may be important in 3D endoscopy; one ENT article and several laparoscopic articles have found that 3D endoscopy reduced task workload, a measure of cognitive processing required.

Medical students are similar in terms of experience to those who will be training in endoscopy for the first time; both groups are novices. On this basis, we recommend the use of 3D technology for surgical training. The use of a single port and limitation of task distances to between 30 and 50 mm ensured this study is relevant to working distances in ESS. The tasks themselves are based on validated endoscopic training tasks. The outcomes of time taken and error rates are highly relevant. When applied to surgery, the incremental effects of decreased time taken to complete tasks would result in quicker and more efficient operating times. There is evidence for 3D allowing a 30-minute reduction in pituitary adenoma resection operating time. A shorter operative time leads to a lower risk of postoperative complications in both general and endoscopic surgery. Furthermore, in our current rationalized healthcare systems, where theater time is at such a premium, any reduction in operative time improves theater productivity and may offset some of the initial higher purchase costs of 3D technology, which is around £20,000 ($25,000) more expensive than 2D.
A number of ergonomic shortcomings, particularly reports of vertigo, have been cited as disadvantages of the 3D technology.\textsuperscript{20,22} With newer technology, reports of vertigo have dwindled.\textsuperscript{8} In our study, some participants reported feeling uncomfortable while adjusting to the 3D effect, but none reported a continuation of these feelings once they had adjusted. It is possible that our tasks were too short for participants to develop the feelings of vertigo that have previously been reported in clinical studies.

Our results suggest that 3D technology is more intuitive, and that it reduces the learning curve associated with endoscopic skills. This is in concordance with other papers.\textsuperscript{20,22,23,46} Although our tasks were simple and quickly mastered, and thus not ideal for measuring a learning curve,\textsuperscript{47} our study certainly provides grounds for further clinical research.

### Limitations

Analysis demonstrated the presence of carryover bias that arose from one technology being used before the other. These biases were partly accounted for by randomizing subjects into the two groups, allowing direct comparison of 2D versus 3D. Randomization eliminated the possibility of allocation bias. Using only one analyst represents another important limitation in our study. Our low exclusion rate would normally be considered a weakness, but the collective lack of endoscopic experience among medical students meant that we acquired a relatively homogenous sample.

### Further Research

Larger prospective randomized studies are required to determine whether the efficacy of 3D endoscopy extends to real-world objective outcomes in endonasal surgery. Given the current evidence, these should be multicenter studies to provide the number of patients and experienced surgeons required to demonstrate significance. More rigorous research should be done assessing the performance of experienced surgeons using 3D versus 2D endoscopy. It would also be worthwhile comparing the

\begin{table}[h]
\centering
\caption{Direct Comparison 2D Versus 3D Using Wilcoxon Tests.}
\begin{tabular}{lccc}
\hline
Variable & 2D & 3D & Difference & \(P\) Value \\
\hline
Adjustment time, sec & 7 (4 to 11) & 5 (3 to 8) & \(-1\) (\(-6\) to 2) & .121 \\
Task 1 time, sec & 43.5 (29 to 57.75) & 36.5 (25.25 to 46) & \(-6\) (\(-24.75\) to 9.25) & \(0.20\) \\
Task 2 time, sec & 39 (25.25 to 56.75) & 32 (25.25 to 45) & \(-4.5\) (\(-20\) to 8.75) & \(0.038\) \\
Total time, sec & 94.5 (68.25 to 122) & 78 (62 to 102.75) & \(-13.5\) (\(-41\) to 14) & \(0.004\) \\
No. of drops & 3 (1.25 to 4) & 2 (1 to 3) & \(-1\) (\(-2\) to 1) & <.001 \\
No. of inaccuracy errors & 2 (2 to 3) & 1 (1 to 2) & \(-1\) (\(-2\) to 0) & <.001 \\
Total no. of errors & 5 (3.25 to 6) & 3 (2 to 4) & \(-2\) (\(-3\) to 0) & <.001 \\
\hline
\end{tabular}
\footnotesize{Data are presented as median (interquartile range). 2D = two dimensional; 3D = three dimensional.}
\end{table}
learning curve among trainee surgeons using 3D endoscopy with those using 2D.

CONCLUSION

As the breadth of endoscopic procedures in endoscopic sinus and skull base surgery grows more expansive, so does the need for more advanced technology. We have demonstrated the efficacy of a new 3D HD endoscope when used by novices to complete simulated surgical tasks. In our sample, it was superior to 2D HD endoscopy in terms of time taken, errors made and the learning curve. This study provides the grounds for further evaluation in a clinical setting. We have shown that 3D endoscopy could be instrumental in training the next generation of surgeons.

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