Review Article

Therapeutic strategies against TGF-β signaling pathway in hepatic fibrosis


Abstract: Hepatic fibrosis is the common wound-healing response to chronic liver injury. In this process, activation of hepatic stellate cells is characteristic of cell proliferation and migration, production of collagen and other extracellular matrix (ECM) molecules, and contraction after transforming into myofibroblasts. It has been shown that the fibrogenic process is prominently regulated by transforming growth factor-β1 (TGF-β1) and that the specific blockade of TGF-β1/Smad3 signaling may therapeutically intervene the fibrosis of various tissues. In this review, we attempt to integrate recent advances in the understanding of the mechanisms underlying TGF-β1/Smad3 pathway modulation of ECM gene expression in the context of liver fibrosis, discuss intervention strategies targeting the blockade of related signal pathways, and look into novel ways to the safe and efficacious prevention and treatment of hepatic fibrosis.

Liver fibrogenesis represents the common response of the liver to toxic, infectious, or metabolic agents and is characterized by excessive accumulation of extracellular matrix (ECM) caused by both increased synthesis and deposition of newly formed components, and decreased or unbalanced degradation of ECM (1, 2), ultimately leading to cirrhosis and many complications: portal hypertension, liver failure, and hepatocellular carcinoma. Both clarification of the molecular mechanisms underlying pathological fibrosis and the development of effective therapy are of clinical importance. A central role in fibrogenesis has been assigned to transforming growth factor-β1 (TGF-β1), which is a particularly well-studied cytokine and widely regarded as a pro-fibrogenic agent in liver injury, particularly after chronic liver injury (3, 4).

The multiple biological actions of TGF-β1, which involves in a variety of biological processes including development, cell growth, differentiation, cell adhesion, migration, ECM deposition, and the immune response, contribute to the regulation of the production, degradation, and accumulation of ECM proteins in a direct or indirect manner. TGF-β1 may play a pivotal role in the fibroproliferative changes that follow tissue damage in many vital organs and tissue, including liver, lung, kidney, skin, heart, and arterial wall (5–7). Fibrotic pathologies are associated with increased levels of TGF-β1 that initially recruit inflammatory cells and fibroblasts into an area of injury and then stimulate these cells to produce cytokines and ECM, because TGF-β1 not only enhances ECM synthesis but also inhibits ECM degradation by downregulating expression of matrix-degrading enzymes and promoting expression of matrix metalloproteinase (MMP) inhibitors (8, 9). In addition, TGF-β1 also appears to induce tissue inhibitor of metalloproteinases-1 (TIMP-1) (9).

High levels of TGF-β1 are often found in hepatic fibrosis and it has been implicated as a mediator of fibrosis in many liver diseases (10). Liver fibrosis occurs as a consequence of the transdifferentiation of hepatic stellate cells (HSCs) into myofibroblasts and is associated with an increased expression and activation of TGF-β1. It is believed that release of TGF-β1 by necrotic hepatocytes may be one of the first signals to activate adjacent quiescent HSCs, resulting in their transdifferentiation into proliferative, fibrogenic, and contractile myofibroblasts.
Blocking TGF-β1 signaling has been implicated in numerous animal models of fibrosis as well as in several human fibrotic diseases, including radiation fibrosis (7, 11). For example, antagonizing TGF-β1 pathway using neutralizing antibodies, soluble type II receptors, antisense oligonucleotides and RNA interference technologies, and small molecular inhibitors has been shown to perturb various types of TGF-β-mediated fibrosis (7, 11–13). So TGF-β1 signaling can be designated as anti-inflammatory and potentially anti-fibrogenic targets (14). These findings have major translational implications for therapeutic strategies aimed at TGF-β1/Smad3 signaling. Indeed, TGF-β1 is crucial in rat liver fibrogenesis in vivo, implicating that inhibition of TGF-β is effective in not only preventing fibrosis, but also preserving organ function.

According to these characteristics, there are three lines of evidence that TGF-β1 has a causal role in pathological fibrosis. Firstly, TGF-β1 levels are elevated in diseased organs and are often specifically localized to fibrotic areas. Secondly, administration of exogenous TGF-β1 to laboratory animals leads to the development of fibrosis in some organs, and to cultured cells leads to excess ECM deposition. Finally, anti-TGF-β1/Smad3 therapies could lessen experimentally induced fibrosis.

An interesting question is whether anti-TGF-β1/Smad3 intervention can prevent fibrogenesis or halt the progression of fibrosis in an organ in which fibrosis is already well established. In this review we will focus on recent insight into the molecular effects of anti-fibrogenic targets, especially the TGF-β1/Smad3 pathway, explore the therapeutic strategies for suppressing the action of several key proteins in the cascade and discuss the advantages and disadvantages of antagonists to the TGF-β pathway.

**TGF-β/Smads signaling pathway**

TGF-β superfamily consists of over 40 ligands including three TGF-β isoforms, activins, inhibins, bone morphogenetic proteins (BMPs), growth and differentiation factors, anti-mullerian hormone (AMH), myostatin, and others (15). Mammal cells express three highly homologous TGF-β isoforms such as TGF-β1–3. They have similar biological activities in vitro with noticeably different biological responses in vivo, although many members of the superfamily signal through a similar pathway. It is thought that TGF-β1 plays the most significant role in wound healing and organs fibrogenesis (16).

Briefly, two types of transmembrane protein kinases, types I and II receptors, mediate signaling by TGF-β. Ligands interact with a homodimer of type II receptors (TβRII), which recruit and activate type I receptors (TβRI, activin receptor-like kinases, ALKs). The TβRII kinase then phosphorylates TβRI in a glycine- and serine-rich juxtamembrane region called the GS box, which is one of the critical events in TGF-β signaling and serves as the initiation point for the downstream events. Activated ALKs phosphorylate a subset of the downstream signaling molecules, the receptor-activated Smads (R-Smads), which enables their binding to the common Smad (Co-Smads). And R-Smad/Co-Smad complex is shuttled into the nucleus where it can interact with various transcription factors and regulate transcription of many target genes (16, 17) (Fig. 1).

Five type II receptors (BMPRII, ActRII, ActRIIB, TβRII, and AMHR), seven type I receptors (ALK1–ALK7), five R-Smads (Smad1, Smad2, Smad3, Smad5, and Smad8), one Co-Smad (Smad4), and two I-Smads (Smad6 and Smad7) are recognized in mammalian cells. ALK1, ALK2, ALK3, and ALK6 phosphorylate and activate Smad1, Smad5, and Smad8, whereas ALK4, ALK5, and ALK7 phosphorylate and activate Smad2 and Smad3 (15, 18, 19).

TGF-β1 is a secreted homodimeric protein that regulates numerous cellular responses such as proliferation, differentiation, migration, and apoptosis, and initiates TβRII–ALK5–Smad2/3 pathway in most cells (19). Reports have pointed out a cooperative genetic interaction between Smad2 and Smad3 (20, 21). Although both Smad2 and Smad3 mediate signals from extracellular TGF-β and activin, it is thought that there may be other accessory proteins involved in regulating the balance of Smad2/Smad3 signaling (21).

It has recently been proved that TGF-β1/Smad3 signaling is mediated via two Smads pathways in endothelial cells: TGF-β1 may activate the two TβRI (ALK1 and ALK5) and then activated ALK5 phosphorylates the Smad2/3 protein while activated Smad1/5 signals through the ALK1 pathway. In the regulation of target gene transcription, ALK5 induces various types of collagen (including COL1A2, COL3A1, COL5A2, COL6A1, COL6A3, and COL7A1), TIMP, PAI-1, and other ECM genes, while ALK1 regulates c-myc gene transcription (9, 22–26). In endothelial cells, ALK5 inhibits their migration and proliferation, whereas ALK1 stimulates both the processes (18). These results indicate that TGF-β1 can initiate ALK5–Smad2/3 and ALK1–Smad1/5 signaling pathway.
As an I-Smad, Smad7 binds competitively to the type I receptor, blocks recruitment and phosphorylation of Smad2/3, and recruits E3-ubiquitin ligase for degradation of types I and II receptor complexes (27–29). In addition, Smad7 has been shown to recruit a complex of GADD34 and the catalytic subunit of protein phosphatase 1 to dephosphorylate and inactivate ALK5 (30). A body of evidence shows that Smad7 expression is induced by TGF-$\beta_1$, enabling rapid downregulation of the TGF-$\beta_1$ response in turn (31–33).

**TGF-$\beta_1$ levels in hepatic fibrosis**

High levels of TGF-$\beta_1$ are often found in many fibrotic tissues. The cytokine has been implicated as a mediator of fibrosis in many liver diseases (34). In fibrotic diseases of all tissues, regions of ECM excessive deposition show high expression of TGF-$\beta_1$ (35). Accordingly, the TGF-$\beta_1$ gene is upregulated in response to tissue injury, which correlates with the fibrogenic activities (7).

In liver disease

In patients with fibrosis and cirrhosis, significantly high level of TGF-$\beta_1$ was detected. For example, the expression of TGF-$\beta_1$ mRNA in peripheral blood mononuclear cells of alcoholic cirrhosis patients was remarkably increased (36), matching with the high protein level in the loci from other reports (37, 38).

The study on 38 children patients with cystic fibrosis liver disease (CFLD) indicated that activated HSCs were the preeminent mediators (39). The dominant stimulus for ECM deposition by HSCs was mediated by the cytokine TGF-$\beta_1$. Active HSCs were demonstrated as the cellular source of excess collagen production in the fibrosis surrounding the bile ducts and the advancing edge of scar tissue. It was shown that bile duct epithelial cells predominantly expressed TGF-$\beta_1$ protein and mRNA. Thus, TGF-$\beta_1$ expression was significantly correlated with both hepatic fibrosis and percentage of portal tracts showing histological abnormalities associated with CFLD.

In fibrotic liver, from patients and fibrotic rats resulted from bile duct ligation and scission, high levels of TGF-$\beta_1$ RNA were present in most mesenchymal liver cells, in most inflammatory cells, and in few bile duct epithelial cells (40). Two models of hepatic fibrogenesis, one induced by the administration of carbon tetrachloride and the other by infection with schistosoma, increased concentrations of TGF-$\beta_1$ mRNA and TGF-$\beta_1$ in perisinusoidal cells paralleled the increased
expression of collagens (41). In addition, total TGF-β was found to increase in porcine serum-induced rat models (42). These suggested that the effects of TGF-β in liver regeneration and fibrogenesis might be central.

In cultured HSCs

The steady advances in basic research exploring mechanisms of hepatic fibrosis have fueled tremendous progress in elucidating its pathophysiology. Central among these has been the identification of HSCs and their myofibroblastic counterparts as key sources of an array of mediators, matrix molecules, proteases, and their inhibitors that orchestrate the wound-healing response in liver. Methods to isolate and characterize HSC have provided tools to explore the pathogenesis of hepatic fibrosis in cultured cells of this type, animal models and human diseases (43).

Transcriptional upregulation of the TGF-β gene has been demonstrated in culture-activated HSCs (44). In the process of HSCs conversion to myofibroblasts, TGF-β mRNA and proteins show a sustaining increase in vitro (42, 45), corresponding with the characteristics of HSCs in vitro from fibrotic models induced by ligation of the bile duct (38). Rat HSCs in early primary culture exhibit a strikingly high expression of TGF-β, while they sustain a new peak of the cytokine after partial heptectomy. In liver fibrotic models induced by ligation of the biliary duct, mRNA of TGF-β was found to increase expression only in HSCs (3).

Others

TGF-β1 plays a central role in diverse forms of wound healing. Evidence supporting this view comes from data indicating that elevated levels of plasma TGF-β correlate with increased fibrogenesis, including lung, kidney, skin, wound healing, eyes, and others fibrotic diseases (46–51).

**Fibrogenesis induced by exogenous TGF-β**

As already noted, TGF-β1 causes the ECM deposition by simultaneously stimulating cells to increase the synthesis of matrix proteins, decrease the production of matrix-degrading proteases, increase the production of inhibitors of these proteases, and modulate the expression of integrins in a manner that increases cellular adhesion to the matrix. Potential evidence provided by a large number of studies is that administration of exogenous TGF-β1 could induce fibrotic lesions in local tissues and organs in vitro or ECM deposition in vivo or ECM deposition in vitro in cultured cells.

**Effects of TGF-β1 on fibroblasts**

HSCs are the major source of ECM components, and the activation of them is a crucial event in liver fibrogenesis, in which TGF-β1 is one of the key cytokines in the process. TGF-β1 treatment stimulates expression of ECM molecules but inhibits proliferation and induces phenotypic transdifferentiation in vitro (52). In addition, TGF-β1 stimulates collagen fiber formation in M cells (53). With regard to other fibroblasts, such as chick embryo backskin fibroblasts, it synthesized new ECM by exogenous TGF-β1 in vitro (54). Furthermore, the mRNA of type I collagen, the predominant matrix component in injured liver, is increased in cultured rat hepatocytes incubated with TGF-β1 (41).

**Effects of TGF-β1 in vivo**

Delivery of exogenous TGF-β1 by various means to tissues could result in severe fibrosis in experimental animals, and hepatic fibrosis was seen, which facilitates the understanding of TGF-β1 action and liver fibrogenic mechanisms. Intravenous administration of recombinant TGF-β1 to rats induced fibrotic lesions in the liver, kidney, pancreas, bone, heart, thymus, stomach, and cecum (55).

Because transgenic models are important and a further answer to the function of TGF-β1, which may also provide an appropriate paradigm for testing therapeutic interventions aimed at neutralizing the detrimental effects of this important cytokine, a large majority employed overexpressed transgenic models. For example, transgenic mice overexpressing a constitutively active human TGF-β1 developed fibrosis of the liver, kidney, and adipose tissue, and exhibited a severe reduction in body fat. Expression of the transgene in hepatocytes resulted in increase of collagen production, altered lobular organization, increased hepatocyte turnover, and, in extreme cases, hemorrhage and thrombosis (56). With a fusion gene consisting of a cDNA coding for the mature form of TGF-β1 under the control of the C-reactive protein gene promoter, a transgenic model with highly TGF-β1 expression was developed, which formed severe liver fibrosis in 6 weeks (57).

Other reports showed that transfection of the TGF-β1 gene into normal mice or rats resulted in the rapid development of liver fibrosis and glomerulosclerosis, which was characterized by ECM deposition including types I, II and IV collagen, and FN (58–60). With expression of high levels of the TGF-β1 in the livers and plasma, transgenic mice died because of hepatic
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fibrosis and apoptotic death of hepatocytes. The fibrotic process was characterized by deposition of collagen around individual hepatocytes and within the space of Disse in a radiating linear pattern. One line even developed glomerulonephritis and renal failure, arteritis and myocarditis, as well as atrophic changes in pancreas and testis (58).

In the other tissues, such as lung (61), renal (60, 62), and wounded skin (48), increase in the tissue levels of TGF-β1 induced fibrogenic effects, including deposition of collagen, FN, elastin, and other ECM proteins.

These studies establish TGF-β1 as a primary mediator in pathological fibrosis, although fibrosis occurred in some but not all tissues in transgenic models of TGF-β1 overexpression, and the significance of local vs circulating TGF-β1 remains unknown.

Anti-fibrogenic approaches

Building of tissue requires coordination of several important cellular actions including fibrogenesis, proliferation, migration, contraction, fibrolysis, and apoptosis. Once an imbalance appears in processes of fibrogenesis and fibrolysis, it may lead to scar formation and tissue fibrosis. At the cellular level, these interrelated events are orchestrated by numerous factors including many cytokines and the ECM. An important early change in the local ECM in response to injury appears to be the addition of EDA fibronectin (6, 63) that is secreted from and endothelial cells stimulated by TGF-β. HSCs functions that may contribute to the formation of permanent scar include proliferation, migration, contraction, and angiogenesis.

The steady advances in basic research exploring mechanisms of hepatic fibrosis have fueled tremendous progress in elucidating its pathophysiology. Central among these has been the identification of HSCs and their myofibroblastic counterparts as key sources of an array of mediators, matrix molecules, proteases, and their inhibitors that orchestrate the wound-healing response in liver (64, 65). One of the responses to injury is migration of activated HSCs termed ‘myofibroblasts’ to the wound area, in which many cytokines maybe involved. TGF-β has been implicated in multiple facets of the injury response. The most direct evidence in the involvement of TGF-β in fibrosis comes from in vivo and in vitro experiments, where agents that block TGF-β function reduce the fibrotic response in the liver and other tissues. For example, administrations of TGF-β antibodies or antisense oligonucleotides, and soluble TβRII are beneficial in liver, lung, renal, skin, and other tissue fibrosis. But the most compelling example of events is that loss of Smad3 might be resistant to fibrogenesis. Based on these and other advances in understanding the fundamentals of the injury response and TGF-β1–Smad3 signal pathway, several strategies now exist for preventing or halting fibrogenesis, ranging from agents that block TGF-β signaling to small molecular compounds.

Indeed, there are a number of reports of cellular or animal models of fibrosis where loss of TGF-β1–Smad3 regulation results in a diminished fibrotic response. The results of these studies will be summarized below.

Disruption of TGF-β1 protein

Overwhelming evidence has demonstrated that sustained overexpression of TGF-β1 is a key mediator of fibrotic disease in all tissues. Because TGF-β1 protein, as an extracellular ligand, initiates the TGF-β1–Smads signal cascade it became a study target early. Several lines of evidence point to TGF-β as a key cytokine that initiates and terminates tissue repair and whose sustained production underlies the development of tissue fibrosis, which suggested that abolishment of TGF-β1 action could halt TGF-β1–Smad3 signaling and distinctly inhibit deposition of ECM in vitro and in vivo. The antibody of TGF-β earlier showed therapeutic intervention, and injecting anti-TGF-β antibody inhibited fibrogenic and inflammatory action of TGF-β1 in the liver, lung, kidney, skin, brain, joint, arterial wall, and other tissues (7).

In culture-activated HSCs, anti-TGF-β1 antibody treatment or the administration of adenoviruses constitutively expressing an antisense mRNA complementary to the 3’ coding sequence of TGF-β1 was able to attenuate the synthesis of TGF-β1 (66) and the production of collagen (42, 66). In addition, adenoviral expressing an antisense complementary to the rat TGF-β1 mRNA treatment could abolish the diverse effects of direct TGF-β1 function in ongoing liver fibrogenesis of rat models induced by ligation of bile duct (67).

TGF-β1 antibody could significantly reduce accumulation of collagen in bleomycin-induced mice lung (68) and prevent fibrotic complication in the lungs of mice with a murine scleroderma-tous graft-vs-host disease (47). Furthermore, TGF-β antibody inhibited both the radiation-induced reduction in clonogenic activity of rat lung fibroblasts and the radiation-induced terminal differentiation of progenitor fibroblasts to
postmitotic fibrocytes, which are essential cellular processes in the development of radiation-induced fibrosis in the lung (12).

A neutralizing monoclonal antibody against TGF-β1 attenuated kidney hypertrophy and the enhanced expression of ECM gene in experimentally diabetic mice (69). Another work showed that the antibody of TGF-β is a promising agent to prevent renal tubular fibrosis and apoptosis in unilateral ureteral obstruction (UUO) (70). In chronic progressive anti-thymocyte serum nephritis, the TGF-β/Smad signaling was upregulated, whereas TGF-β blockade by antibody suppressed the progression of renal scarring, at least in part, via inhibition of activated TGF-β/Smad signaling (71). Earlier reports showed that an intraperitoneal or subcutaneous treatment of murine anti-TGF-β1 antibodies could effectively prevent this disorder in adult rodents (48). A free myocutaneous flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gracilis flap was transplanted from the groin to the neck region in experimental rats, before gras

Block TGF-β1 signal halt liver fibrosis

For the type II TGF-β receptor, three strategies to block its signaling have efficaciously prevented fibrogenesis in the levels of cell and experimental models. One uses a ‘dominant-negative’ receptor strategy, in which a TβRII with a truncated cytoplasmic domain is delivered through a certain vector in which the adenovirus is generally used. The second approach is administration of a ‘soluble TGF-β receptor’, which consists of the extracellular portion of the TβRII spliced into chimeric IgG. Thirdly, the disruption of the gene interest is a consensus and authoritative technology, which includes gene knockout and knockdown, and the latter consists of both antisense and RNA interference methods.

Firstly, the ‘dominant-negative receptor’ strategy takes advantage of the high transfection of the adenovirus vector and the no-kinase action of the truncated TβRII. The adenovirus holds particular interest for the liver because of the fact that this vector homes predominantly in the liver after its intravenous administration (80). The strategy was proved to be able to abolish all the diverse signaling from TGF-β in arterial endothelial cells, lung epithelial cell, smooth muscle cells, and rat HSCs (81, 82). This type of receptor treatment could not only enhance hepatocyte regeneration in vivo (82), but also therapeutically attenuate liver fibrosis in dimethylnitrosamine (DMN)-induced rats (82–84). Using this approach, investigators not only decreased pancreatic fibrosis and protected the pancreas against chronic injury by preventing acinar cell apoptosis (85), but also inhibited luminal loss after percutaneous transluminal coronary angioplasty (PTCA) in porcine coronary arteries, which was caused by local deposition of collagen (86).

Secondly, the soluble TβRII, consisting of the extracellular portion of the TβR-II fused to the Fc or other portion of IgG, presumably functions as a competitive binder of TGF-β, preventing interaction of the cytokine with its normal receptor. As a distinct advantage over a small peptide competitor, which would be expected to disappear within a few minutes of injection, the IgG can circulate for several days. The intervening vehicle was often used the adenovirus vector mentioned above, too.

The soluble receptor not only bound TGF-β and blocked TGF-β-signaling in vitro, but also...
abrogated the fibrogenetic effect of TGF-β in animals subjected to bile duct ligation, DMN, and CCl4 treatment (84, 87, 88). There is now unequivocal and mounting evidence that fibrotic diseases of other tissues can be prevented or attenuated with this strategy, including hamster’s lung fibrosis induced by bleomycin and experimental renal disease (89–91).

Finally, although knockdown of TβRII gene led to a lethal inflammatory disease in adult animals (92), the gene knockdown by administration of an antisense TβRII recombinant plasmid was proved to halt formation of rat liver fibrosis induced by pig serum (93), and a small interference RNA (SiRNA), as a new tool for silencing of targeting gene, targeting TβRII could not only knockdown the TβR-II gene but also prevent ocular inflammation and scar formation in vitro and in vivo (94).

Inhibition of type I receptor

In most mammal cell types, TGF-β1 signals through ALK5, the TGF-β type I receptor, although TGF-β1 can bind to and transduce signals through ALK1 and ALK5 in other cell types (95, 96). It is notable that ALK5-deficient endothelial cells show an impaired TGF-β–ALK1 response (96), implicating that activated ALK5 is very important in TGF-β1–Smads signaling pathway and that disruption of TβRII biological action will effectively block TGF-β–Smad2/3 signal cascade. For example, administration of an antisense TβRI recombinant plasmid was proven to halt formation of rat liver fibrosis induced by pig serum (93).

Small molecular inhibitors had been proven extremely useful for investigating signal transduction pathways and have the potential for development into therapeutics for inhibiting signal transduction pathways whose activities contribute to human diseases. A new class of water-soluble small molecular inhibitors, related to imidazole inhibitors of p38, have recently been shown to inhibit the kinase activity of ALK4, ALK5, and ALK7. An initial inhibitor in this class, SB-431542, inhibited TGF-β-induced phosphorylation and nuclear translocation of Smad3 as well as TGF-β-induced COL1A1 mRNA levels (97–99). The compound inhibits TGF-β1-induced FN and Col Iα1 in renal epithelial carcinoma A498 cells and selectively inhibits kinase activity of ALK5 with IC50 of 94 nM in vitro. Another similar compound, SB-505124, was found to selectively interfere with ALK5 more potently than SB-431542 and abrogate cell death induced by TGF-β1 (100).

Intriguingly, a recent study demonstrated that blocking TGF-β effect through ALK5 inhibition displayed a promising approach for the treatment of liver fibrosis (101). GW6604, another small molecular inhibitor of ALK5, could not only inhibit TGF-β1-induced transcription of PAI-1 in vitro, but also facilitate the regeneration of liver that had undergone partial hepatectomy in TGF-β1 overexpressing mice. In addition, the compound significantly decreased the deposition of ECM and meliorated liver dysfunction in a DMN-induced fibrotic model.

These results further suggested that inhibition of ALK5 is an attractive new approach to treat liver fibrosis by both preventing matrix deposition and promoting hepatocyte regeneration.

Deletion of Smad3

Smad3 protein has been identified as an intracellular mediator in the fibrogenic process via TGF-β, p38 MAPK, and ERK MAPK signaling pathways (102, 103), and increasing evidence implicates Smad3 as at least a partial mediator of the fibrosis (21). For example, Smad3 completely mediates the expression of Col Iα1 in activated HSCs (104). In addition, Smad3 overexpression increased FN promoter activity, an effect that was enhanced by treatment with TGF-β. The TGF-β-stimulated activity of FN promoter was prevented by transfection with either a dominant-negative Smad3 or Smad7 in mesangial cells (105). The use of animals with a targeted deletion of Smad3 showed that most of the fibrogenic activities of TGF-β were mediated by Smad3. The loss of Smad3 interferes with TGF-β-mediated induction of epithelial–mesenchymal cell transition (EMT) and the expression of genes for collagens, PAI-1 and TIMP (21, 106). Smad3 null inflammatory cells and fibroblasts also do not respond to the chemotactic effects of TGF-β and do not autinduce TGF-β secretion (21).

Although TGF-β signaling plays a prominent role in liver fibrogenesis by HSCs and myofibroblasts during chronic liver injury, other cytokines also are involved in the process of fibrogenesis. For example, PDGF could lead to activation of p38 MAPK through binding PDGF receptors, and activated p38 MAPK pathway phosphorylates Smad3 at the linker region (102). It is suggested that basal Smad3 activation in myofibroblasts might be induced partially by PDGF via p38 MAPK signaling. Also, bodies of evidence indicate that MAPK and Smad3 pathway can interact with different outcomes, depending on the cellular context, although
Smad3 phosphorylation by p38 MAPK was unable to activate the transcription of PAI-1 (102). It is perfect that anti-fibrogenesis focuses at the Smad3 level, because the deactivated Smad3 could block not only TGF-β–Smad3 but also p38 MAPK–Smad3 and even other undefined pathways.

Another work, which explored the contribution of Smad3 in mediating TGF-β fibrotic responses in an acute liver injury model and in cultured HSCs, showed that hepatic Col I z1 and a2 mRNA of Smad3 homozygous knockout mice were significantly reduced than that of wild-type mice 72 h after CCl4 was induced. In culture-activated HSCs from Smad3 null mice, mRNA of Col I z1 was decreased (104). Smad3 null mice could resist lung fibrosis transient induced by using adenoviral vectormediated gene transfer TGF-β, associated with high spontaneous presence of MMP-9 and MMP-12 in the lung (107). Smad3 deficiency attenuated renal fibrosis, inflammation, and apoptosis after UUO. The deposition of types I and III collagens was significantly reduced in the obstructed kidney of Smad3 null mice. In addition, the numbers of myofibroblasts, macrophages, and CD4/CD8 T cells infiltrated into the kidney were significantly attenuated in the obstructed kidney of these mice (108). These results suggest that the Smad3 pathway plays a pivotal role in ECM metabolism, and involves pathogenic mechanisms mediating tissue destruction and fibrogenesis.

The study, which investigated the potential role of Smad3 in Smad3-null mice using a bleomycin-induced model of skin fibrosis, showed that lesional skin from null mice attenuated fibrosis, reduced synthesis and accumulation of collagen, and inhibited collagen gene transcription in situ, compared with wild-type mice, and that CTGF and a-SMA expressions in lesional skin were also significantly attenuated (109). Furthermore, the a-smooth muscle actin (a-SMA) was reduced in corneal repair tissue of Smad3−/− mice, although the expression of FN was unaffected (110).

Taken together, these data showed Smad3 as a pivotal mediator for TGF-β in modulating fibrogenic function and implicated that inhibition of Smad3 protein function might be a potential and effective therapeutic strategy to anti-fibrogenesis.

**Other strategies**

Besides the TGF-β signaling pathway, other pathways and factors have been found to involve tissue fibrosis. They include BMP-7, hepatic growth factor (HGF), protease inhibitors, and others. BMP-7, a member of TGF-β superfamily, has been shown to impede the progression of fibrotic disease and decrease interstitial volume, and prevent glomerular sclerosis. Experimental evidence suggests that administration of BMP-7 may be an effective treatment to restore or preserve renal histology and renal function (111). As KCP, an enhancer of BMP signaling, binds to BMP-7 and enhances binding to the type I receptor, Smad1-dependent transcription and phosphorylated Smad1 (P-Smad1) levels are increased. Further experiments indicated that Kcp(−/−) animals displayed reduced levels of P-Smad1, and became more susceptible to developing renal interstitial fibrosis (112) (BMP-7/Smads pathway in Fig. 1).

HGF has been identified to have antifibrogenic activity in rats. Several investigations demonstrated that HGF could inhibit stellate cell activation, decrease the mRNA levels of procollagenz2 (I), z1 (III), and z1 (IV), and influence the expression of a-smooth muscle actin, desmin, and TGF-β1. Furthermore, HGF plays anti-fibrogenic roles even after liver fibrosis has been established (113). Subsequently, Liu et al. found that SnoN physically interacted with activated Smad2 to form a transcriptionally inactive complex, which in turn superseded the profibrotic action of TGF-β1. The results suggest that HGF can interplay with TGF-β signaling pathway and block EMT through the upregulation of Smad transcriptional co-repressor SnoN expression (114). In addition, HGF stimulates or induces proteases involved in the breakdown of ECM proteins including MT1-MMP, uPA, and some MMPs, whereas it reduces TIMP-1 and TIMP-2 expression. Recently, Watanabe et al. reported that the addition of exogenous HGF significantly decreased TNF-a, IL-6, and collagen synthesis after bleomycin injury. Thus, HGF is likely to be against fibrosis in multiple ways (113, 115) (HGF pathway in Fig. 1).

Similarly, some protease and chemical inhibitors have been investigated in vitro and in vivo. In fibrotic models, TGF-β expression was suppressed and the tissue fibrosis was reduced by chymase inhibitors. Obviously, chymase inhibitors may be useful for preventing fibrosis via inhibition of TGF-β activation (116). Interestingly, Pirfenidone (PFD) is a recently developed antifibrotic agent. Chemically, PFD is a substituted pyridine molecule 5-metyl-1-phenil-2-(1H)-pyridine. This small molecule can prevent or even revert ECM accumulation, as found in pulmonary fibrosis, peritoneal sclerosis, cardiac fibrosis, and progressive renal fibrosis. PFD notably inhibits the stellate hepatic cell proliferation in rats, significantly reduces the mRNA level of...
TIMP-1, and suppresses the increment in TGF-β (117).

Upregulation of Smad7 expression

The interaction of R-Smads with their receptors is governed by several different regulators including Smad7. Smad7 is termed an inhibitory Smad because it competes with R-Smads for the type I receptor and blocks signal transduction (27–29). The introduction of Smad7 inhibits experimental fibrogenesis in vivo, while many studies with isolated HSC indicate that the underlying mechanisms involve inhibition of TGF-β signaling. The steady advances in basic research exploring mechanisms of hepatic fibrosis have indicated that the specific blockade of TGF-β signaling by expression of Smad7 may provide a new therapeutic potential for tissue fibrosis.

The most exciting report may be that Smad7 overexpression by adenovirus carrying Smad7 cDNA displays inhibited collagen and α-SMA expression and reduced hydroxyproline content in the common bile duct ligation rat livers (118). Smad7 expression totally blocked TGF-β signal transduction by inhibiting Smad2/3 phosphorylation, and nuclear translocation of activated Smads complexes resulted in decreased collagen I expression. Exogenous Smad7 also abrogated TGF-β-dependent proliferation inhibition of HSCs and destructed the fibrillar organization of the actin cytoskeleton (118).

The intratracheal administration of an adenovirus expressing Smad7 could prevent bleomycin-induced lung fibrosis in mice (119). Similar results from another study showed that the ectopic overexpression of Smad7 prevents the downregulation of surfactant protein C gene expression and blocks the phosphorylation of Smad2 induced by TGF-β in cultured lung (28).

Like liver fibrosis, TGF-β-mediated renal fibrosis is regulated positively by Smad3, but negatively by Smad7. The levels of Smad7 protein display a progressive decrease in UUO nephropathy in mice, whereas Smurf1 and Smurf 2 with eliminated Smad7 in turn show increased levels (120). The exogenous Smad7 introduced by recombinant adenovirus vector or ultrasound-mediated inducible gene transfection significantly inhibited renal fibrosis on UUO-induced renal fibrosis in rats (121, 122). In mesangial cells, the reporter gene showed that overexpression of Smad7 effectively blocked the activity of FN, Col Iα2 promoter, and other effects stimulated by TGF-β (33,105). Furthermore, the overexpression of inhibitory Smad7 in renal and vascular cells had been shown to suppress high glucose-induced Smad2 and Smad3 activation and collagen synthesis (73).

Smad3 phosphorylation and PAI-1 expression were augmented in systemic sclerosis (SSc) fibroblasts as compared with normal fibroblasts, while adenovirus-mediated overexpression of Smad7 restored normal PAI-1 production in SSc fibroblasts (123). In addition, adenovirus-mediated transient expression of Smad7 prevented the injury-induced EMT of lens epithelial cells and the sealing of capsular broken with fibrous tissue (124). Furthermore, anti-TGF-β effects of IFN-α on diverse cellular functions, specifically anti-liver fibrosis, might be through inducing the expression of Smad7 (125, 126).

Gene silencing of TGF-β/Smad3 pathway

A potent strategy to anti-fibrosis

As new approaches to gene therapy, except the transgenic approach, there are two methods that interfere with the manufacture of proteins in mammal cells such as antisense and RNA interference. Numerous experiments have shown that gene silencing may be a new way to treat fibrosis.

Antisense and ribozyme oligonucleotides

Introducing a neutralizing ‘antisense’ version of RNA can modify TGF-β mRNA bioactivity, showing anti-fibrogenic characterization. An antisense complementary to the 3' portion of rat TGF-β1 mRNA, expressed by an adenoviral vector, could abolish the diverse effects of direct TGF-β1 function in ongoing liver fibrogenesis (67). The TβRII gene knockdown by administration of antisense TβR-II recombinant plasmids was proven to halt formation of rat liver fibrosis induced by pig serum (93). A recent study showed that TGF-β1 expression was significantly down-regulated in activated HSCs by U1 snRNA chimeric ribozymes, and that U1 snRNA chimeric ribozymes reduced the synthesis and deposition of Col I in transfected HSC-T6 cells. In addition, the ribozyme expressed by adenoviral vector could alleviate fibrotic pathology in rats treated with carbon tetrachloride (127).

In UUO rat kidneys, it has been revealed that TGF-β1 antisense oligodeoxynucleotides treatment dramatically decreased TGF-β1 and type I collagen mRNA levels, and significantly reduced the interstitially fibrotic area of the obstructed kidneys (128, 129). Because TGF-β2 is the predominant form in the eyes (49), antisense oligonucleotides against TGF-β2 remarkably reduced postoperative scarring and improved surgical outcome of eyes in two different animal models.
(130, 131). In addition, the ribozyme oligonucleotides to actively cleave the targeted TGF-β gene suppressed the TGF-β1 expression in vivo (132), reduced collagen synthesis and their mRNA level, and significantly inhibited neointimal formation after vascular injury in the rat carotid artery model. The results indicated that ribozyme gene therapy, like antisense oligonucleotides, could act as a new avenue for the treatment of diverse diseases caused by TGF-β1 overexpression (132).

Although antisense phosphorothioate oligonucleotides and ribozymes anti-TGF-β1 could reverse the character of tissue fibrosis in vitro and improve fibrotic pathology in vivo, their effectiveness, stability, specificity, and security are still in debate, whereas RNA interference may be a new way to inhibit tissue fibrosis.

RNA interference (RNAi)–small interfering RNA (siRNA)

The discovery of RNAi has opened an unanticipated new window on gene expression regulation. RNAi technology has been employed as a facile and effective tool for function valuation and target gene identification (133, 134). A large number of studies with animal models have confirmed that RNAi may conceivably be exploited for human therapeutics in the future, possibly bringing greater clinical excition than have the so far disappointing antisense endeavors (134, 135).

As a new technology for silencing of targeting gene, siRNA targeting Smad3 could not only inhibit Smad3 transcription and nuclear localization, but prevent TGF-β1-induced growth arrest and promoter activity in murine B-cell lymphoma lines and mink lung epithelial cell line (Mv1Lu) (135). A common siRNA targeting the cognate sequence of Smad3 mRNAs from human, rat, and mouse species designed by our group could effectively decrease levels of Smad3 mRNA and collagen I mRNA in cultured rat HSC-T6 cell line. This approach had also had similar applications for other tissues, including eyes, skin, kidney, and lung. For example, siRNAs targeting TβRII could not only knockdown the TβR-II gene but also prevent ocular inflammation and scar formation in vitro and in vivo (94).

Moreover, the knockdown of TGF-β1 and TGF-β2 by siRNA technology could prevent the downregulation of NKG2D on immune cells mediated by LNT-292 gioma cell supernatant, strongly enhance MICA expression in the glioma cells and promote tumor recognition and lysis by CD8(+)+T and NK cells. TGF-β silencing could also lead to a less migratory and invasive glioma cell phenotype in vitro (136).

Block TGF-β1 signal halt liver fibrosis

The antisense oligonucleotides, ribozymes, and RNAi can reverse fibrotic pathology in vitro and in vivo, indicating that TGF-β1 might be a novel candidate for therapeutic strategies against hepatic fibrosis.

Conclusion and perspectives

Overwhelming evidence has demonstrated that sustained overexpression of TGF-β is a key mediator of fibrotic tissues. The potentially fibrogenic effects of TGF-β include stimulation of matrix synthesis, inhibition of matrix degradation, and modulation of matrix receptor expression. In addition, TGF-β1 also alters the number and expression of various integrins on some cells, and potentially enhances their adhesion to the ECM (137, 138). Hence, anti-TGF-β1/Smad3 intervention might be therapeutic in already-established fibrotic livers, not only by suppressing fibrosis, but also by facilitating hepatocyte regeneration (82).

Although TGF-β1/Smad3 antagonists have been shown to be effective anti-fibrogenic agents, they need detailed safety testing and efficacy evaluation. Firstly, besides TGF-β, many signaling agents, including platelet-derived growth factor (PDGF), endothelin (ET), TIMP, and TNF-α, are likely to contribute to liver injury and repair (6, 65, 102, 139). And it has been proposed that the combination of connective tissue growth factor (CTGF) and TGF-β is needed for optimal matrix synthesis (6, 140). Second, inhibition of the TGF-β/ALK5 pathway may activate TGF-β/ALK1 in endothelial cells (18) and BMP/Smad1 pathways in HSCs (141). Third, the anti-proliferative action of TGF-β has been documented largely with particular evidence in HSCs and rats (4). It has been shown that inhibition of TGF-β during liver fibrogenesis leads to increased HSCs proliferation (87). Moreover, it should be emphasized even more that up to now there are no long-term animal experiments available systematically studying side effects of systemic TGF-β inhibition. Thus, it is attractive to speculate that the high dose of antagonists of TGF-β signaling might potentially stimulate proliferation of HSC (53, 142) and offset their antifibrotic effects such as precancerous risks, various autoimmunopathies, atherosclerotic lesions, and chronic inflammatory diseases (143). Finally, TGF-β is a potent immunosuppressive agent and plays a role in the pathogenesis of chronic inflammatory diseases, so that blocking TGF-β may stimulate the development of autoimmune diseases (14, 143–145).
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Considered together, one concern is that long-term administration of TGF-β antagonists, including antibody, soluble receptor, small molecular inhibitors, and siRNAs, might increase the immunoinflammatory axis of diseases and result in the exacerbation of inflammation and the unexpected injury of the liver and other organs. In addition, because TGF-β/Smad signaling forms cross-talk networks with other signal pathways, inhibition of the signaling certainly affects the intricate networks and leads to unwanted side effects. Furthermore, a practical consideration with any method of blocking TGF-β can result in growth dysregulation (146) and increase risks of neoplasia issue (147, 148). All of them require careful planning in any clinical trial, although a report has showed an attractive experimental result that a soluble TβRII antagonist has potential for long-term clinical use in preventing metastasis (149, 150).

Because Smad3 plays such a critical role in mediating the pathology of fibrotic disease, inhibition of Smad3 may be a prime target for intervention in fibrotic conditions (102–110). A therapeutic agent that blocks only signaling through Smad3 might be ideal to inhibit fibrosis with minimal side effects. Concern about the safety, efficacy, and possible side effects of gene therapy strategies or systemic cytokine administration to inhibit fibrotic disease makes the use of small molecule inhibitors of Smad3 attractive therapeutic agents. And traditional Chinese herb extracts may be a new area, because several traditional Chinese herbs have been demonstrated by some reports to have preventive effects on hepatic fibrosis (140, 151). One possible mechanism is that those herb extracts might be involved in inhibiting TGF-β1/Smad3 signaling pathway (152).

In addition, as knowledge advances concerning the details of the pathways subserving individual responses to TGF-β/Smad3 signaling, it will improve the targeting, and presumably the safety, of intervention based on modulating the effect of this important cytokine.

References


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