Background: Pancreatic stellate cells (PSCs) have been implicated in pancreatic fibrosis as they synthesise increased amounts of extracellular matrix proteins in response to activation by profibrogenic mediators such as cytokines.

Aims: The purpose of this study was to analyse cytokine receptor stimulated signalling pathways involved in PSC activation. Using a rat culture model of PSCs, we have also tested the potential of the platelet derived growth factor (PDGF) antagonist trapidil and PD98059, a specific inhibitor of extracellular signal regulated kinase (ERK) activation, to suppress PSC growth.

Methods: Cultured PSCs were stimulated with PDGF, and the signal transduction pathways activated in response to the mitogen were analysed by immunoblotting, kinase assays, and electrophoretic mobility shift assays. Furthermore, comparison of signalling cascades activated in PSCs before and after completing transdifferentiation to α-smooth muscle actin expressing myofibroblasts was performed. Biological effects of PDGF, trapidil, and PD98059 were analysed by proliferation assays and correlated with molecular effects of the substances.

Results: PDGF induced rapid activation of Raf-1, ERKs 1 and 2, as well as AP-1 proteins. The transforming growth factor β activated transcription factor Smad2 was found to be constitutively phosphorylated in PSCs of different transdifferentiation grades. Furthermore, the results indicate a correlation between ERK activities and induction of PSC activation. Trapidil efficiently inhibited both PDGF induced ERK activation and, in common with PD98059, PSC proliferation.

Conclusions: Our data suggest that ERKs play a key role in the regulation of PSC growth and that inhibition of the ERK signalling pathway may become a strategy to prevent activation of these cells.
HCl, pH 7.5, 150 mM NaCl, 0.1% sodium dodecyl sulphate was measured according to the manufacturer's instructions. Indicated agents. After three hours of labelling, BrdU uptake by cells plated in 96 well plates were treated for two days with the immunoassay kit (Roche Diagnostics), quantitating deoxyuridine (BrdU) labelling and detection enzyme linked immunosorbent assay kit (Matreya, Pennsylvania, USA). The samples were incubated for 20 minutes. PSCs were then isolated and cultured from the pancreas of male LEW.1.W inbred rats according to the procedure described by Apte and colleagues. Isolation and culture of pancreatic stellate cells (Bad Soden, Germany). Stellate cells were isolated from the pancreas of male LEW.1.W inbred rats according to the procedure described by Apte and colleagues. After reaching confluency, cells were harvested by trypsinisation and replated at equal seeding densities. All experiments were performed with cells before or after the first passage.

**MATERIALS AND METHODS**

**Reagents**
Collagenase P, deoxyribonuclease, polynucleotide kinase, poly(dIdC), and Pefabloc were purchased from Roche Diagnostics (Mannheim, Germany), protease IX and α-SMA antibody from Sigma-Aldrich (St Louis, Missouri, USA), nitrocellulose, peroxidase labelled antibodies, and (γP) ATP from Amerham Pharmacia Biotech (Freiburg, Germany), Nycodenz from Nycomed (Oslo, Norway), antibodies to phospho-Raf-1 (Ser 259 of human Raf-1) and phospho-ERK 1 and 2 (Thr 202/Tyr 204 of human ERK 1) from New England Biolabs (Frankfurt, Germany), the phosho-Smad2 (Ser 465/467 of human Smad2) antibody from Upstate Biotechnology (Lake Placid, New York, USA), and all further antibodies from Santa Cruz Biotechnologies (Santa Cruz, California, USA). Hank’s buffered salt solution (HBSS), media, and supplements for cell culture were obtained from Life Technologies (Eggenstein, Germany) and rat PDGF-BB from R&D Systems (Minneapolis, Minnesota, USA). The PDGF receptor antagonist twistipilin (5-methyl-7-dimethylamino-5-triazolo 1,5-pyrimidine) was from Rodleben Pharma (Rodleben, Germany), and the MEK (mitogen/extracellular signal regulated kinase) inhibitor PD98059 (2′-amino-3′-methoxyflavonone) from Calbiochem (Bad Soden, Germany).

**Isolation and culture of pancreatic stellate cells**
Stellate cells were isolated from the pancreas of male LEW.1.W inbred rats according to the procedure described by Apte and colleagues. Briefly, the pancreas was digested with a mixture of collagenase P (0.05%), protease IX (0.02%), and deoxyribonuclease (0.1%) in HBSS. PSSCs were separated from acini and other cells by density gradient centrifugation (12% Nycodenz; centrifugation at 1400 g for 20 minutes). PSSCs were then collected from the top of the gradient, washed, and resuspended in Iscove's modified Dulbecco's medium supplemented with 10% fetal calf serum, 1% non-essential amino acids (dilution of a 100× stock solution), 100 U/ml penicillin, and 100 µg/ml streptomycin, and cultured in six well culture plates at 37°C in a 5% CO2 humidified atmosphere. With the first two medium changes (24 and 48 hours after seeding), most of the contaminating cells were removed, and almost (>95%) pure PSC cultures (assessed by light phase contrast fluorescence and electron microscopy) were obtained.

After reaching confluency, cells were harvested by trypsinisation and replated at equal seeding densities. All experiments were performed with cells before or after the first passage.

**Cell proliferation assay**
To assess cell proliferation, we used a 5-bromo-2′-deoxyuridine (BrdU) labelling and detection enzyme linked immunosorbsent assay kit (Roche Diagnostics), quantitating BrdU incorporation into newly synthesised DNA. Therefore, we analysed intracellular signal transduction pathways involved in PSC activation. Furthermore, we have evaluated the potential of the PDGF antagonist twistipilin to inhibit PSC proliferation and studied the correlation between ERK activity and PSC growth.

**Electrophoretic mobility shift assays (EMSA)**
Cells growing in six well culture plates and pretreated as indicated were washed once with PBS (pH 7.4) before addition of 1 µl of ice cold hypotonic lysis buffer (10 mM HEPES, pH 7.9, 10 mM KCl, 1.5 mM MgCl2, 0.5 mM dithiothreitol, 1 mM sodium orthovanadate, 1 mM Pefabloc) directly to the cell monolayer. After an incubation period of 10 minutes at 4°C, lysates were collected and precleared by centrifugation at 4°C for five minutes at 10000 g. Protein concentrations in the supernatants were determined by the method of Lowry and colleagues using bovine serum albumin (BSA) as the standard. Immunoblotting was performed as described previously. Briefly, proteins (15 µg per sample) were separated by SDS-polyacrylamide gel electrophoresis and blotted onto nitrocellulose filters. Next, membranes were blocked with 1% BSA and incubated with the indicated protein specific antibodies overnight at 4°C. After a final incubation with a horseradish peroxidase labelled antirabbit or antimouse Ig antibody, blots were developed using the Enhanced Chemiluminescence Plus kit (Amersham Pharmacia Biotech). For reprobing with additional antibodies, blots were stripped by incubation in stripping buffer (62.5 mM Tris HCl, pH 6.7, 2% SDS, 100 mM 2-mercaptoethanol) at 50°C for 30 minutes. All results shown are representative of at least three independent experiments.

**ERK assay**
Precleared lysates of 5×105 cells per sample (received as described above) were incubated with 2 µg of an anti-ERK 1/2 antibody for one hour. Thereafter, protein A-agarose (10 µl beads per sample) was added, and incubation continued for another hour. In vitro kinase assays with ERK immunoprecipitates were performed essentially as described previously using (γP) ATP and myelin basic protein as substrates. Reactions were terminated by spotting the supernatants (received by a short centrifugation at 10 000 g) onto phosphocellulose discs. The filters were washed once in 1% acetic acid and three times in H2O. Afterwards, myelin basic protein associated radioactivity to the phosphocellulose was quantitated by Cerenkov counting.
RESULTS

PDGF stimulates PSC proliferation and induces activation of RAF-1, ERK 1/2, as well as AP-1 proteins

To investigate the mitogenic effect of PDGF on PSCs, cell proliferation in response to PDGF stimulation was assessed using the BrdU DNA incorporation assay (fig 1). PDGF significantly stimulated DNA synthesis in the concentration range 0.3–30 ng/ml.

As indicated by immunoblotting using phospho-protein specific antibodies, PDGF-BB stimulation of cultured PSCs induced rapid activation of Raf-1 as well as ERK 1 and 2 (fig 2), suggesting activation of the Ras-Raf-ERK signal transduction pathway in response to the mitogen. Activation of ERK 1/2 was also confirmed by the results of in vitro kinase assays (fig 3). Under serum free conditions, a significant increase in ERK activity (lasting at least four hours) in response to PDGF stimulation was observed.

EMSA experiments (fig 4) revealed that PDGF stimulation of PSCs for 30–120 minutes induced binding of protein complexes to an oligonucleotide probe containing an AP-1 consensus sequence (lanes 1–3). Binding was specific because it could be displaced by an excess of unlabelled wild-type probe but not by a mutant probe without the AP-1 motif (fig 4, lanes 4 and 5). Incubation of the DNA/protein complexes with Fos or Jun specific antibodies resulted in the appearance of distinct supershifted bands (fig 4, lanes 6–8), indicating firstly the presence of both Fos and Jun transcription factors and secondly the formation of heterogenous probe binding complexes that may contain different Fos and Jun proteins.

Activation of pancreatic stellate cells in vitro correlates with ERK activity

We next compared ERK as well as Smad2 activities in early and late primary cultures of PSCs. Furthermore, protein levels of α-SMA were analysed to monitor PSC transdifferentiation (fig 5).

On days 3 and 5 in primary culture, PSCs expressed low levels of α-SMA only (fig 5A, lanes 1 and 2). Between day 5 and day 10, primary cultured PSCs proliferate at a high rate, and a strong increase in α-SMA expression was observed (fig 5A, lane 3 and 4).

Smad2, a key mediator of TGF-β induced signals, was found to be activated in three and five day old cultures (fig 5B, lanes 1 and 2). Furthermore, the phospho-Smad2 protein (representing the activated form of the transcription factor) was also present in seven and 10 day old PSC cultures that proliferate rapidly and express high levels of α-SMA (fig 5B, lanes 3 and 4).
Immunoblots indicated that the level of phospho-ERK 1 and 2 was very low in three day old PSC cultures (fig 5C, lane 1). In contrast, in PSCs on days 5–10 in primary culture much more ERK 1 and 2 protein was found to be activated (fig 5C, lanes 2–4). Noteworthy, the anti-ERK-protein reprobing of the phospho-ERK blot was stripped and reprobed first with an anti-ERK 1/2 protein specific antibody (D) and afterwards with an antibody to \(\alpha\)-SMA (A). Phospho-ERK levels were further confirmed the increase in the phospho-ERK 1/2 fraction in the course of primary culture (fig 5E).

Taken together, the results indicate that both Smad2 and ERK 1/2 are activated in PSCs before increased levels of \(\alpha\)-SMA can be detected. However, whereas our data do not show if Smad2 activation is a very early event during PSC activation or even takes place in resting cells, they strongly suggest that increased ERK activities correlate with induction of PSC activation.

**Figure 4** Activation of activator protein 1 (AP-1) proteins in platelet derived growth factor (PDGF) stimulated pancreatic stellate cells (PSCs). PSCs of the second passage were starved from serum for 12 hours before they were stimulated with PDGF-BB (10 ng/ml) for two hours (B) or the indicated periods of time (A). Nuclear extracts were subjected to electrophoretic mobility shift assay analysis using a \(^{32}P\)-labelled oligonucleotide probe with an AP-1 motif. For competition analysis (A, lanes 4 and 5), 100-fold molar excess of unlabelled wild-type (WT) or mutant probe (Mut) was added to the binding reaction. Supershift analysis (B) was performed by incubating the binding reactions with antibodies to pan-Fos (lane 7) or pan-Jun (lane 8). Shifted complexes are indicated by an arrow.

**Figure 5** Expression of \(\alpha\)-smooth muscle actin (\(\alpha\)-SMA) (A) and Smad2 as well as extracellular signal regulated kinase (ERK) 1 and 2 phosphorylation (B–E) in primary cultured pancreatic stellate cells (PSCs). PSCs were cultured for the indicated periods of time, and cell lysates were resolved by 8% sodium dodecyl sulphate-polyacrylamide gel electrophoresis. After blotting, one part of the membrane (proteins > 60 kDa) was incubated with a phospho-Smad2 (P-Smad2) and the other (proteins < 60 kDa) with a phospho-ERK 1/2 (P-ERK 1/2) specific antibody. The phospho-ERK blot was stripped and reprobed first with an anti-ERK 1/2 protein specific antibody (D) and afterwards with an antibody to \(\alpha\)-SMA (A). Phospho-ERK levels were further analysed by scanning densitometry and related to the ERK 1 and 2 protein level (E). Therefore, the sum of the band intensities of phospho-ERK 1 and 2 (C) as well as the sum of the corresponding ERK protein band intensities (D) were determined, and the ratio of phospho-ERK/ERK-protein was calculated. The results shown are representative of three independent experiments.
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Figure 7  Trapidil inhibited platelet derived growth factor (PDGF) induced extracellular signal regulated kinase (ERK) 1 and 2 activation in pancreatic stellate cells (PSCs). PSCs of the second passage were starved from serum for 12 hours before they were exposed to trapidil (200 µg/ml) for 30 minutes as indicated. Afterwards, PDGF (10 ng/ml) was added as indicated and incubation continued for one hour. Cell lysates were resolved by 8% sodium dodecyl sulphate-polyacrylamide gel electrophoresis. (A) ERK 1 and 2 activation was analysed by immunoblotting using a phospho-ERK 1/2 (P-ERK 1/2) specific antibody. (B) To show equal loading, the membrane was stripped and reprobed with an anti-ERK 1/2 protein specific antibody.

Inhibition of ERK activation correlates with suppression of PSC growth

The competitive PDGF antagonist trapidil has previously been shown to be an efficient suppressor of the growth of several types of cells, including BALB/c 3T3 and corneal fibroblasts. Although the molecular effects of trapidil are not completely understood, inhibition of ERK signalling is likely to play an important role in the action of the drug. As shown in fig 6A, trapidil 20–400 µg/ml (concentrations which did not affect cell viability) significantly inhibited PDGF stimulated proliferation of PSCs. Diminished BrdU incorporation into DNA was also observed when trapidil was substituted by PD98059, a specific inhibitor of the ERK 1/2 activator MEK, in non-toxic concentrations (fig 6B). At 100 µmol/l, a PD98059 concentration sufficient to inhibit ERK activation completely, more than 50% reduction of PSC proliferation was observed. Similar data were obtained with an alternative (indirect) method of analysing cell proliferation based on bioreduction of the tetrazolium compound 3-(4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulphophenyl)-2H-tetrazolium in viable cells, the CellTiter assay (Promega, Madison, Wisconsin, USA) (data not shown).

In subsequent experiments, serum starved PSCs were stimulated with PDGF in the presence or absence of trapidil (200 µg/ml). Immunoblotting with the phospho-ERK 1/2 specific antibody revealed that PDGF dependent ERK activation was blocked in trapidil pretreated cells (fig 7).

DISCUSSION

The pathogenesis of pancreatic fibrosis, a constant feature of chronic pancreatitis, remained obscure until the discovery that PSCs are capable of producing increased amounts of ECM proteins in response to activators such as cytokines or ethanol. Activation of PSCs has been shown to be associated with fibrosis in both an animal model and in human pancreas. Taken together, these data suggest that PSCs, similarly to their hepatic counterparts, play a key role in the development of organ fibrosis. Hence pharmacological inhibition of PSC activation may have the potential to become a new therapeutic approach for the treatment of chronic pancreatitis. To date, the development of strategies aimed at preventing pancreatic fibrosis has been hampered by incomplete knowledge of the molecular processes that underlie PSC activation.

In this study, we have addressed the question, which intracellular signal transduction pathways are involved in induction of PSC proliferation and myofibroblastic transdifferentiation? Our data show for the first time that PSC activation, induced by sustained culture, and PDGF stimulated mitogenesis correlate with the activity of the ERK 1 and 2 signalling cascade. In many types of cells, a central role of the Ras-Raf-ERK 1/2 signal transduction pathway in the regulation of cell growth and differentiation is well documented. It has also become clear however that control of multiple cellular functions by the ERK cascade occurs in a cell specific fashion. In HSCs, ERK activation has been demonstrated to be involved in the regulation of both proliferation and chemotaxis, suggesting that PSCs and HSCs show similarities not only in their morphology but also with regard to the molecular mechanisms of activation. This hypothesis is also supported by our finding of constitutive Smad2 activation in early cultures of PSCs, because key mediators of TGF-β receptor downstream signals are also activated in HSCs (before phenotypic transition to myofibroblasts) stimulated with TGF-β, a cytokine that exerts its effects on both HSCs and PSCs, at least in part, through autocrine loops.

In addition to Smad transcription factors, AP-1 proteins may play an important role in the mediation of activation signals into the nucleus of PSCs, as suggested by our data, indicating induction of AP-1 DNA binding by the PSC mitogen PDGF.

In an attempt to suppress PSC proliferation through interruption of mitogenic signals, we evaluated the effects of trapidil, a drug that has been shown to act as a competitive antagonist of PDGF-BB binding to its specific receptor. Developed as a coronary vasodilator and later tested for its efficacy in preventing restenosis after coronary angioplasty, the drug has also been shown to be an efficient inhibitor of fibroblast growth. At the subcellular level, inhibition of phosphodiesterases and a protein kinase A mediated inhibition of the Raf-1/ERK signal transduction pathway have been implicated in the action of trapidil.

Our data indicate that trapidil 20–400 µg/ml reduced PDGF stimulated PSC growth in a dose dependent manner; a concentration range comparable with that required to inhibit proliferation of BALB/c 3T3 and corneal fibroblasts. The observation that PDGF dependent ERK activation is prevented by trapidil provides further evidence for a crucial role of the ERK 1/2 signal transduction pathway in induction of PSC proliferation, a conclusion also supported by the significant growth inhibitory effect of the MEK inhibitor PD98059. Interestingly, trapidil also suppressed PSC growth in the absence of PDGF, suggesting that trapidil suppressed PSC growth at sites where endogenous PDGF is produced. The effect of trapidil on PSC growth was not due to toxicity, as determined by the tetrazolium assay (data not shown).}

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increased amounts of ECM proteins—are regulated at the subcellular level.

In summary, our results suggest that ERKs are key mediators of mitogenic signals in PSCs and that these enzymes are potential targets for pharmacological inhibition of PSC activation.

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Extracellular signal regulated kinases are key mediators of mitogenic signals in rat pancreatic stellate cells

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