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The "Iceberg Phenomenon": As Soon as One Technological Problem in NOTES Is Solved, the Next One Appears!

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Abstract

Purpose. Though already proclaimed about 7 years ago, natural orifice transluminal endoscopic surgery (NOTES) is still in its early stages. A multidisciplinary working team tried to analyze the technical obstacles and identify potential solutions. *Methods*. After a comprehensive review of the literature, a group of 3 surgeons, 1 gastroenterologist, 10 engineers, and 1 representative of biomedical industry defined the most important deficiencies within the system and then compiled as well as evaluated innovative technologies that could be used to help overcome these problems. These technologies were classified with regard to the time needed for their implementation and associated hindrances, where priority is based on the level of impact and significance that it would make. *Results*. Both visualization and actuation require significant improvement. Advanced illumination, mist elimination, image stabilization, view extension, 3-dimensional stereoscopy, and augmented reality are feasible options and could optimize visual information. Advanced mechatronic platforms with miniaturized, powerful actuators, and intuitive human–machine interfaces could optimize dexterity, as long as enabling technologies are used. The latter include depth maps in real time, precise navigation, fast pattern recognition, partial autonomy, and cognition systems. *Conclusion*. The majority of functional deficiencies that still exist in NOTES platforms could be overcome by a broad range of already existing or emerging enabling technologies. To combine them in an optimal manner, a permanent dialogue between researchers and clinicians is mandatory.

Keywords

NOTES, autonomy, visualization, actuation, robotics, platforms

Introduction

It took about 7 years, after it was first introduced into clinical practice in the 1990s, to make minor access surgery firmly established in medical care. Seven years after the invention of natural orifice transluminal endoscopic surgery (NOTES)—the same period of time—this new technique is still in its infancy. This striking difference has to be explained.

NOTES is certainly by far more technique dependent than laparoscopic surgery, and new tools are essential to overcome the numerous hurdles that had soon been compiled in the famous "white paper" of the NOSCAR (Natural Orifice Surgery Consortium for Assessment and Research™) group.[1] The so-called "platforms" play a key role.

Accordingly, many research teams all over the world focused on the creation of mechanical and mechatronic

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support systems. Many impressive results were achieved. Mechanical platforms, such as the EndoSamurai (Olympus, Tokyo, Japan)[2,3] or the Anubis (Karl Storz, Tuttlingen, Germany),[4] and other devices seemed to be promising approaches to promote NOTES. However, it soon became evident that purely mechanical systems are not sufficient in producing a real breakthrough. The 2010 assembly of the Euro-NOTES society stated clearly that mechatronic support systems are required to overcome the crucial barriers of NOTES.[5]

Various kinds of mechatronical hardware have been produced in the meantime. Some impressive examples include the MASTER,[6,7] IREP (insertable robotic effector platform),[8,9] and the HVSPS (highly versatile single port system),[10] which presented very innovative technical solutions. However, the real breakthrough still could not be achieved; this was emphasized in the second SAGES/ASGE White paper of 2011.[11]

It was the aim of a group of surgeons, gastroenterologists, and engineers, who met at the annual assembly of the German society for NOTES (D-NOTES) 2012 in Hannover, to analyze in detail why mechatronic systems that are currently available are not adequate to perform clinical NOTES interventions to create a base for further improvement.

Methods

An electronic keyword literature search using PubMed of the US National Library of Medicine was performed with the aim to identify all relevant articles devoted to the topic of NOTES platforms. The reference lists of all identified papers were checked to find additional contributions to the issue.[12,13] The relevant articles were distributed to the participants prior to the meeting.

The group consisted of 3 surgeons, 1 gastroenterologist, 10 engineers, and 1 representative of biomedical industry.

The most important fields that are currently deficient and the need of future activities were defined. Innovative technologies that could be used to help overcome the problems were compiled and evaluated under the following criteria: (*a*) short-term, midterm, or long-term implementation and (*b*) associated technical difficulties.

Results

It was decided to separate the various problems into 2 groups: One dealt with aspects of visualization and the other related to actuation.

Visualization

One of the main preconditions for reliable and safe medical intervention is a high-quality image of the surgical site at every single stage of the procedure. In NOTES using the same or slightly modified endoscopes, which are normally designed for endoluminal endoscopy, visualization is much worse than would be acceptable. Illumination is too weak, since the optical system is constructed for use within the gastrointestinal lumen—that is, for a limited space—but not for the comparatively large abdominal cavity. Because of the limited field of view of the laparoscope (telescope), only a tiny segment of the abdominal anatomy is visible, which makes orientation and surgical manipulation very difficult. Finally, no information about the third dimension is provided.

These problems are certainly not specific to the use of NOTES mechatronic platforms but they are of particular importance within this context. Hence, 6 issues were addressed in detail to evaluate innovative approaches to overcome these limitations: (*a*) illumination, (*b*) fog/mist elimination, (*c*) image stabilization, (*d*) view extension, (e) 3-dimensional (3D) stereoscopy, and (*f*) augmented reality.

Illumination. It is quite obvious that flexible glass fibers are limited in delivering the amount of light that is required to visualize not only the center but also the periphery of the image. An alternative is to make use of new light sources such as light emitting diodes (LEDs). LEDs are comparatively small and only need 2 thin cables for power supply. This certainly helps reduce the maximum diameter of the instrument significantly. On the other hand, there is considerable production of heat, and special cooling systems might be required, if the efficiency of LEDs is not further improved. *Period of implementation: short term*.

Though the idea appears to be uncommon today, it should also be conceivable to position additional light sources into the abdomen, which are independent of the main platform. They would not only create a better illumination of the scenario but would induce shadowing effects, which could be particularly helpful in depth estimation. Hardly any development projects are known to the authors. *Period of implementation: short term to midterm*.

Finally, it may be expected that progress in photonics will lead to more efficient optical sensors. High dynamic range sensors would be able to provide better visibility of both the objects in the center as well as in the periphery by avoiding underexposure and overexposure. *Period of implementation: short term*.

Fog/Mist Elimination. The production of fog and mist is a well-known problem in minimally invasive surgery. Induced by electrocautery or ultrasound dissection, it frequently obscures the view severely.

Up to now, the only way to reestablish a clear view was to change the intra-abdominal gas. Recently, an additional solution was invented to remove the smoke particles, based on electrostatic precipitation. However, both methods are more or less time-consuming and result in high gas consumption or they require the procurement of additional devices.

Modern image processing offers new options. One of them is known as recursive temporal filtering. Since fog and/or mist particles are moving in the field of view, the respective pixel is obscured only for a short moment. If this particular pixel is eliminated, and if only the previous and the following pixels are considered, a virtual non-blinded sight could be created. The algorithm of choice is similar to the ones used for noise reduction in image processing. It is the best choice for fog and/or mist or even fat particles, which do not exceed an area of 5 pixels (based on typical HD [high definition] video resolution of 1920 × 1080 pixels).

Another image-processing method is the local spatial filtering. For larger areas (20 pixels or more in 1 dimension) and only slightly textured fog/mist, local spatial filtering is the better choice to eliminate or reduce fog/mist. This approach works with contrast correction methods for restoring the original contrast before fog/mist appears.

Challenges still exist due to fog and/or mist for affected image sizes between, the aforementioned 5 pixels, up to which temporal-recursive filtering can be used, and the 20 pixels in 1 dimension, where the local spatial filtering shows best results. *Period of implementation: short term.*

Stabilization of the Horizon. In flexible endoscopy, it is very difficult to continuously maintain the view in a strictly horizontal orientation. This is of minor importance in endoluminal endoscopy but is a serious concern in NOTES, since intuitive spatial orientation and recognition of the surgical site is massively impaired. However, the rotation of the image can easily be "derotated" using a miniature microelectromechanical triaxial inertial sensor that is placed at the distal tip of the telescope. By measuring the impact of gravity on each of the 3 orthogonal axes, the rotation angle can be estimated from these 3 acceleration values, which can then be used to automatically rectify the endoscopic image. If fast image-processing methods are available, rectification is almost feasible in real time.[14,15] *Period of implementation: short term.*

Modern image processing enables horizon stabilization even without additional sensors. Some poignant landmarks in every single image are identified. If the horizon is defined once, the following images can then be automatically rotated to the correct angle. However, light reflections and deforming of tissue makes the retrieved landmark positions complex. *Period of implementation: long term.*

The same result can be achieved if the telescope is continuously tracked during the course of the NOTES procedure. Any rotation of the tip of the telescope is immediately compensated for. This works for rigid laparoscopes with an optical tracking system and for flexible endoscopes with an electromagnetic tracking system. However, both systems are usually too expensive, bulky, and complex for this application. *Period of implementation: midterm.*

View Extension. The "tunnel effect," which means that only a very small segment of the whole panorama of the surgical site is visible, has to be overcome to improve safety and operating time of NOTES.

Several approaches could be considered. The direct way is to improve the optical features of the chip. A "fish-eye" lens or photochip, which produces an almost 180° panoramic view, could be helpful if image distortion could be eliminated. Furthermore, lenses with mechanical zoom were introduced, for example, by Berliner Glas KGaA, Berlin, Germany. *Period of implementation: short term.*

A competitive option is called mosaicing or image stitching. The individual frames of the video sequence are registered and appropriately combined to produce a "synthetic" panoramic view of the surgical site. Over the past few years, considerable progress has been made.[16-19] *Period of implementation: midterm.*

Three-Dimensional Stereoscopy and Intraoperative Imaging

The problem of 3-D viewing was a matter of debate as soon as video-based visualization began to play a role in surgery. However, stereoscopy never became popular, and still isn't now, since it is still unclear whether it is really helpful for the experienced laparoscopist.[20] Theoretically, 3-D vision could be of particular value in NOTES, since it improves spatial orientation and could, potentially, reduce the cognitive load of the surgeon.[21] It is technically feasible, but it will, at least, enlarge the diameter of the endoscope.

The endoscopist mainly deals with soft tissue, which poses difficulties with manipulation, and execution of preoperative planning—usually the intraoperative situation (eg, shape and position of organs) changes significantly during the intervention. Intraoperative imaging (mainly computed tomography [CT] and magnetic resonance imaging [MRI]) may help solve this problem and has already been established in many operating rooms. However, each of the aforementioned modalities has its specific pros and cons. CT provides high resolution of bony structures but is based on harmful ionizing radiation, whereas MRI is well suited for soft-tissue visualization but image resolution is unsatisfactory and choice of materials (for instruments, actuators, etc) is very limited. *Period of implementation: short term.*

Table 1. Upcoming Developments for NOTES I: Visualization.

		Expected	Need
Illumination	LED (light-emitting diode)	Short term	Must have
	Detachable light source	Short term/midterm	Nice to have
	High dynamic range sensors	Short term	Must have
Fog and mist elimination	Electrostatic precipitation	Short term	Nice to have
	Recursive temporal filtering	Short term	Must have
	Local spatial filtering	Short term	Must have
Stabilisation of the horizon	Tri-axial inertial sensors	Short term	Must have
	Landmark-based reorientation	Long term	Must have
View extension	Fish-eye lenses	Short term	Must have
	Mechanical zoom	Short term	(Either/or)
	Image stitching	Midterm	
3-dimensional (3-D) enteroscopy	Binocular cameras	Short term	Must have
	"Pseudo" 3-D	Short term	(Either/or)
Intraoperative imaging	Radiographic volume datasets	Short term	Must have
	MRI (magnetic resonance imaging)	Midterm	Must have

An overview of all expected developments in visualization is given in Table 1.

Actuators and Tissue Manipulation

In all, available technology is not sufficient to provide clinical applicability of current platform systems. The following 5 main fields of activity were identified: (*a*) dexterity, (*b*) instrument exchange, (*c*) force transmission, (*d*) miniaturization, and (*d*) human–machine interface.

Dexterity. Dexterity is more than usability. The aim is to conceive the platform in a way that the manipulative skills of the surgeon are translated into the respective actions of the 2 instruments. Therefore, the instruments have to provide sufficient degrees of freedom (ie, 6 for independent positioning and orientation of the instrument tip and additional ones for the functional end itself), sufficient collision and singularity free range of motion (in order to be able to fulfil the surgical task), and precision manipulation of human tissue. Furthermore, the instruments' kinematics should allow for triangulation and should not obstruct the field of view of the camera. An important task is to measure and define the performance (for example: workspaces, velocities, forces, and access), needed to execute a specific intervention. With this information, the implementation of several distal degrees of freedom is currently realizable. Also systems with redundant degrees of freedom are possible, but the full actuation of flexible shafts with a plurality of degrees of freedom is still an open challenge. *Period of implementation: midterm*.

Instrument Exchange. A simple and quicker way to exchange the surgical instruments is a prerequisite before it can be thought of to perform NOTES interventions beyond a very primitive surgical level. Rapid exchange of instrument should be feasible in selected situations. In case of severe bleeding, the dissecting instrument must be replaced by the coagulating instrument as quickly as possible. Otherwise, the patient will be significantly endangered. In systems that are currently available, the exchange of instruments is either completely impossible (eg, Master) or time-consuming (HVSPS). At least 2 different but complimentary strategies could solve the problem.

Automated exchange of instruments is the state of the art in industrial applications and seems to be feasible even in the surgical environment.[13,22] Accordingly, an instrument exchange system should be mandatory in each platform for NOTES.

However, the selection of instruments that can be provided by an automated instrument changer will always be limited. Therefore, the development of multifunctional instruments in parallel has to be considered as well. *Period of implementation: long term*.

Force Transmission. Even in NOTES interventions, considerable force is required at the tip of the instrument. Grasping tissue needs at least 15 to 20 N, but additional force is necessary to overcome the inherent stiffness of the inserted instrument. Neither of the currently existing mechatronic platforms are equipped to offer the necessary power needed.

Bowden wires are the backbone of conventional endoscopes. Their usage in mechatronic devices is limited to

3-fold: Small curvature radii cause severe mechanical bending stress and high forces occur due to small lever arms. Furthermore, abrasion is imminent if the choice of material combination is wrong. Further research needs to be done to improve their functionality. In addition, the quantity of the actuated degrees of freedom is limited by the space needed to guide the parallel wires. *Period of implementation: short term*.

In addition, alternative or complementary actuation principles have to be investigated. The miniaturization of hydraulic or pneumatic actuators is possible.[23] Since it is possible to bend the supply pipes arbitrarily without causing any friction and, theoretically, a very high force to size ratio, especially in hydraulic actuators, they have a high potential for use in NOTES applications. The main tasks for the application of these principles is the handling of the required high pressures, the miniaturization or reduction of their complex mechanical components (eg, valves, seals), and achievement of precise control despite their nonlinear behavior (eg, elasticity of tubes), which makes precise control difficult to achieve. However, some functionalities could be implemented by these new approaches. *Period of implementation: midterm*.

A direct way to create mechanical power where it is needed is by using micromotors.[24] However, with reduced size, motor torque is reduced too, and the available gears necessary to achieve the aforementioned forces at the tool tip are hardly available. Further difficulties arise from the need for sterilization (choice of material), isolation to protect the patient from current leakage (thick isolation reduces bending radii), and the reliability of the components. *Period of implementation: midterm*.

Finally, motor units could be directly integrated into the structure of the actuators or of the instruments, for example, as electroactive polymers,[12,25] piezoelectrical elements,[26] or shape memory alloys.[27] Each of these actuation principles has promising properties arising from its small size and flexibility. Although their potential field of application is impressive, research is still necessary to overcome their individual drawbacks, including low actuation frequency, heating/cooling (eg, shape memory alloy),[28] small forces (eg, electroactive polymers), and small displacement (eg, piezoelectrical elements). *Period of implementation: long term*.

Miniaturization. Miniaturization is a cross-sectional topic. Some principal problems could certainly better be managed if new materials were available. This holds true, for example, for the aforementioned Bowden wires. Both, bending radii and the diameter of the wires, could be reduced if better materials were available, for example, synthetic fiber. Also, shape memory alloys with lower and more specific transition temperatures, which may be more suitable for medical applications.

A smart reduction of the available degrees of freedom or a better distribution could be helpful as well. Redundancy in function costs space! *Period of implementation: continuous improvement*.

Human–Machine Interface. In mechatronic platforms, one of the greatest challenges is to translate the intentions of the surgeon on how to proceed into the corresponding adequate and precise activities of the machine, in a reliable and safe manner.

Interfaces for NOTES must provide a range of many additional functionalities that exist neither in traditional laparoscopic surgery nor in endoluminal interventions. To overcome the specific and immanent methodical limitations of the new operative approach, these features include scaling of surgeon's hand motion, definition of virtual fixtures to preserve delicate tissue, as well as simultaneous control of platform, instrument tip, and telescope. Furthermore, it is evident that effective control of these augmented functionalities can no longer be warranted by only 1 or 2 surgeons.

For performing surgery with the HVSPS, a team of 5 endoscopists/surgeons and assistants has to cooperate.[10] It goes without saying that this is very difficult even under experimental conditions with a highly trained team, and it would be almost impossible under routine clinical conditions. *Period of implementation: long term*.

An overview on current developments concerning actuators and tissue manipulation is given in Table 2.

Enabling Technologies

The systematic analysis of surgical expectations, the actual capabilities of the systems currently available, and the horde of emerging technologies, which could help bridge the discrepancy between expectations and reality, led us to define a selection of enabling technologies that could play a key role in making mechatronic platforms the perfect tools we need to establish NOTES in clinical routine (Table 3).

Depth Maps in Real Time. Depth maps help the surgeon improve his or her spatial orientation.[29] They have the capability to reduce operation time and enhance patient safety. Furthermore, if texture is mapped onto the 2.5D information, tissue can be visualized under different points of view, thus virtual cameras can be implemented. Several technologies are around the corner that have the potential to provide depth maps in real time, however, further research is still necessary: (*a*) Two miniaturized cameras integrated into the tip of the endoscope lay out the basis for triangulation. Difficulties occur due to specular reflections in 1 of the 2 images, with dense texture information complicating pattern matching, small base distance, and high computational costs. (*b*) Time-of-flight

Table 2. Upcoming Developments for NOTES II: Actuators and Tissue Manipulation.

		Expected	Need
Dexterity	Optimized kinematics	Midterm	Must have
Instrument exchange	Automated instrument exchange	Long term	Must have
	Multifunctional instrument	Long term	Must have
Force transmission	Improved Bowden wires	Short term	Must have
	Hydraulic/pneumatic actors	Midterm	Must have
	Micromotors	Midterm	(Either/or)
Miniaturization	New materials	Midterm	Must have
Human–machine interface	"Cooperative interfaces"	Midterm	Must have

Table 3. Enabling Technologies.

Depth maps in real time
Precise, reliable navigation
Fast pattern recognition
Task reduction/partial autonomy
Cognitive systems

technology provides a 2.5D image with a high frame rate. The main drawbacks include the coarse spatial resolution and the low signal-to-noise ratio if the light is transmitted via optics from outside the patient into the operation area. *Period of implementation: midterm to long term.*

Precise, Reliable Navigation. Because of the limited field of view in the large surgical site and the unstable horizon, spatial orientation and navigation is significantly impeded and so is the transfer of preoperative data into the operational site. Technologies that provide the relative pose between anatomical landmarks, instrument tip, and patient-specific planning are necessary. This is a difficult task, as there is usually soft, deformable tissue and flexible instruments present. Therefore, external tracking as recently presented by Olympus (Scope Guide), where miniaturized electromagnetic coils were integrated into the endoscope, fails in this case. Optical 2-D and 3-D sensors, in combination with appropriate tissue excitation and reliable feature detectors computed in real time, may in future allow for matching between preoperative and intraoperative data. Further difficulties arise because of the different imaging modalities. Data fusion with MEMS (microelectronic and mechanical systems) may increase robustness as the motion of the endoscope can be measured with a high update rate (and, unfortunately, drift). However, this is still a challenging task. *Period of implementation: short term.*

Fast Pattern Recognition. During intervention and examination, a huge amount of data are acquired, and manual inspection is hardly possible. Therefore, robust pattern recognition algorithms are necessary to support the surgeon in both navigation (see above) and evaluation (eg, determination of cancerous tissue). The main difficulties from an image processing point of view occur from soft tissue deformation, wet and glossy surface with specular reflections, insufficient or even unspecific training data, and the changing characteristics of, for example, cancerous tissue. These make robust and reliable discrimination of pattern and associated properties difficult. *Period of implementation: long term.*

Task Reduction/Partial Autonomy. It would be a big leap ahead if the range of mechanical tasks that have to be carried out until now by human assistants could be reduced by the use of automatons. The exchange of instruments as mentioned above is just one such example.

Another approach is to work out procedural routines: A number of well-defined activities are performed in multiple simultaneous actions of the 2 actuators and the endoscope in an adequate sequence that is initiated by 1 command. As an example, the complicated process of inserting the whole system into the abdomen and the unfolding of the actuators and of the camera could be made significantly easier to perform—the same applies to withdrawal of the system.

The workload of the surgical team could be reduced even more if the platform would be capable of autonomously carrying out at least some of the tasks which, up until now, have to be performed by humans. In this context, "autonomy" means that the respective action is done in a way which is orientated to the specific situation, that is, adapted to the real requirements but not to a schematic pattern. One good example is camera guidance. However, it has to be ensured that the human operator can always overrule the machine and finish an autonomous task in a way that is best suited for them. *Period of implementation: long term.*

Cognitive Systems. Cognitive systems provide assistance on a high level. The transition between autonomous tasks and cognitive systems is somehow fluent. A cognitive system has, in contrast to an autonomous system, the capability to flexibly react to changing circumstances, to adapt itself to new situations, and to draw its own conclusions. One example in NOTES may be autonomous tissue discrimination in combination with task execution (eg, tissue ablation in the case of cancer or nearby delicate tissue). Autonomous tissue discrimination allows for the automatic definition of forbidden zones (ie, virtual fixtures), which help preserve healthy tissue and avoid unnecessary harm to the patient. Cognitive systems have the potential to make NOTES interventions more reliable, robust, and safe. They may have the greatest impact and are definitely seen as long-term research. *Period of implementation: long term*.

Conclusions

The creation of dedicated platforms is still the Achilles heel of NOTES. First experience with mechanical platforms clearly demonstrates that mechatronic platforms are required to enable surgeons to perform more challenging NOTES interventions. However, both visualization and actuation of currently existing systems still have to be improved. A broad range of technological innovations is available today to overcome the majority of current shortcomings, but it is still unclear how to use and to combine them in an optimal way. An intensive, permanent dialogue between researchers (engineers, computer scientists, etc), users (surgeons), and industry is mandatory.

Author Contributions

HF was the moderator. AF, AS, TO, JHB contributed to literature review. TC, JC, CVT, KH, OW, RK, ME, SR were the members of the working team.

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