The field of pancreatic stellate cell (PSC) biology is very young, as the essential in vitro tools to study these cells (ie, methods to isolate and culture PSC) were only developed as recently as in 1998. Nonetheless, there has been an exponential increase in research output in this field over the past decade, with numerous research groups around the world focusing their energies into elucidating the biology and function of these cells. It is now well established that PSC are responsible for producing the stromal reaction (fibrosis) of two major diseases of the pancreas—chronic pancreatitis and pancreatic cancer. Despite exponentially increasing data, the methods for studying PSC remain variable. Although within individual laboratories methods are consistent, different methodologies used by various research groups make it difficult to compare results and conclusions. This article is not a review article on the functions of PSC. Instead, members of the Pancreatic Star Alliance (http://www.pancreaticstaralliance.com) discuss here and consolidate current knowledge, to outline and delineate areas of consensus or otherwise (eg, with regard to methodological approaches) and, more importantly, to identify essential directions for future research.

PANCREATIC STELLATE CELLS

Hepatic stellate cells (HSC) were first described by Karl von Kupffer in 1876; however, similar cells in the pancreas were first observed in the 1980s.1-3 In 1998, Apte et al4 and Bachem et al5 isolated and cultured PSC.4 5 In the normal pancreas, PSC are located in close proximity to the basal aspect of pancreatic acinar cells. In sections immunostained for the marker desmin (a cytoskeletal protein), quiescent PSC can be seen as cells with a central cell body and long cytoplasmic projections extending along the base of adjacent acinar cells similar to that of pericytes in the mammary gland. In health, PSC exist in their quiescent phenotype and exhibit the presence of abundant vitamin A-containing lipid droplets in their cytoplasm. It is estimated that quiescent PSC form 4–7% of all parenchymal cells in the normal pancreas.3 5 During pancreatic injury, resident PSC transform into an activated phenotype that secretes excessive amounts of the extracellular matrix (ECM) proteins that comprise fibrous tissue. Recent evidence suggests that a small proportion of activated PSC may also be derived from circulating bone marrow (BM)-derived cells that home to the pancreas during pancreatic injury.

STELLATE CELL SYSTEM AND THE ORIGIN OF PSC AND HSC

In the human body, the stellate cell system consists of retinoid-storing cells in various organs, including the liver, pancreas, lung, kidney, intestine, spleen, adrenal gland, ductus deferens and vocal cords showing a perivascular location with a distribution typical of a pericyte.6 7 However, the origin of stellate cells is still being debated. Mesenchymal,8-10 endodermal11-12 as well as neuroectodermal13-15 origins are suggested. Neuroectoderm and mesoderm were considered as two potential origins of HSC—these cells and PSC share numerous characteristics as indicated by morphological, functional and gene expression studies. Expression profiling of PSC, HSC and fibroblasts has demonstrated that PSC and HSC are distinctly different from fibroblasts, but share many homologies including the expression of genes related to ECM proteins, contractility, retinoid metabolism (although lower retinoid content in PSC compared with HSC) and growth factors.16 In fact, both cells (in comparison with fibroblasts) have more similarities than differences.17 It is therefore possible that HSC and PSC share a common origin.

The neuroectodermal proposal for the origins of HSC was refuted by a study by Cassiman et al,10 who used a genetic cell lineage mapping technique with Rosa26YFPlox mice crossed with mice expressing Cre under the control of the neural crest-specific Wnt1 promoter/enhancer. Definitive novel evidence for the mesodermal origin of HSC has recently been presented by Ashahina and colleagues8 10 with the use of the mesoderm-specific MesP1Cre. A conditional cell lineage analysis using Wt1CreERT/ Rosa26LacZlox or ROSA26mTmGlox mice,
revealed Wt1-positive septum transversum giving rise to mesothelial cells, submesothelial cells, HSC and perivascular mesenchymal cells during liver development. That study also demonstrated Wt1-positive mesothelial/submesothelial cells migrating inward from the liver surface to generate liver mesenchymal cells including HSC. Similar lineage tracing techniques need to be used to determine the exact origin of PSC.

ROLE OF PSC IN FIBROSIS AND REGENERATION

The origin and fate of stellate cells in the context of injury and regeneration are also a matter of ongoing debate. Regarding the contribution of BM and epithelial mesenchymal transition (EMT) of acinar cells to the PSC population, the data are limited and restricted to studies in mice. In 2006, it was reported that BM is a source of myofibroblast-like cells in fibrotic liver tissue, but the involvement of these cells in the progression of liver fibrosis remains questionable as their contribution to collagen synthesis appears to be limited. Recent studies have now also addressed the role of BM-derived cells in pancreatic regeneration and fibrosis.

Using a similar experimental approach, namely the transfer of green fluorescent protein (GFP)-expressing BM cells to lethally irradiated small rodents followed by the induction of chronic pancreatitis with cerulein or dibutyltin dichloride, it was described a subset of mitoxantrone (a type II topoisomerase inhibitor that disrupts DNA synthesis and DNA repair in both healthy cells and cancer cells) resistant pancreatic cells that exhibit PSC markers, and can be induced to differentiate into insulin producing β cells when exposed to an appropriate culture medium. It is possible that PSC may also express various markers that are expressed in stem cells. However, convincing functional data showing that PSC may in fact transform into other cell types of the pancreas are not yet available. Whether PSC contribute to pancreas regeneration in a manner similar to the contribution of HSC to liver regeneration, by supporting the epithelial cells and by developing into epithelial cells, remains to be analysed. As of now, the situation in humans remains completely unknown.

METHODOLOGY FOR ISOLATION OF PSC

Isolation of quiescent PSC from rat pancreas was first reported by Apte and colleagues from Professor Wilson’s laboratory in 1998. This method took advantage of the known vitamin A content (stored in cytoplasmic lipid droplets) of PSC, which allowed the cells to be separated by a single density gradient method using nycodenz. More recently, a similar method (albeit with some modifications) was used to isolate quiescent PSC from normal human pancreas. The gradients can be developed not only with nycodenz but also with other colloids such as percoll, iohexol, iodixanol, optiprep. The average yield of cells from a rat pancreas is approximately 3 million cells per gram of pancreas. The yield of PSC is much lower from human pancreas due to limited tissue availability and due to the higher amount of fatty tissue surrounding the resected pancreas (compared with rat pancreas), which can impede tissue digestion. PSC can also be isolated from cancerous or fibrotic human pancreas, as well as normal rat pancreas, using the outgrowth method first described by Bachem and colleagues from Professor Adler’s laboratory in 1998. The PSC obtained by the outgrowth method comprise cells of different age due to temporal differences in their growing out from fibrotic tissue blocks. Both methods yield a mixed population of stromal cells, which are globally named PSC but have different subpopulations with various sizes, α-smooth muscle actin (α-SMA) expression and adhesiveness on plastic. Neither method yields absolutely pure PSC populations, although the nycodenz method yields a more homogeneous population of PSC at the point of isolation than the outgrowth method, which is inherently prone to possible contamination by other cells. In early primary cultures obtained by outgrowth methods, the contaminating cells are predominantly macrophages and acinar cells. After passaging, the cultures may also contain α-SMA-negative fibroblasts while acinar cells and macrophages are eliminated. Tumour cells almost never grow out from primary tumours, but may seldom grow out from metastasis samples. Nonetheless, good practice requires checking cell preparations for quality and purity regardless of the isolation method used.

MARKERS OF QUIESCENT AND ACTIVATED PSC

When isolating primary cells from the pancreas, it is of vital importance to assess the purity of the cultures not only for the homogeneity of PSC but also for the
absence of possible contaminants. Another confounder is the activation of PSC on plastic, which creates differences between early and late passages. Therefore, several PSC selective markers have been proposed to assess their purity and activity (figure 1). The most consistent marker of PSC quiescence is the presence of vitamin A droplets in the cytoplasm. With regard to activated PSC, it is currently not clear whether these are different from myofibroblasts of the pancreas and whether there are markers to differentiate these two cell types. However, there is strong agreement that α-SMA is not an exclusive marker for activated PSC. It is also expressed by myofibroblasts, smooth muscle cells and pericytes in blood vessels as well as the gut wall (ie, duodenum and papilla vateri). During activation, quiescent PSC lose their intracellular retinoid (vitamin A) droplets (detectable by fluorescence microscopy as a characteristic blue-green autofluorescence (rapidly fading) upon exposure to ultraviolet light at 328 nm or 350 nm) and start to express α-SMA. The active phenotype of PSC defined by α-SMA expression may have contrasting functions, eg, profibrogenic or profibrotic, therefore α-SMA is considered to be more a transdifferentiation marker indicative of a myofibroblast-like phenotype than a marker of PSC activity per se.30

With regard to other PSC markers, researchers are in agreement that the expression of desmin is highly variable in PSC (variance of expression also exists between different species). Similarly, there is currently not enough evidence to conclude that nestin alone is a sufficient marker to monitor the activation of PSC in rodents and humans. A more commonly used and reliable immunostaining marker selective for rat and human PSC (and absent in fibroblasts) is glial fibrillary acidic protein. Some researchers have reported the absence of glial fibrillary acidic protein expression in quiescent PSC, but in the opinion of experienced workers in the field this is more likely to be due to differences in the quality of the antibody used for immunostaining than a true absence of expression of the protein.

The dynamic change in gene expression during PSC activation can be monitored by several gene products. There is some early evidence that although expressed in activated PSC, Notch3, secreted frizzled related protein 5, Wnt4 and Wnt5a are absent in quiescent PSC (C. Kordes, unpublished data); however, there is agreement that these findings need further validation.

PARAMETERS OF PSC ACTIVATION

There is strong agreement that activation of PSC in culture can be assessed by several functional parameters. However, it is also recognised that the results of studies of PSC activation may be influenced by many different factors including stellate cell purity, culture media used and age of animals harvested or (for humans) donor age and disease (normal pancreas, chronic pancreatitis, pancreatic cancer). While the response of PSC to individual activating factors has been well characterised in vitro, researchers are also mindful that this may not reflect the true in vivo situation in which: (1) PSC are exposed to a multiplicity of factors at any one time; (2) there is often redundancy of the effects of cytokines; (3) culture conditions may influence ECM composition; and (4) isolated PSC in culture may behave differently from those in situ where they are surrounded by other cell types (figure 2). Once activated, PSC also secrete endogenous factors that can further activate transformed PSC via autocrine pathways.

INTRACELLULAR SIGNALLING PATHWAYS INVOLVED IN STELLATE CELL ACTIVATION/DEACTIVATION

The intracellular pathways involved in the ‘activation’ of PSC have also been intensively analysed as the activity of the stroma significantly impacts on the course of pancreatitis and on tumour behaviour.31 Therefore, intracellular pathways are considered to be important as potential therapeutic targets to inhibit/revert stellate cell activity. Pertinently, kinases of the mitogen-activated protein kinase family have been implicated in many aspects of PSC activation, but have been linked most consistently to the transcription of mitogenic signals and the stimulation of cytokine/chemokine (eg, MCP-1 and IL-6) production.32 The latter effect is transcriptionally mediated by AP-1 and nuclear factor kappa B transcription factors. On the other hand, Smad transcription factors are key mediators of the biological consequences of transforming growth factor β1 in PSC, stimulating transformation to a myofibroblastic phenotype.
and increased ECM synthesis. However, while several signalling pathways mediating PSC functions have been identified, it is currently not possible to clarify their ‘restricted’ role as other pathways mediating similar functions are increasingly being identified and the cross-talk between these pathways is also being elucidated.

Signalling pathways that are responsible for PSC inactivation (reversal to a relatively quiescent phenotype) have also been identified in recent years. Inhibition of mitogen-activated protein kinase (ERK, JNK and p38 kinase) signalling in PSC mediates the induction of quiescence in response to retinol and retinoic acid. There is some evidence that the forced expression of PPAR-γ, C/EBP-α, or albumin may also inactivate PSC. Therefore, modulation of PPAR-γ and STAT1, which can be targeted by clinically applicable drugs (thiazolidinediones and interferons, respectively), deserves further investigation.

**PSC ARE THE KEY FIBROGENIC CELLS IN THE PANCREAS AND ARE DIFFERENT FROM PFB**

Differentiation between PSC and pancreatic fibroblasts is an important issue given that the outgrowth method of PSC isolation involves the use of fibroitic pancreatic tissue. In contrast to pancreatic fibroblasts (PFB), PSC express α-SMA and form dense bodies (microfilaments) like myofibroblast-like cells. Compared with PSC, PFB are less adherent therefore detach earlier from plastic during trypsinisation. Using this difference, pure cultures of PSC and PFB can be obtained after repeated mild trypsinisation and separate cultivation. In contrast to PSC, which show a star-like shape (few are also triangular or spindle-shaped), cultured PFB are spindle-shaped and smaller. Both cell types are vimentin positive; 20–40% of PSC are desmin positive and more than 90% are α-SMA positive (positivity increases as cells are kept on plastic). In contrast, PFB are desmin and α-SMA negative. Importantly, PSC produce higher amounts of ECM proteins compared with PFB, and express the scavenger receptor CD36, CCK receptors 1/2 and ACh receptor while PFB do not express any of these receptors.
VARIANCES OF PSC BETWEEN SPECIES, DONORS AND IMPACT OF IMMORTALISATION ON INTERPRETING RESULTS

There is strong agreement that there are species as well as donor-dependent vari-
ances between murine and human PSC. As a result of the limited access to human pancreatic tissue at several institutions, immortalised PSC have been proposed as an alternative model to study pancreatic stroma. Immortalised PSC may be useful for studies of molecular signalling that require manipulation of gene expression and use in in-vivo models that require cells to remain viable for a relatively longer time period. However, it is important to note that differences exist between immortalised and primary PSC, and therefore caution must be exercised when extrapolating findings with immortalised PSC to the clinical situation. Of more concern is the observation that immortalised PSC were able (albeit occasionally) to form aggressive anaplastic tumours when injected alone into nude mice (M. Buchholz et al, unpublished data). This raises the possibility that the immortalisation procedure resulted in the preferential selection of malignant subclones. Therefore, there is strong agree-
ment that the results of experiments obtained by using murine or immortalised PSC should ideally be verified using several different primary human PSC cultures to maximise the robustness of the data.

PSC AND PancreATIC DISEASES

Compelling evidence has accumulated in recent years to support a major role for PSC in both fibrogenesis and fibrol-
ysis. During pancreatic injury, PSC are transformed (in response to factors that are now well identified, including oxidant stress, cytokines, growth factors and toxins such as alcohol and its metab-
olite acetaldehyde) from their quiescent state to an activated myo-
blast-like phenotype that synthesises and secretes excessive amounts of ECM proteins (increased fibrogenesis). Activated PSC are seen in the early phases of alcoholic chronic pancreatitis and in autoimmune pancreatitis. However, it is unclear how fibrogenesis is initiated in the inflamed pancreas. There are currently two concepts. The first concept focuses on the direct activation of PSC by acetaldehyde (the oxidative metabolite of alcohol) and oxidant stress (as shown in vitro and in animal experiments). The second concept is based on the necrosis–fibrosis sequence as the underlying pathogenic mechanisms of alcoholic chronic pancrea-
titis. It is proposed that the initial lesion is autodigestive tissue necrosis, which is followed by inflammation and the induc-
tion of the fibrotic reaction. In stage I with overt tissue injury, PSC are found in close association with macrophages around areas of necrosis. In stage II with extensive cellular fibrosis, PSC are found in the peribular spaces. In stage III with established dense fibrosis in the peribular spaces, PSC are conspicuously reduced in number, and in stage IV, when in addition to peribular fibrosis calculi in the ducts are present, PSC are mainly detected adjacent to duct ulcerations caused by calcii. There is general agreement that in the early stages (I and II) cessation of alcohol would prevent the formation of organ fibrosis, predominantly through increased apoptosis of activated PSC. However, there is currently not enough evidence showing that increasing the fibrolytic activity of PSC reverts organised fibrosis of the pancreas.

The tumour microenvironment is known to be an important contributor to the malignant phenotype. New animal experiments suggest that PSC can promote local tumour growth and metastatic spread and can also increase resistance to chemo and radiation treatment. The vascularity of the tumour is believed to play a role in the aggressive behaviour of pancreatic cancer. Pancreatic ductal adenocarcinoma as well as chronic pancreatitis is characterised by hypoxia and fibrosis. It remains unclear whether pancreatic cancer is a result of the excessive matrix deposition correlated with a favourable outcome in pancreatic cancer. In the genetically engineered mouse models of pancreatic ductal adenocarcinoma, the earliest stromal activation and ECM deposition are found around metastatic/ dysplastic lesions such as tubular complexes and to a lesser extent around PanIN lesions. However, it is not clear whether this stromal activation is a part of carcinogenesis or an epiphenomenon representing an effort to confine the preneoplastic lesions. In breast and prostate cancers, such a stromal reaction has been shown to precede the actual cancer. However, despite early evidence in pancreatic cancer, judging by the stromal activation, it is currently not clear whether tubular complexes are an additional precursor lesion in pancreatic ductal adenocarcinoma.

CONCLUSIONS

Pancreatic fibrosis, which develops as a consequence of chronic inflammation, leads to the loss of functional parenchyma and probably increases the risk of cancer. As the role of PSC in chronic pancreatitis and pancreatic cancer is increasingly
clarified, it is anticipated that effective approaches to target FSC specifically will be developed. Such therapeutic strategies would be expected to reduce the fibrosis of chronic pancreatitis, thereby retarding the development of exocrine and endocrine insufficiency, and interrupt the interaction of FSC in the stromal reaction with pancreatic cancer cells, thereby inhibiting tumour progression and improving the otherwise dismal prognosis of this disease. Therefore, at present, the field of PSC research is dynamic and wide open, with significant potential for novel discoveries and major breakthroughs that could have a lasting impact on the treatment of patients with pancreatic diseases. The Pancreatic Star Alliance would particularly encourage young researchers to enter this exciting area of pancreatology.

FUTURE RESEARCH DIRECTIONS

1. PSC origin (lineage tracing studies).
2. Functions in health.
3. Interactions with other pancreatic cells (endocrine cells, immune cells, Schwann cells, nerve cells).
4. Role in pancreatic repair/regeneration.
5. Therapeutic targeting.

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References


