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DYNAMIC MANUSCRIPT

Augmented reality in gynecologic surgery: evaluation of potential benefits for myomectomy in an experimental uterine model

Nicolas Bourdel[1,2] · Toby Collins[2] · Daniel Pizarro[2] · Adrien Bartoli[2] · David Da Ines[2,3] · Bruno Perreira[4] · Michel Canis[1,2]

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Abstract

Background Augmented Reality (AR) is a technology that can allow a surgeon to see subsurface structures. This works by overlaying information from another modality, such as MRI and fusing it in real time with the endoscopic images. AR has never been developed for a very mobile organ like the uterus and has never been performed for gynecology. Myomas are not always easy to localize in laparoscopic surgery when they do not significantly change the surface of the uterus, or are at multiple locations.

Objective To study the accuracy of myoma localization using a new AR system compared to MRI-only localization.

Methods Ten residents were asked to localize six myomas (on a uterine model into a laparoscopic box) when either using AR or in conditions that simulate a standard method (only the MRI was available). Myomas were randomly divided in two groups: the *control group* (MRI only, AR not activated) and the *AR group* (AR activated). Software was used to automatically measure the distance between the point of contact on the uterine surface and the myoma. We compared these distances to the true shortest distance to obtain accuracy measures. The time taken to perform the task was measured, and an assessment of the complexity was performed.

Results The mean accuracy in the control group was 16.80 mm [0.1–52.2] versus 0.64 mm [0.01–4.71] with AR. In the control group, the mean time to perform the task was 18.68 [6.4–47.1] s compared to 19.6 [3.9–77.5] s with AR. The mean score of difficulty (evaluated for each myoma) was 2.36 [1–4] versus 0.87 [0–4], respectively, for the control and the AR group.

Discussion We developed an AR system for a very mobile organ. This is the first user study to quantitatively evaluate an AR system for improving a surgical task. In our model, AR improves localization accuracy.

Keywords Gynecologic surgery · Laparoscopy · Augmented Reality · Myomectomy · MRI

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✉ Nicolas Bourdel
nicolas.bourdel@gmail.com

1 Department of Gynecological Surgery, CHU Clermont Ferrand, 1 Place Lucie Aubrac, 63000 Clermont-Ferrand, France

2 Faculté de Médecine, ALCoV-ISIT (UMR6284 CNRS / Université d'Auvergne), 28 Place Henri Dunant, 63000 Clermont-Ferrand, France

3 Department of Radiology, CHU Clermont Ferrand, 1 Place Lucie Aubrac, Clermont-Ferrand, France

4 Biostatistics Unit, Department of Clinical Research and Innovation, CHU Clermont Ferrand, 63000 Clermont-Ferrand, France

Uterine incision is the starting point to gain access to interstitial myomas in laparoscopic surgery. Optimization of this incision is crucial to facilitate the best access to the myoma. This means determining the correct incision length, orientation and position, and also to decrease the number of incisions required for access. Number and size of incisions, suturing and number of knots were found to influence de novo adhesion formation in a randomized double-blind study assessing the use of 4 % icodextrin solution and reported by Trew et al. [1]. However, myomas are not always easy to correctly localize when they do not significantly change the surface of the uterus, or are in multiple locations [2]. MRI (magnetic resonance imaging) provides a good cartography of myomas; however, using it for intra-operative navigation remains challenging. Augmented Reality (AR) is a technology that can allow a surgeon to see subsurface structures in an endoscopic video [3–5]. This works by overlaying information from another modality, such as MRI and fusing it in real time with the endoscopic images [3–7]. AR systems have been successfully developed to assist surgical procedures including adrenalectomy [3], prostatectomy [7], liver resection [4, 8] and neurosurgery [9]. However, AR has never been attempted on a very mobile organ like the uterus and has never been developed for gynecology. As the first AR system for uterine surgery, we targeted assisted laparoscopic myomectomy. Our objective was to test our system for its potential benefit for myomectomy by answering the question: Can we localize small sized intramural myomas more accurately using an Augmented Reality (AR) system?

Materials and methods

AR software (supplemental material: video 1): We have developed an intra-operative myoma visualization system based on AR [10]. Two phases are necessary: the segmentation phase and the fusion phase. In the segmentation phase, the outer surface of the uterus and myomas are delimited (segmented) in the preoperative MRI by the radiologist and a 3D mesh model is constructed (Fig. 1). This 3D model is then automatically positioned (or "aligned") and fused with the laparoscopic image of the uterus in real time (real-time fusion phase) [10] (Fig. 1, supplemental material: video 1). The fusion gives the impression that the uterus is semitransparent and the surgeon can see the exact location of the myoma inside it. The fusion stage is fully automatic. *In vivo* accuracy results were reported showing that the system could correctly align the uterus to within ± 1 mm despite the movement of the uterus. The system was shown to be robust to other challenges including occlusion with surgical tools, rapid camera motion and motion blur. Our algorithms run on a standard PC with a GPU equipped graphics card [10].

Synthetic uterus model We used a synthetic 3D printed uterus model with the typical shape of the uterus during laparoscopy, after insertion of a uterine manipulator. We applied a realistic texture to the model by texture mapping it with five images of a real uterus. The model was printed in color with a Z-Corp multicolor 3D printer (3D Systems Rock Hill, USA). The synthetic uterus was inserted into a pelvic trainer box; a laparoscope (Karl Stortz 10-mm HD laparoscope) was inserted through one trocar and a laparoscopic pointing instrument through a second trocar (Fig. 3).

Myomas We simulated six synthetic myomas (Fig. 2). These were modeled as 20-mm spheres and positioned within the uterine wall. The distance of the myomas to the outer surface of the uterus varied between 3 and 30 mm. For each myoma, a synthetic MRI was created (sagittal, axial and coronal slices, supplemental material Fig. 1). The synthetic MRI has the ability to recreate the different slices available in clinical practice.

Measures The objective was to evaluate how accurately surgeons could localize the myomas when either using the AR system or in conditions that simulate the gold standard method (where only the MRI was available for the surgeon). Ten residents trained in laparoscopy and in interpreting MRI were asked to perform a measurable task: to touch with the laparoscopic pointing instrument where on the uterine model surface (point of contact) that they believed was the closest point to the myoma (Fig. 3). Each resident performed the task six times (one time for each myoma). For three of the myomas, AR was activated, and for the other three AR was deactivated. This was done by dividing the six myomas into two sets of size three [set 1 (myomas 1, 4 and 6) and set 2 (myomas 2, 3 and 5)]. The use of AR for set 1 or 2 was randomly determined for each resident. We refer to the "control group" as the all the tasks performed without the AR system (30 myomas: three

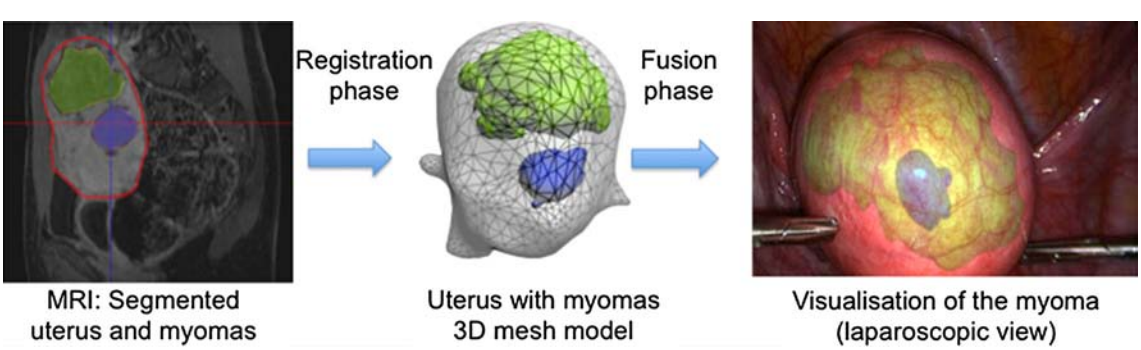

Fig. 1 Overview of AR system for visualizing the locations of myomas in laparoscopic video of the uterus

Fig. 2 Six virtual myomas positioned within the uterus body. Each myoma was tested separately

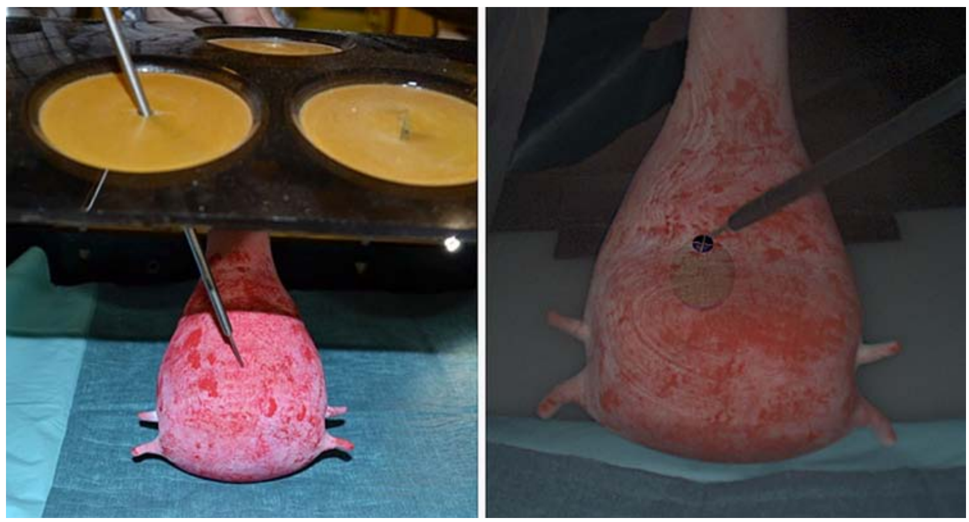

Fig. 3 On the *left*: external view of the pelvic trainer with the pointing instrument used to assess task 1. On the *right*: laparoscopic images of uterus model with rendered virtual myomas with the pointing instrument

myomas per resident, ten residents) and the "AR group" as the all the tasks performed with the AR system activated. In total, 60 myomas were tested (30 samples for control and 30 samples for AR). The AR software was used to automatically measure the distance d in mm between the point of contact on the uterine surface and the myoma. We denote d_1 in mm to be a sample distance for the control group and d_2 in mm to be a sample distance for the AR group. We compared these distances to the true shortest distance (d_0 in mm) to obtain accuracy measures $|d_1 - d_0|$ and $|d_2 - d_0|$. $|d_{(1 \text{ or } 2)} - d_0|$ was measured for each myoma (if this distance was zero, it meant the surgeon touched the surface at the closest point to the myoma). The time between the insertion of the pointer and the localization of the closest point was also measured for all the myomas. The surgeon was then asked to evaluate the difficulty of the task using a Likert scale [task complexity: How complex was the procedure? very easy, easy, moderately difficult, difficult, very difficult corresponding, respectively, to scores of difficulty: 0, 1, 2, 3 and 4, corresponding to one of the items (simplified) described in the Surgical Task Load Index (SURG-TLX)] [11].

Statistical analysis: Statistical analysis was performed using Stata software, version 13 (StataCorp, College Station, TX, U.S.). The tests were two-sided, with a type I error set at $\alpha = 0.05$. Random effects models were used to compare accuracy, time of the localization and surgeon's appreciation between control and AR groups. These models allow to study fixed effects as group (control or AR) taking into account between and within surgeon variability (random effects) due to repeated correlated data for a same surgeon. The normality of residual was studied for each model, by the Shapiro–Wilk test.

Results: (Table 1)

Accuracy and time of the localization The mean accuracy in the control group ($|d_2 - d_0|$) was 16.80 mm [0.1–52.2]. In the AR group, the mean accuracy ($|d_1 - d_0|$) was 0.64 mm [0.01–4.71] with $p < 0.001$ between the two groups (Table 1). Intra-class correlation coefficient (ICC) according to surgeon was 9 % (low ICC, which means no dependence in between every single task of one surgeon).

Table 1 Results of accuracy, time and difficulty, all data are expressed as mean ± SE

	Mean accuracy		Mean time		Mean difficulty	
	AR	Control	AR	Control	AR	Control
R01	0.47 ± 0.6	11.6 ± 15.4	18.16 ± 10.3	12.0 ± 3.3	1.00 ± 0.0	2.33 ± 0.6
R02	1.87 ± 3.0	23.9 ± 7.4	6.44 ± 2.5	10.3 ± 3.7	1.33 ± 0.6	2.33 ± 0.6
R03	0.07 ± 0.1	27.3 ± 17.1	23.53 ± 8.1	32.1 ± 16.7	0.33 ± 0.6	2.67 ± 0.6
R04	0.38 ± 0.2	5.2 ± 4.8	39.60 ± 32.9	23.1 ± 6.0	1.33 ± 0.6	1.33 ± 0.6
R05	0.32 ± 0.3	21.7 ± 12.1	14.09 ± 6.8	22.5 ± 10.8	1.00 ± 0.0	2.67 ± 0.6
R06	0.64 ± 1.1	14.4 ± 11.5	14.55 ± 2.6	16.9 ± 7.0	0.33 ± 0.6	2.33 ± 0.6
R07	1.68 ± 2.6	29.5 ± 13.8	21.93 ± 5.2	18.9 ± 7.9	1.67 ± 1.2	2.00 ± 0.0
R08	0.23 ± 0.1	0.9 ± 1.3	17.27 ± 3.0	34.6 ± 7.8	0.00 ± 0.0	3.00 ± 0.0
R09	0.08 ± 0.0	6.8 ± 6.4	18.72 ± 9.8	14.7 ± 3.1	0.67 ± 0.6	2.33 ± 0.6
R10	0.65 ± 0.7	26.6 ± 25.3	12.54 ± 11.0	11.0 ± 2.6	1.00 ± 0.0	2.67 ± 0.6
Total	0.64 ± 1.26[a]	16.8 ± 8.94[a]	18.68 ± 13.4	19.6 ± 10.6	0.87 ± 0.68[b]	2.37 ± 0.6[b]

AR Augmented Reality group, *R* resident 1–10

[a] $p < 0.001$; [b] $p < 0.001$

In the control group, the mean time to perform the task was 18.68 [6.4–47.1] s compared to 19.6 [3.9–77.5] s in the AR group ($p = 0.73$). ICC according to surgeon was 21 %.

Surgeon's appreciation The mean score of difficulty (evaluated for each myoma) was 2.4 [1–4] versus 0.87 [0–4], respectively, for the control and the AR group with $p < 0.001$ with no ICC according to surgeon.

Discussion

Research on AR in gynecology has never been reported. One of the reasons is most likely the technical challenge, as the uterus and ovaries are very mobiles organs. Moreover, there is no automatic segmentation available for abdominal MRI [12], and the segmentation phase is still manually based. The radiologist must delimit the entire surface of the uterus and the entire surface of all the myomas. This phase is time consuming but not truly challenging. Our system solves the most challenging phase: the registration phase. The main problem is to achieve registration accurately, reliably and in real time. Currently, the main approach for registration is SLAM (simultaneous localization and mapping). This technique, which can be used without any other hardware such as magnetic or optical tracking devices [6, 7], is usable when the surgical scene is approximately rigid. However, it fails when there is a mobile organ such as the uterus because it requires the entire scene to be rigid. Moreover, even if the scene is rigid, SLAM during laparoscopy is still proving challenging, due to the repeated nature of tissue texture, rapid camera motion, blur appearance changes caused by blood or coagulation. We used a novel two-phase approach (Wide-Baseline Multi-Texturemap Registration) that was shown to significantly outperform SLAM [10].

Our study shows that the AR improved the mean accuracy of localization by a factor of about 20. There was no significant difference in the time to perform the task. When observing residents completing the task, this appears to be due to the time spent on "fine localization." This is because when the AR system was activated the residents spent more time to perfect the localization to submillimeter accuracy. This was not observed with the control group, since without AR, once the surgeon had decided on the point of contact it was not usually refined. Without the AR, the first phase of "global" localizations seems to be longer. Using the AR, in one case and for a posterior myoma with a difficult approach, the localization was defined as "difficult" (score = 3) and 27 localizations (for a total of 30) were defined as "easy" or "very easy." Without AR, 29 localizations were defined as "moderately difficult" or "difficult." Although this score of complexity is subjective, it portrays the confidence of the surgeon in the localization of the myoma. The localization of myomas during laparoscopy can be very simple when the deformation of the serosa is present, but for small myoma, it can be difficult since there is no tactile feedback. Moreover, although MRI provides a good cartography of myomas, to transpose it for intra-operative navigation using a 2D vision is still challenging. The radiologist anatomical landmarks are at times different than those used by surgeons [13]. The range of accuracy in the control group [0.1–52.2(!)] shows that MRI might be completely misinterpreted. The highest number in the control group range (52, 17) corresponds to localization on the wrong side of the uterus. We can argue that this is due to the inexperience of the resident (e.g., more experimented surgeon might have decreased the significance of the results), but on the other hand, wrong side error is still, unfortunately, an important issue in surgery even for trained surgeons and even when surgery concerns a very well determined side of the patient (joint, ureter, etc.) [14–16].

The choice of 2-cm fibroids was made to model cases when interstitial myomas do not deform the surface of the uterus, which makes them hard to localize [17]. No myomas were physically present in the model to avoid any bias of adding information of tactile feedback in the model or any deformation, as the objective was to compare MRI “navigation and tracking” to MRI plus AR “navigation and tracking.” Of course, an isolated 2-cm myoma is rarely an indication for surgery [18], but 2-cm or less myomas are often present in patients with multiples myomas [19, 20], and recurrence after laparoscopic myomectomy has been described as more likely than after laparotomy. Because the localization of these myomas is still challenging, small myomas are probably more often left in place after laparoscopy [20–22]. This indicates the necessity of a better localization of the myomas during laparoscopy [20–22]: Recurrence rate 5 years after laparoscopic myomectomy reaches 50 % or more in many series reported in the literature [20, 22, 23]. Robotic myomectomy also requires technical improvements since the residual fibroids volume was described as much as five times greater then after laparotomy [24]. The cost-effectiveness of MRI [compared to ultrasound (US)] has to be proved. However, MRI is the most sensitive modality of imaging (for identification of uterine fibroids (particularly for detection of small fibroids) and in differentiating leiomyoma from adenomyosis) [25–29]. Moreover, our system runs on a standard Intel i7 desktop PC costing <1000 Euros (with the cost dropping each year for the same level of hardware) and does not need any other device.

Owing to the fact that no previous data was reported, no sample estimation was carried out. We performed a post hoc estimation to ensure the statistical power of our study and to define sample size for future research in this field. For the measure of accuracy, the statistical power seems satisfactory with a high effect size [1.53 (CI 95 % [0.95; 2.11]), 16.81 mm ± 14.86 vs. 0.64 mm ± 1.26]. This effect size (difference between the means divided by standard deviation) is above 0.8 and classified as “large” [30] (magnitude of improvement between the two groups considered as major). The statistical power was greater than 95 % (taking into account between and within surgeon variability (random effects) due to repeated correlated data for the same surgeon). These results confirmed that the statistical power was satisfactory and confirmed that the sample size was sufficient.

Conclusion

In an experimental model, using our new method of fusion of both MRI and laparoscopic images, the myomas can be seen inside the uterus during a laparoscopic procedure (real-time fusion). Our new AR system enhances the accuracy of the localization of myomas by a factor of about twenty. The comfort of surgeons is also enhanced with an easier localization of myomas. This could be a way to make laparoscopic myomectomy easier, safer and faster. The different steps of surgery could also be planned preoperatively using this method. For example, the optimized incision could be predefined before laparoscopic surgery and then visualized during fusion to guide the surgeon (video 1). The technique could be used in other gynecological surgeries with slight adaptation, such as endometriotic nodules and ovarian cysts [31]. In the near future, intra-operative localization of all anatomical structures (including ureters, uterine arteries, uterine cavity, insertion of the tube, complete vascularization of the myoma) will be possible using our AR system.

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Compliance with ethical standards

Disclosures N. Bourdel, T. Collins, D. Pizarro, A. Bartoli, D. Da Ines, B. Pereira, M. Canis have no conflicts of interest or financial ties to disclose.

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