Rapamycin Inhibits Formation of Urethral Stricture in Rabbits

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ABSTRACT

Rapamycin has been reported to inhibit hepatic fibrosis, lung fibrosis, renal fibrosis, and subglottic stenosis. Fibrosis is also involved in urethral stricture. Therefore, we investigated the effect of rapamycin on the inhibition of urethral stricture formation in a rabbit model. First, models of urethral stricture were successfully established by electrocoagulation of the bulbar urethra in adult New Zealand male rabbits. Forty-six model rabbits were randomly assigned to four groups: high-dose rapamycin (RH, 1.0 mg/day), low-dose rapamycin (RL, 0.1 mg/day), dimethyl sulfoxide (DMSO) alone (DMSO, solvent control), and normal saline (NS). Urethral stricture was assessed by a retrograde urethrogram and video-urethroscopy. Urethra pathology was evaluated by hematoxylin and eosin and Sirius red staining. After 28 days of treatment, lumen reduction in the RH, RL, DMSO, and NS groups was 36.0, 56.5, 69.1, and 82.9, respectively. Comparison of the rapamycin groups (RH and RL) and control groups (DMSO and NS) indicated significantly less restriction in the rapamycin groups. Histopathological analysis confirmed the presence of fibroblasts and an increase in collagen at the stricture site in the two control groups but not in the RH or RL groups. These results indicate that rapamycin inhibits experimentally induced urethral stricture formation in rabbits. This effect may be due to its inhibition of fibroblast proliferation and collagen expression.

Introduction

Urethral stricture is a frequent source of lower urinary tract disorders in men. In this condition, there is a narrowing of the urethra by a noncompliant section of urethral scar tissue that is caused by repair of an insult. The most common causes of urethral stricture are idiopathic, transurethral resection, urethral catheterization, pelvic fracture, and surgery for hypospadias (Lumen et al., 2009). Urethral dilation and visual internal urethrotyomy are the most common treatments for urethral stricture. These procedures can transiently improve urinary flow, but repeated instrumentation may exacerbate scar formation and complicate subsequent reconstruction (Waxman and Morey, 2006). Repeat dilation or urethrotyomy is considered to be neither clinically effective nor cost-effective (Greenwell et al., 2004). Urethroplasty has a better cure rate (Langston et al., 2009) but is not a routine procedure because it requires certain expertise.

Fibrosis, caused by excessive collagen synthesis and changes in the composition of the extracellular matrix, is a key event in the pathogenesis of urethral stricture. Varying degrees of spongiofibrosis lead to poorly compliant tissue and decreased urethral lumen caliber (Brandes, 2008). Elongated myofibroblasts, involved in continuous collagen synthesis, occur in the early stages of stricture formation.

On the basis of treatments for organ fibrosis, previous studies have examined the effect of antifibrotic drugs, such as halofuginone (Nagler et al., 2000; Krane et al., 2011), mitomycin C (Mazdak et al., 2007), botulinum toxin A (Kherra et al., 2004), somatostatin analog (Andersen et al., 2003a), and glucocorticoid (Sciarra et al., 2005), in limiting urethral stricture formation. However, there have been no systematic studies of the effect of drugs on urethral stricture, and further studies are needed to evaluate the effectiveness and safety of drugs before clinical testing. Therefore, there is an urgent need to identify new agents that can be used in the treatment of urethral strictures.

Rapamycin, an immunosuppressive agent, inhibits proliferation of diverse cell types, including smooth muscle cells, endothelial cells, and fibroblasts, which are crucial to the development of fibrosis. Previous studies have reported that rapamycin significantly inhibited hepatic fibrosis (Biecker et al., 2005), lung fibrosis (Korfhagen et al., 2009; Mehrad et al., 2009), renal fibrosis (Damião et al., 2007), and subglottic stenosis (Branch et al., 2004). Fibrosis is also involved in

ABBREVIATIONS: DMSO, dimethyl sulfoxide; RH, high-dose rapamycin; RL, low-dose rapamycin; NS, normal saline; H&E, hematoxylin and eosin; mTOR, mammalian target of rapamycin.
urethral stricture. In the present study, we investigated the effect of rapamycin on the inhibition of urethral stricture formation in a rabbit model.

Materials and Methods

Experimental Animals. All experiments were performed according to the guidelines of the committee of animal research at Xi’an Jiaotong University and the Principles of Laboratory Animal Care (National Institutes of Health publication 86-23, revised 1985; Institute of Laboratory Animal Resources, 1996). All animals were adult male New Zealand rabbits, 4 months old, with a weight of 2.00 ± 0.19 kg. Rabbits were kept in special cages in a specific pathogen-free environment and were allowed free movement and free access to food and drink.

Surgical Induction of Urethral Stricture. All rabbits were anesthetized with intravenous diazepam (25 mg/kg) and ketamine (2.5 mg/kg). A 13-French pediatric resectoscope (Hangzhou Hawk Optical Electronic Instruments Co., Ltd., Hangzhou, China) was used for endoscopic procedures. For surgery, rabbits were placed in a supine position and a standard 10-mm-long circumferential electrocoagulation of the bulbar urethra was induced under sterile conditions. This procedure was performed distal to the verumontanum and away from the external sphincter with a hook-shaped electrode at a power of 40 W (Jaidane et al., 2003). Electrocoagulation was continued until blanching and ulceration of the mucosa occurred (Meria et al., 1999; Jaidane et al., 2003), typically approximately 1 min. All electrocoagulation procedures were performed by the same urologist (H.L.) who aimed to use the same length and depth for all animals. Urine was not diverted deliberately, and no antibiotics were given.

Drug Administration. After electrocoagulation, animals were randomly allocated into four groups: 1) DMSO (50 g/l DMSO, 10 ml/day, n = 8); 2) high-dose rapamycin in DMSO (RHL) (1.0 mg in 10 ml of solvent/day, n = 15); 3) low-dose rapamycin in DMSO (RL) (0.1 mg in 10 ml of solvent/day, n = 15); or 4) normal saline (NS) (9 g/l NaCl, 10 ml/day, n = 8). Drugs were given once per day for 28 days by retrograde urethral injection for 1 to 2 min, beginning on the 1st day after electrocoagulation.

Evaluation of Urethral Stricture. During the radiological, urethroscopic, and histopathological evaluations, the evaluator was blinded to treatment group. Twenty-eight days after electrocoagulation, urethral gross morphology was evaluated by retrograde urethrogram and urethroscopy. Contrast medium (20 ml of 760 g/l meglumine amine diluted by 20 ml of 9 g/l sodium chloride) was injected slowly and directly into the urethra by the same experienced urologist (H.L.) who aimed to use the same length and depth for all animals. Urine was not diverted deliberately, and no antibiotics were given.

Histological Examination. All urethras were processed for histological examination as described by Andersen et al. (2003b). Formaldehyde was injected into the urethra under a pressure of 1.8 kPa for 30 min. Then, the urethra was removed, fixed in formaldehyde for 24 h, and embedded in paraffin. Sections were cut corresponding to the two distension sites, longitudinal to the posterior wall and perpendicular to the posterior wall, and stained with Sirius red and H&E. All slides were reviewed by the same uropathologist (K.W.). The severity of scar formation was classified as light, medium, or heavy.

Statistical Methods. Means and S.D.s were calculated and presented for each group. Comparisons were performed using analysis of variance with post hoc comparison adjusted by the Bonferroni method. Data were analyzed using SAS 9.0 (SAS Institute Inc., Cary, NC). p < 0.05 was considered statistically significant.

Results

One rabbit in the RH group and one rabbit in the NS group died during anesthesia. Urethral bleeding occurred in almost all rabbits after electrocoagulation but was not severe and stopped after 3 days in all cases. Two rabbits in the RH group, three rabbits in the RL group, and two rabbits in the DMSO group developed diarrhea and were sacrificed during the 1st week. Thus, we evaluated treatment effects for 12 rabbits in the RH group, 12 rabbits in the RL group, 6 rabbits in the DMSO group, and 7 rabbits in the NS group. There were no obvious abnormal reactions during the 28-day treatment period.

Retrograde Urethrography and Urethroscopy. All rabbits in the control groups had significant urethral strictures. The lumen diameter decreased 82.9 ± 17.2% in the NS group and 69.1 ± 8.81% in the DMSO group. Two of the 12 rabbits in the RH group (17%) and 8 of 12 rabbits in the RL group (67%) developed significant strictures. The mean lumen diameter decreased 36.5 ± 21.5% (range, 12.9–79.3%) in the RH group and 56.6 ± 17.4% (range, 13.8–77.3%) in the RL group. Urethral stricture was significantly greater in the NS group than in the RH group (p < 0.05) and the RL group (p < 0.05). The DMSO group had significantly more stricture than the RH group (p < 0.05) but not the RL group (p > 0.05) (Fig. 1; Table 1). In five rabbits of the RH group, contrast medium leaked out of the urethral tract.

Based on urethroscopy, the urethral epithelium covered the traumatized surface, except in five rabbits in the RH group, in which leaking contrast medium was observed on the urethrogram. The unhealed mucosa had a rugose surface with slight edema and hyperemia (Fig. 2).

Histology. We observed varying degree of fibrosis beneath the epithelium in rabbits given different treatments (Fig. 3). The two rapamycin-treated groups had fibrosis that was mainly localized in the submucosal layer (Fig. 3, A and B). However, the two control groups had fibrosis distributed over the submucosal and muscular layers (Fig. 3, C and D). In all cases, there were abundant cells present in the fibrotic tissues.

Finally, we performed Sirius red staining to identify the presence and amount of collagen in the urethral tissues (Fig. 4). The two rapamycin-treated groups had light red staining of the urethral stricture site, indicating relatively low collagen concentration (Fig. 4, A and B). However, the two control groups had a darker crimson staining, indicating the presence of abundant collagen (Fig. 4, C and D).

Discussion

In this pilot study, we used an animal model of urethral stricture to test the efficacy of intraurethral injection of rapamycin on the amelioration of urethral stricture. We found that rapamycin significantly reduced urethral stricture, an effect mediated by its inhibition of urethral fibroblast formation and/or reduction of collagen accumulation.

Previous researchers adopted rabbit models to investigate urethral stricture. Meria et al. (1999) developed a urethral stricture model in rabbits by use of endoscopic electrocoagulation. This is a particularly suitable model for study of urethral stricture because the rabbit urethra is similar to that of humans, rabbits are inexpensive experimental ani-
mals, and rabbits have relatively large-diameter urethras. Meria et al. (1999) performed 3- to 5-mm circumferential electrocoagulation of the bulbar urethra of New Zealand male rabbits and reported that 50% of the rabbits developed significant bulbar strictures at day 15. Jaidane et al. (2003) used the same model to study the amelioration of urethral stricture by halofuginone, an inhibitor of collagen expression. They performed 15-mm almost circumferential electrocoagulation of the bulbar urethra, leaving two free areas at the 11 o'clock and 1 o'clock positions. All rabbits had significant and severe urethral strictures, with a mean lumen decrease of 87.5%.

In this animal model of urethral stricture, it is important to induce a trauma that is neither too mild (which would have negligible physiological effects) nor too severe (which can lead to severe urine retention and death). Therefore, in our study, we performed a 10-mm-long circumferential electrocoagulation on all animals. We did not administer antibiotics during the perioperative period, because inflammation may play an important role in the formation of urethral strictures. Our procedure resulted in a mean 82.9 ± 17.1% reduction in lumen in the NS group with no evidence of urine retention.

This suggests that our procedure is appropriate for study of the formation of urethral strictures.

We used urethrogram to demonstrate that the urethral lumen was significantly reduced in the DMSO and NS control groups and that animals given low-dose or high-dose rapamycin had significantly less stricture. These results were confirmed by urethroscopy. Although our DMSO group

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<th>Group</th>
<th>n</th>
<th>Lumen Reduction</th>
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<tr>
<td>RH</td>
<td>12</td>
<td>36.5 ± 21.5</td>
<td>12.9–79.3</td>
</tr>
<tr>
<td>RL</td>
<td>12</td>
<td>56.6 ± 17.4</td>
<td>13.8–77.3</td>
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<tr>
<td>DMSO</td>
<td>6</td>
<td>69.1 ± 8.81</td>
<td>55.6–81.6</td>
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<tr>
<td>NS</td>
<td>7</td>
<td>82.9 ± 17.2†</td>
<td>55.6–96.5</td>
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* p < 0.05 compared with the RH group after Bonferroni adjustment.
† p < 0.05 compared with the RL group after Bonferroni adjustment.

Fig. 1. Representative retrograde urethrograms of rabbits in the RH (A), RL (B), DMSO (C), and NS (D) groups. Note the significant stricture formation in C and D but less stricture in A and B (arrows).
had slightly less urethral stricture than the NS group, this difference was not statistically significant. In addition, our results suggest that there may be a dose-dependent effect of rapamycin, on the basis of the slightly larger lumen size of the RH group (although this difference was not statistically significant). Although there are limitations to this pilot study, it is the first to demonstrate that rapamycin inhibits urethral stricture formation in an animal model. Previous studies have shown that rapamycin inhibits fibrotic diseases, including coronary artery restenosis after stent implantation (Moses et al., 2003), hepatic fibrosis (Biecker et al., 2005), lung fibrosis (Korfhagen et al., 2009; Mehrad et al., 2009),
myocardial fibrosis (Gao et al., 2006), and renal fibrosis (Wu et al., 2006; Damião et al., 2007). These physiological effects may be due to the rapamycin-mediated reduction in the number of fibrocytes (Mehrad et al., 2009) and/or prevention of collagen expression (Korfhagen et al., 2009; Mehrad et al., 2009). The inhibitory effects of rapamycin on cell growth have been demonstrated. A study by Faiivre et al. (2006) showed that rapamycin induced cancer cell death either by inducing apoptosis or autophagy; in that study, rapamycin induced a decrease in cyclin D expression, which led to an increase in p27 and eventually to late G1/S cell cycle blockage. As a “master-switch” between catabolic and anabolic metabolism, the mammalian target of rapamycin (mTOR), a kinase, is part of the phosphatidylinositol 3-kinase/AKT/mTOR pathway of cancer cell metabolism, and rapamycin is an established mTOR inhibitor; thus, rapamycin-mediated metabolic effects and blockage of cell cycle progression have been shown to slow the proliferation of several human cancer cell lines in a dose-dependent manner (Faivre et al., 2006).

Previous research also supports the role of collagen alterations induced by antifibrotic agents. Halofuginone-coated urethral catheters prevented periurethral spongiosis, which formed via an altered ratio of collagen type I relative to type III in a rat model of urethral injury (Krane et al., 2011). Fibrotic diseases are characterized by abnormal accumulation of extracellular matrix proteins and the resulting fibrotic lesions disrupt normal tissue architecture, contributing to organ failure; the multifunctional protein that is the mTOR regulates cell growth, proliferation, and differentiation and was shown to positively regulate collagen type I production via a phosphatidylinositol 3-kinase-independent pathway (Shegogue and Trojanowska, 2004). Rapamycin also inhibited platelet-derived growth factor-induced collagen synthesis in rat mesangial cells, inhibiting both cell proliferation and collagen synthesis (Kim et al., 2004). Results of these studies strongly suggest that if rapamycin can be a critical mediator of cell production and collagen overproduction, it can be a viable target for drug or gene therapies.

In the present study, our H&E staining and Sirius red staining results confirmed that there was less fibrosis and lower collagen content in the two groups treated with rapamycin and fewer fibroblasts in the two rapamycin groups. Thus, our histopathological findings are consistent with the hypothesis that rapamycin inhibits the proliferation of fibroblasts and reduces collagen expression, as proposed by Korfhagen et al. (2009) and Mehrad et al. (2009).

The purpose of this pilot study was to investigate the efficacy of rapamycin in reducing urethral stricture. We compared two dose rates (1 versus 0.1 mg/day) based on the dose rates of rapamycin used for immunosuppression during human renal transplantation and the fact that rabbits are approximately 10-fold more tolerant of rapamycin than humans. We observed no adverse effects on the general state of the rabbits. However, we did note unhealed urethral mucosa in five rabbits of the RH group. This observation indicates that 1 mg/day of rapamycin in our rabbit model may have adversely affected the post-traumatic healing process of the urethral epithelium, possibly due to the powerful inhibitory effect of rapamycin on fibroblast proliferation (Kahn et al., 2005). We suggest that future studies examine further the dose dependence of rapamycin on the amelioration of urethral stricture.

In conclusion, our results indicate that rapamycin significantly reduced urethral stricture and that this physiological effect may be mediated by its inhibition of the proliferation of urethral fibroblasts and/or its reduction of collagen accumulation. We suggest that future studies of the effect of rapamycin on urethral stricture include more animals, provide more detailed examination of the dose dependence of rapamycin, and use longer follow-up periods.
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Authorship Contributions

Participated in research design: Chong, Fu, and Li.
Conducted experiments: Chong and Fu.
Contributed new reagents or analytic tools: Li.
Performed data analysis: H. Zhang, P. Zhang, and Gan.
Wrote or contributed to the writing of the manuscript: Chong, Fu, and Li.

Other: Li and Wang acquired funding for the research.

References

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