Amniotic membrane transplant (AMT) is a surgical technique for ocular surface reconstruction that should be considered for acute chemical or thermal burns, painful bullous keratopathy, shield ulcers, severe bacterial keratitis, necrotizing herpetic keratitis, corneal thinning, refractory neurotrophic keratitis, and other persistent epithelial defects (PED). The literature describes several techniques to place and fix the amniotic membrane (AM). The amniotic membrane may be used as a graft (inlay technique), patch (overlay technique), or combination of both (filling-in or multilayer technique). When used as a patch, the AM covers the epithelial defect without stromal loss and is temporarily sutured to the episclera near the limbus. The patch technique is safe, easy to perform, and effective in promoting corneal epithelial healing and reducing ocular surface inflammation underneath the AM.

Robotic surgery has expanded during the last 20 years in abdominal and endoscopic procedures and macrosurgery in general. Microsurgical specialties, including ophthalmology, have progressed neither to the same extent nor at the same pace. To our knowledge, no human clinical procedures have been reported. Potential reasons for this discrepancy include the following: (1) ocular surgery is minimally invasive microsurgery yielding excellent results; (2) a true microsurgical robot does not currently exist; and (3) the cost of robotic systems. We used the high-definition robotic da Vinci Si Surgical System (Intuitive Surgical Inc) to perform robotically assisted AMT, penetrating keratoplasties, and pterygium surgeries on porcine eyes. This version provided greater magnification and better resolution of the operative field than the previous high-definition model. Our conclusions were that robotically assisted ocular surface surgeries such as AMT might be technically feasible for humans. This study aims to investigate the feasibility and safety of robotically assisted AMT and report the first human cases of robotic ocular surgery, to our knowledge.

Surgical Technique
The study was approved by the ethics committee of the Strasbourg University Hospital and the French national drug and medical devices security agency. It included patients with painful PED and low visual acuity potential (Table). All patients provided written informed consent prior to participation.

The da Vinci Si Surgical System consists of 3 components (Video 1). Amniotic membrane transplant surgeries were performed using the da Vinci Si Surgical System on June 26, 2014 (eFigure 1 in the Supplement). An ophthalmic surgeon with prior experience in robotic microsurgery certified by the Robotic Assisted Microsurgical and Endoscopic Society performed the procedures. Surgical movements were scaled to a 1.5:1 ratio. For each procedure, operative time and successful completion of the surgery with or without complications or unexpected events was assessed.

Procedures started with the debridement of cellular debris, exudates, and loose corneal epithelium in and around the PED (eFigure 2 in the Supplement, Video 2). A 12 × 12-mm square piece of AM was prepared (Assistance Publique, Hôpitaux de Paris Tissue Bank). The AM patch was placed over the entire corneal surface. It was sutured to the perilimbal episclera with 8 stitches (eFigure 3 in the Supplement). After completion of each procedure, a 14-mm bandage contact lens (Bausch & Lomb) was placed and maintained in position for 1 month. Dexamethasone, 1%, and ofloxacin eye drops, 0.3% (Laboratoires Thea), were administered at the end of surgery and postoperatively, 3 times daily for 30 days.

Patient Outcome
Three consecutive surgical procedures were performed. The da Vinci Si Surgical System provided appropriate dexterity to perform delicate ocular surface manipulations. Although robotic tools are not as perfectly adapted to microsurgery as conventional instruments, they were safe for the ocular surface tissues in this study. There were no intraoperative complications and no need for conversion to conventional surgery. In all 3 cases, the different steps of AMT were feasible. Operative time and steps for each procedure are presented in the eTable in the Supplement. The 3 patients were discharged within 24 hours. In all cases, stable adherence of the AM was maintained.
tained until the epithelialization of the cornea was completed, 1 to 2 weeks after surgery. All patients acquired a smooth corneal surface without infection or ulceration.

Discussion
To our knowledge, the da Vinci Si Surgical System is the only surgical robot commercially available at this time. It has been used in experimental conditions to suture corneal lacerations (porcine eyes)\(^6\), perform penetrating keratoplasties (porcine and cadaver eyes)\(^6\), and remove foreign bodies, lens capsules, and vitreous (porcine eyes).\(^7\) Authors reported a lack of precision resulting from poor visualization of the operative field and the absence of microsurgical instruments. These elements were considered hurdles to further clinical investigations.\(^6\) After performing experimental ocular surface surgery including AMT on porcine eyes, we confirmed the feasibility of the procedures with the da Vinci Si Surgical System high-definition version. We performed AMT surgery using the patch technique in a clinical setting because it is one of the simplest and most commonly performed procedures in ocular surface surgery.

As previously reported by Mines et al.\(^8\) Tsirbas et al.\(^5\) and Bourges et al.,\(^6\) we confirmed that robotic procedures last longer than manual procedures. This is in part owing to the lack of the surgeon’s experience in robotic surgery compared with conventional manual ophthalmological microsurgery (2 years vs 20 years). Additionally, the remote center of motion of the da Vinci Si Surgical System (pivot point) is too proximal when compared with conventional manual surgery where surgeons directly handle the instruments with their fingertips. However, the extreme mobility of the distal articulation of the arm supporting the robotic instrument and the suppression of physiological tremor improves the quality of surgical movements. This is useful when surgeons have to work in a small operative field, in positions with poor ergonomics, or on patients with prominent noses or superciliary arches. Concerning the visualization of the operative field, we found that both the magnification and quality of the 3-dimensional image were good in the da Vinci Si Surgical System high-definition version and close to those that one finds in modern surgical microscopes. The millimetric precision provided was acceptable for ocular surface surgeries such as AMT, but this precision must be increased to the micrometer level for intraocular anterior or posterior segment surgery. We appreciated being able to use both consoles. The robotic surgeon and the assistant in conventional manual ophthalmological surgery simultaneously manipulated the 3 robotic arms.

Conclusions
Robotic assisted ocular surgery is technically feasible and safe for humans. Continued research will certainly lead to improvements in robotically assisted microsurgery, such as the development of specific microsurgical instruments, automatization of repetitive movements, and implementation of imaging and laser delivery systems. Experimental prototypes of robots entirely dedicated to eye surgery are currently being developed.\(^9\)\(^10\) Use of a robot for an AMT may seem superfluous because there is currently no notable improvement when comparing robotically assisted surgery and conventional manual surgery. Nonetheless, we are confident that future studies will allow for the definition of override indications for robotic ocular surgery directly linked to its specific advantages including increased precision and maneuverability, scalability of motion, tremor filtration, better ergonomics, the ability to simultaneously manipulate 3 surgical instruments and cameras, improved patient access to surgeons, and surgical training. Robotic surgery is now a clinical reality in ophthalmology.

REFERENCES