Immersive Mixed Reality Training Concept for Mastering Surgical Knot-tying

Moritz Queisner*
Charité – Universitätsmedizin Berlin

Christopher Remde
Charité – Universitätsmedizin Berlin

Robert Luzsa
University of Passau
University of Applied Sciences Landshut

Igor M. Sauer
Charité – Universitätsmedizin Berlin

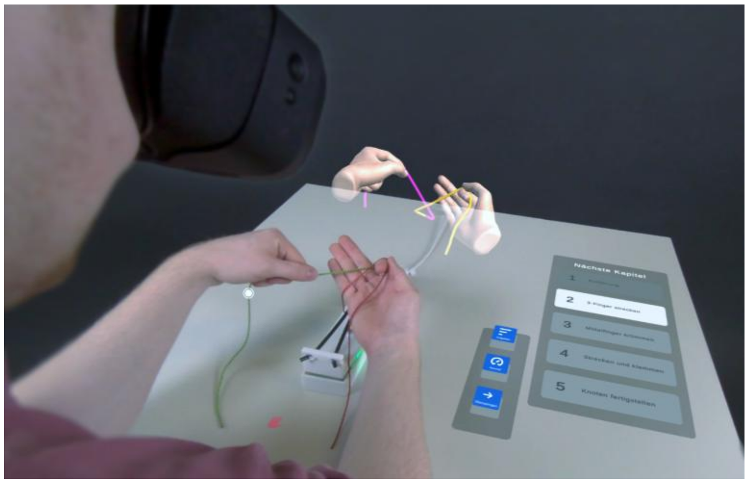

Figure 1: Prototype of the surgical knot-tying trainer with 3D instructional hands, measuring tensile strength and knot tightness.

Abstract

This study presents a mixed reality training concept designed to enhance medical students' acquisition of surgical knot-tying skills, a fundamental component of surgical training critical for effective wound closure and tissue healing. Utilizing a virtual reality headset with video passthrough functionality, the system provides adaptive visual instructions tailored to the user's hand movements during the knot-tying process. A prototype was developed based on the concept, featuring three-dimensional videos in which virtual instructor hands demonstrate each step of the procedure. The training concept was derived from an iterative, user-centered process encompassing requirement analysis, prototype development, and evaluation. Key functionalities include the ability to display thread tension and tensile strength, dynamically adapt learning speed to the user's progress, and deliver personalized feedback by visually augmenting the hands and fingers. Evaluation results indicate that spatial and tangible interactions facilitated by the mixed reality training prototype support the acquisition of practical skills, bridging the gap between digital and physical simulation training.

Index terms: knot tying, surgery, mixed reality, hand tracking, training, tangible media.

*e-mail: moritz.queisner@charite.de

1 Introduction

The concept of extended reality (XR) offers advantages for conveying spatial relationships. Unlike traditional two-dimensional screens, XR enables users to perceive image data with visual depth cues, accessible from every angle. Moreover, mixed reality (MR) visualization techniques, implemented through transparent head-mounted displays and virtual reality (VR) headsets with video passthrough capabilities, integrate digital and physical bodies and objects. This integration facilitates interaction with the physical environment, creating opportunities for novel training methods involving physical objects, such as surgical instruments. Recent advancements in body and object sensing and tracking technologies, such as hand tracking algorithms, have further enhanced the tangibility of interaction. Users are no longer bound to controllers, but can now use their bodies, hands, and even individual fingers to interact directly with digital objects. Altogether these features expand the potential of XR for immersive, hands-on learning and training scenarios that require spatial reasoning.

In this paper, we present the concept for an extended reality surgical knot-tying trainer designed for medical students to independently practice and refine their knot-tying skills (Fig. 1). Mastering knotting techniques is a fundamental part of surgical training, essential for ensuring effective wound closure and tissue healing. Surgical procedures typically involve making incisions in the skin that require precise suturing to close the wound and facilitate tissue healing. This process involves the use of a needle and thread to suture the dissected area, followed by the application of special, well-defined knots in a certain order to secure the sutures. These knots must provide adequate tension to maintain tissue approximation without compromising microvascular blood supply. The proposed XR training system aims to address these training needs by offering a novel approach for hands-on practice in a tangible and immersive environment.

2 Related works

In the medical field, XR has been shown to enhance learning and training, particularly in scenarios requiring spatial understanding. For instance, XR applications in medical imaging facilitate the comprehension of anatomical structures displayed as volumes, supporting surgical planning [3, 4]. Over the past decade, XR has also improved medical training, offering a means to simulate complex interactions that are otherwise challenging to replicate in traditional training scenarios [2]. Currently, most medical training applications using XR are implemented in virtual reality. However, many tasks in healthcare professions require interaction with physical objects and situations, which emphasizes the need for tangible elements in training systems. Despite the demonstrated benefits, such as improving understanding of spatially complex tasks [11] and human anatomy [9], integrating physical objects into XR training remains technologically demanding and difficult to scale.

While approaches to tangible interaction in XR are still uncommon in medical training, advancements in hand-tracking technology open new possibilities to interact with physical objects, such as medical instruments. Although hand gestures are increasingly reliable to capture even in the presence of visual occlusions [12], accurate finger tracking remains a challenge. Methods that can estimate the deviation of a user's knot tying motions from predefined expert motions have been explored [8]. However, optical thread tracking in the context of knot-tying has not yet achieved the precision required for surgical training due to the fineness of the thread, severe occlusions, and hand obstructions. To date, no XR-based training systems specifically designed for surgical knot-tying have been developed.

Figure 2: Workshop on surgical knot-tying conducted by an experienced surgeon, emphasizing the spatial and tactile complexities inherent in mastering surgical knotting techniques.

In current medical practice, knot-tying training is often conducted informally, primarily through face-to-face workshops or one-on-one instruction by experienced surgeons (Fig. 2). Learners rely on passive resources, such as illustrations and video tutorials, which lack interactivity, guidance, and feedback, limiting their effectiveness in skill acquisition. These methods only permit observation and imitation, without opportunities for active, iterative learning. Furthermore, the traditional model of hands-on instructions guided by skilled surgeons is costly, resource-intensive, and not systematically embedded into medical curricula. Accordingly, students, trainees, and professionals face a significant gap between theoretical knowledge and practical application in their training.

3 Methods

The development of the XR knot-tying trainer followed an iterative process model throughout the design, development, and evaluation process. This user-centric approach emphasizes the active involvement of stakeholders to understand user needs, define requirements, and iterate system features. This process was conducted in three phases: a requirement analysis to establish the didactic training framework (3.1), the integration of user perspectives to iterate the concept based on user tests (3.2), and an evaluation to validate the final concept and the eligibility and usability of the prototype within a medical training environment (3.3). A comprehensive account of the methods used, and their theoretical and empirical basis can be found in *Luzsa et al.* [7].

3.1 Requirements analysis: didactic approach

The definition of the didactic training framework addressed both sides of knot-tying training, the teaching and the learning part. To understand how knot-tying skills are acquired, we conducted an exploratory online questionnaire study with 80 medical students. The questionnaire included closed-ended questions covering socio-demographics, study phase, knot-tying experience, learning and training methods, preferred training approaches, as well as openness to and perceived advantages and disadvantages of MR-based training. Participants with prior knot-tying experience also responded to open-ended questions regarding the most challenging and critical steps in the knot-tying process. The open-ended responses were analyzed inductively using Kuckartz's qualitative content analysis approach [5], and category frequencies were quantified.

To establish a didactic approach and define the knot-tying choreography, we conducted a qualitative survey with four experienced surgeons from Charité – Universitätsmedizin Berlin; Dept. of Surgery (two assistant physicians and two senior surgeons with knot-tying experience ranginging from junior to expert level). Semi-structured expert interviews were conducted following Wassermann's guidelines [13], with audio recordings capturing the discussions. The interviews addressed three core topics: the experts' knot-tying techniques, essential steps and quality criteria for surgical knots, and their teaching experiences and recommendations.

Additionally, each expert demonstrated knot-tying techniques using a knot bank and braided sutures while verbalizing their thought process ("think-aloud" method), with video recordings capturing their demonstrations. In a second demonstration, the experts wore the Varjo XR-3 (Varjo, Helsinki, Finland) virtual reality headset to provide specific feedback on the usability of video pass-through based headsets for knot tying, including factors such as weight, comfort, and image quality. This comprehensive analysis of both learner and expert perspectives provided the foundation for developing an effective XR-based training concept for surgical knot-tying. The concept was implemented into a prototype, to verify its technical and didactic feasibility in the field, and to allow for iterative development of the concept based on user feedback.

3.2 Iteration: integrating user perspectives

To incorporate both user and expert insights during the development phase, the UEQ-S [10] was used to assess the quality of the training concept and the prototype with eight standardized questions. The studies aimed to refine the concept, design and usability of the system while aligning it with the needs of its target audience. An online experiment involving 46 medical students was conducted. The experiment employed a between-subjects design, wherein participants were randomly assigned to one of three design variants of texts, virtual hands, and instructional elements. Each participant viewed videos simulating the experience of using the system through mixed reality (MR) glasses. The objective was to identify the most effective design while gathering feedback on usability, user experience, and learnability. For this, 5-point Likert scales were used (e.g., ranging from "not at all helpful" to "very helpful"). Responses from the study were systematically categorized to inform iterative improvements to the system's design and functionality.

3.3 Evaluation: testing system design and usability

For a final evaluation of the concept and its accompanying prototype, interviews were conducted with five surgeons, representing a range of expertise and roles. The group included two senior physicians, a teaching coordinator who facilitates suturing and knotting courses, a specialist surgeon, and a junior doctor. The participants were first introduced to the project and provided with a detailed description of the prototype. A five-minute video demonstrated the system from the learner's perspective, showcasing the menu, preparatory steps, and key learning units. Following this, the surgeons were asked to provide qualitative feedback, focusing on the system's strengths, weaknesses, and areas for improvement. Additionally, they were asked how the system could specifically enhance teaching, training, and clinical practice in their fields.

4 RESULTS

The results are presented in three distinct sections: first, the didactic training concept derived from the requirement analysis; second, the implementation of the prototype, guided by the training concept and the specific XR system architecture; and third, the evaluation of the prototype's functions and usability.

4.1 Training concept

The results of the requirements analysis emphasized the need for a training concept that seamlessly integrates real-world physical elements with virtual elements. Users should be able to train independently, without the physical presence of an instructor, while still receiving individual guidance and feedback. These two aspects were identified as essential to creating a tangible, interactive, and risk-free training system tailored to medical students' needs.

Findings from the user studies showed that students expect the system to offer comprehensive support, guidance, and individualized feedback akin to that provided by a human instructor. Insights from expert interviews identified specific technical and procedural requirements for the MR-based knot-tying trainer. The system should teach critical skills including proper thread handling, hand coordination, knot tightening, and the correct sequence of counter knots. The training system should furthermore demonstrate a knot consisting of two knots tied in the same direction involving the middle finger and the ring finger, which is then secured with a counter knot tied with the index finger.

While some surgical procedures or certain tissues require the use of advanced knotting techniques, the most basic knot for surgeons is the "granny" knot, sometimes also referred to as surgeon's knot. Due to its wide applicability, this knot is usually the first knot taught to surgical trainees and has therefore been selected as the knot displayed in the concept.

Due to the spatial complexity of knot tying, experts emphasized that three-dimensional instructions, which adapt to the user's own speed and recognise the progress and correctness of the knot tying process, should form a core part of the knot tying training application. To enhance realism and precision, tensile force measurements should be incorporated, providing feedback if excessive force is applied. For training purposes, experts suggested using a tensile force threshold of approximately five Newtons, as this is the point at which tissue damage becomes likely. In addition, the system should prioritize ease of use to ensure accessibility for users without prior experience of MR technology.

The derived training concept is guided by three core principles:
a) Knot-tying requires precise spatial understanding. Therefore, it is essential to present the learning content in three dimensions. This approach ensures a clear and accurate representation of the spatial relationships of objects and fingers.
b) Instructions should be directly mapped to the learner's fingers and their movements. By spatially overlaying guidance on the learner's actions, the system can provide intuitive and context-aware support.
c) The system should dynamically adapt the content to the learner's progress and pace. This feature is particularly important, as manual control of learning steps during the knot-tying process could lead to rushed movements and, consequently, an increased likelihood of errors. Automatic adjustment ensures that learners can focus fully on skill development without interruptions.

This combination of user-centered design and expert-informed requirements forms the foundation for a robust MR-based training system, addressing the unique challenges of surgical skill acquisition in a safe and controlled environment.

4.2 Implementation into a prototype

The training concept was then implemented as a prototype. The system architecture is designed around the idea that users wear a headset, which projects instructions into their field of view and onto their hands while they tie a knot. Accordingly, users need to be able to perceive both the MR content and their physical environment simultaneously, including their arms, hands, a knotting bank, and the thread. To fulfill these requirements from a technical perspective, a headset with transparent displays or video-pass through technology is required. The pass-through stream should have a high pixel-per-inch density, allowing the users to clearly identify small structures, such as fine filaments.

Headsets with transparent displays, such as the Hololens (Microsoft Corporation, Redmond, Washington, USA) or Magic Leap (Magic Leap, Plantation, Florida, USA)) were found to be not adequate for the task, due to their low field of view obstructing the instructional content while users are focussed on their hands. Low-cost video pass-through devices such as the Meta Quest Pro or Meta Quest 3 (Meta, Menlo Park, California, USA) were not able to accurately represent finer structures, such as threads. For the implementation, the Varjo XR3 (Varjo, Helsinki, Finland) headset was selected, due to its high quality pass-through, built-in LeapMotion V2 (Ultraleap Inc, San Francisco, California, USA) hand tracking sensor and raw camera data access. The Varjo XR-3 requires connection to a high-performance PC to ensure optimal performance. For this purpose, a Microsoft Windows 11 based system equipped with an AMD Ryzen 9 5900X CPU, 32 GB of DDR4 RAM, and an Nvidia RTX 3080 GPU were utilized. The prototype was implemented with the Unity game engine, version 2022.3 (Unity Technologies, San Francisco, California, USA).

The core feature of the prototype are three-dimensional instructional animations that demonstrate the knot-tying process through virtual instructor hands, which are displayed next to the learner's real-world hands from a first-person perspective (Fig. 3). Creating accurate three-dimensional instructional animations for knot-tying presents significant challenges due to the intricate and dynamic nature of the process, particularly the motion of the suture thread. While motion capture processes are well-established in industrial contexts, these systems typically only capture human body motion, and lack the precision for hand and thread motion. Handmade animations of the instructional content are possible, but time-consuming and expensive to create. Therefore, the system relies on a volumetric video capture of the hands for visualizing the instructions: Five RGB-D cameras (Azure Kinect, Microsoft Corporation, Redmond, Washington, USA) were utilized in combination with the open-source software LiveScan3D [6] to capture volumetric video recordings of an expert surgeon demonstrating the knot-tying process.

While the volumetric video accurately represents the knotting choreography, users complained that the low resolution and artifacts in the videos decrease legibility. Consequently, the volumetric videos were enhanced with static animated 3D hand models that highlight key poses to improve readability (Fig. 3). The instructions are segmented into sub-steps, which users are required to replicate with their hands. In this way different knots could be implemented efficiently, due to the low effort required for creating instructions with this setup. Auditory guidance delivered via text-to-speech narration explains each step. To enhance this guidance, color-coded visual overlays on the user's hands highlight incorrect positioning and indicate which fingers require particular attention during each stage of the process. Upon successful completion of a step, the user's hands are briefly illuminated in green, providing immediate positive feedback.

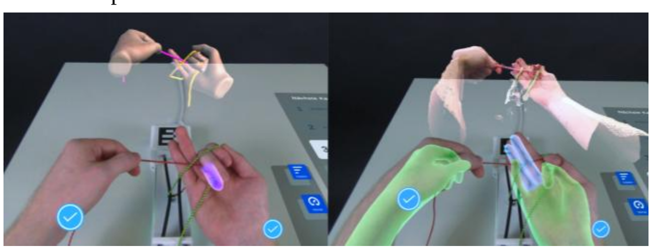

Figure 3: Key gestures are shown using animated hands. The purple indicator shows which finger needs to be moved during each step (left). Volumetric video shows the knot-tying sequence, with green hands marking completed steps (right).

The system uses hand and finger tracking to recognize learners' progress based on specific key gestures, dynamically adapting the speed and progress of the instructional content. To provide individualized feedback and adapt to the user's learning speed and progress, the system needs to rely on accurate recognition of hand and thread positions. For hand tracking, the Ultraleap Unity package is utilized. Ultraleap hand tracking, integrated into the Varjo XR-3 headset, enables real-time registration of hand and finger movements without the need for external tracking hardware. The raw input data from the finger tracking system is processed to provide supervision and feedback on the progress of the knot-tying process. This data is interpreted spatially and temporally to determine the user's position within the knot-tying choreography and assess whether their hand movements align with the expected sequence at the start and end of each step. Given that the choreography of knot tying is predefined, the system matches the user's hand gestures to these predefined gestures to offer feedback and adjust the timing and positioning of instructions. This approach eliminates the need to track the thread itself, which is inherently challenging due to frequent occlusions.

Tracking the thread and knot itself is challenging. However, assuming that the choreography for tying a specific knot is predefined, and the knot is a direct result from the hand motions, the correctness of the knot can be estimated by surveilling the user's hand and fingers. A robust hand-tracking is therefore required for the implementation. Most modern XR headsets provide built-in hand tracking solutions.

The knot tying choreography is split into small and distinct steps. For each step, a critical gesture is defined that is expected to be replicated by the user in their knot tying process. The prototype continuously monitors the user's hands via skeletal hand tracking data received by UltraLeap sensor. The user's finger poses are compared to the expected gesture by calculating a differential score based on the relative finger bend and pointing direction, without taking the absolute hand position and rotation into account. If the differential score crosses a certain threshold over multiple frames, the step is marked as completed. For some gestures, the absolute rotation and position of the hand in the world is important and therefore considered in the calculation as well. Upon successful completion of a step, the system advances to the next; otherwise, the instructions for the current step are repeated. Initially, the application evaluates only the knot-tying technique. As users progress, the system also assesses whether appropriate tension is applied during knot-tying and identifies any air gaps in the completed knot.

Excessive tension can lead to tissue damage, while insufficient tension may result in a knot that fails to hold dissected tissue together. To address this, a custom-designed knot-tying bench was developed. This bench consists of two parallel rubber bands and a weighted base, capable of digitally measuring and displaying thread tension and tensile strength in real-time on a color scale (Fig. 4). During exercises, learners are required to ensure that the rubber bands remain in contact and the base stays grounded, as lifting the base indicates excessive tensile strength. These features allow users to practice achieving the optimal balance of tension to avoid potential tissue damage while ensuring the knot is secure. The XR headset can track the device through an ArUco marker, to be able to place UI elements relative to it. The blueprint, CAD models, and assembly instructions for the trainer bench are provided as an open-source resource on GitHub, facilitating accessibility and reproducibility for future research and training applications (provided in the supplementary material section).

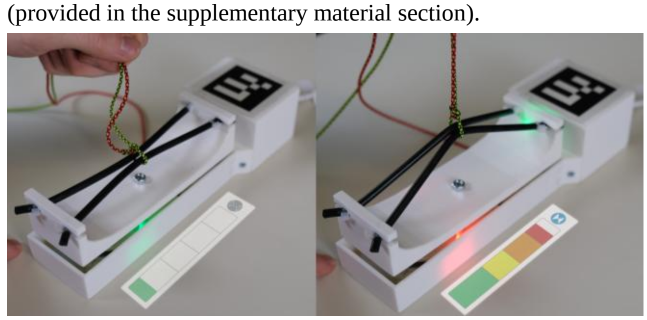

Figure 4: Knot-tying trainer bench: A green LED and XR meter indicate correct tension (left), while red signals excessive tension (right). A green LED near the bands shows sufficient suture pressure.

The system includes a touch- or gaze-operated menu that allows users to also adjust the instructional pace manually, view their current progress, and navigate to the previous or next step. The application includes a comprehensive tutorial and step-by-step guidance to accommodate users without prior mixed reality experience. To avoid mental overload of the users, the app gradually introduces the users to new concepts. At the beginning, users are only required to learn the knot choreography, without pressure from any time or accurateness measurements. In a second stage, the users also need to adhere to the tensile and knot strength limits, while still being guided by the instructions. In a final stage, users can train their knot tying skills under time pressure and without guidance. At the end of each session, users are provided with a dashboard, showing a comprehensive overview of their performance. The dashboard features a timeline, at which critical events, such as too much pressure applied are marked. Additionally, an overall performance score, rating is shown.

4.3 Evaluation by students and teachers

Overall, while both students and experts acknowledged the app's potential, they identified areas requiring significant improvement to optimize its usability, functionality, and effectiveness as a training tool. Detailed statistical results of the experimental evaluation are reported in *Luzsa et al.* [7].

Students evaluated the app positively, describing it as useful, innovative, and pleasant to use. Among different iterations, the variant that incorporated virtual trainer hands, a virtual thread, real-time coloring of the learner's hands to provide feedback on hand positions, and directional arrows received the highest ratings. Features such as the LED indicator on the knot bank, which conveyed thread tension feedback, and the hand-coloring mechanism to highlight correct or incorrect poses were particularly preferred for their essential role in supporting learning success.

However, significant criticism was directed at the visual representation of the virtual elements. Students highlighted issues with low resolution and pixelation, as well as difficulty in distinguishing virtual components from the background or the user's hands. Suggested improvements included increasing contrast, reducing transparency, using non-skin-colored virtual hands, and darkening the background during action demonstrations. Additional recommendations included integrating auditory feedback, such as sounds to indicate excessive tension or incorrect movements and providing an initial demonstration of the entire knotting process with labeled steps for enhanced clarity and comprehension.

Experts similarly noted the app's suitability for beginners and its alignment with existing knot-tying curricula but emphasized the need for refinement. They criticized the segmentation of steps as insufficiently seamless and suggested incorporating a feature to display the entire knotting process prior to individual step-by-step guidance. Expanding the training content to include different knot types and thread materials was also proposed to broaden the system's applicability. Moreover, experts highlighted the importance of providing opportunities for frequent, intensive practice, suggesting the incorporation of gamification elements to reinforce learning. Further recommendations included enhancing the user interface for improved clarity, streamlining menu navigation, and refining tension measurement capabilities to accommodate various materials.

5 Discussion

By incorporating stakeholder perspectives and integrating user feedback and expert insights throughout the design process, the development of a robust and effective MR-based training concept tailored to fundamental medical training was achieved. The prototype demonstrates how MR-based training with tangible objects can combine the advantages of digital simulation and instructor-led learning in a self-directed training environment.

However, the prototype currently achieves a technology readiness level of five, primarily due to limitations in the quality of finger-tracking. Initially, the pose-matching system was designed to continuously track users' hands. User testing revealed that this approach was unstable due to the complexity of the knot-tying process producing difficult occlusions during the interactions of multiple fingers. The variability in individual hand movements to perform each step made comparisons to a predefined sequence challenging. Consequently, the system was adjusted to match only key hand poses. With more robust hand- and finger-tracking capabilities, both educators and learners could imagine potential applications of the system in skills labs for students, residency training programs, and surgical internships. Integration into medical curricula would, however, require the inclusion of additional knot types and thread materials.

Furthermore, the system should become more interactive, particularly through the incorporation of knowledge assessments. More realistic simulations contextualized within actual surgical procedures, would further enhance its educational value, such as the simulation of consequences of decision-making, where learners could observe the real-world outcomes of selecting a specific suture or knot type. However, the knot tying trainer could be expanded with more advanced knots, as these rely on the same concepts and implementations. Interviewees also identified opportunities to adapt the training concept and learning principles to other surgical skills and applications, including laparoscopy, blood sampling, trauma surgery (e.g., splinting and plastering), anastomoses, tumor resections, and organ resections. However, these expansions would require simulating more complex scenarios, such as differing tissue types, body structures, and organ shapes.

Another limitation highlighted was the current gap in adequately trained staff within medical education facilities to oversee and support XR training systems. Onboarding processes for students unfamiliar with XR applications also need to be standardized and are now subject to more systematic research [1]. In summary, the interviews indicate that the system has potential for application in diverse educational contexts, and the foundational technology and learning strategy could be extended to other medical domains. Nonetheless, further optimization is necessary for practical implementation, and appropriate framework conditions must be established to support its adoption.

Figure Credits

Supplemental Materials

– Source code, installation instructions for the knot tying trainer, www.github.com/ExperimentalSurgery/Knot-Tying-Trainer-Prototype, released under GPLv3 license.
– Supplemental materials for the knot-tying bench, www.github.com/ExperimentalSurgery/Digital-Knot-Trainer, released under CC BY-NC-ND 4.0.
– Video of the knot-tying trainer, www.doi.org/10.5281/zenodo.14712546, released under CC BY 4.0.

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