Multiple roles of mucins in pancreatic cancer, a lethal and challenging malignancy.

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Minireview
Multiple roles of mucins in pancreatic cancer, a lethal and challenging malignancy

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Mucins are members of an expanding family of large multifunctional glycoproteins. Pancreatic mucins have important biological functions, including the protection, lubrication, and moisturisation of the surfaces of epithelial tissues lining ductal structures within the pancreas. Several lines of evidence support the notion that deregulated mucin production is a hallmark of inflammatory and neoplastic disorders of the pancreas. Herein, we discuss the factors that contribute to the lethality of pancreatic cancer as well as the key role played by mucins, particularly MUC1 and MUC4, in the development and progression of the disease. Aspects pertaining to the aberrant expression and glycosylation of mucins are discussed, with special emphasis on their potential impact on the design and implementation of adequate diagnostic and therapeutic strategies for combating this lethal malignancy.

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Mucins are a large family of glycoproteins that, either directly or indirectly, act to maintain the integrity, lubricate and protect the epithelial surfaces within the human body. In general, mucins exhibit a defined spatial and temporal pattern of expression throughout the development of an organism (Braga et al, 1992). In numerous pancreatic pathologic situations, however, their expression is deregulated, and their aberrant expression is often associated with a poor prognosis (Braga et al, 1992; Reis et al, 1999; Andrianifahanana et al, 2001). This paper will review the role played by mucins, particularly MUC1 and MUC4, in the development and progression of pancreatic cancer (PC) and will highlight key aspects that may account for the lethality of this malignancy.

THE MUCIN FAMILY
For long, mucins were known as high molecular weight O-glycoproteins, secreted by specialised epithelial cells. As main contributors to the rheologic properties of the mucus, mucins were thought to have the sole functions of protecting and lubricating epithelial surfaces. Following the development of molecular biological methods, however, a wide range of mucin structures became available and gave rise to a plethora of biochemical definitions of mucins. As the diversity of mucin structures grew in importance, a variety of functions were assigned accordingly. At present, a total of 21 genes have received the appellation MUC: MUC1-2, MUC3A, MUC3B, MUC4, MUC5AC, MUC5B, MUC6-13,

MUC15-20 (Moniaux et al, 2001; Hollingsworth and Swanson, 2004; Andrianifahanana et al, 2004). In all, 14 of these code for proteins presenting the five common features of a mucin, including (I) secretion into the mucus layer, (II) high molecular weight O-glycoprotein, (III) presence of a tandem repeat array encoded by a unique and centrally positioned large exon, (IV) presence of a predicted peptide domain containing a high percentage of serine and threonine residues, and (V) a complex pattern of mRNA expression.

The 14 classical mucins can be further grouped into two subfamilies: secreted and membrane-bound. Typically, secreted mucins are expressed exclusively by specialised epithelial cells, are secreted in the mucus, and display a restricted expression pattern within the human body. Among these, MUC2, MUC5AC, MUC5B, and MUC6 are expressed in the pancreas either under normal physiologic or tumoral conditions. These four mucins, referred to as the gel-forming mucins, have a common architecture with a high level of similarity to the pro-von Willebrand factor. The secreted mucins whose genomic sequences have been fully characterised are known to harbour five D domains, thus called because of their homology to the D domains of the von Willebrand factor. The D1, D2, D3, and D4 domains are located in the N-terminal region and the D4 and CK (Cystine Knot) domains in the C-terminal region. Moreover, cystein-rich domains (called Cys) alternate with the tandem repeat sequences in a variable number depending on the mucin (for a review, see Moniaux et al, 2001). The gel-forming mucins form intermolecular disulphide-linked multimers. Mucin subunits initially form homodimers through the disulphide bonds from their CK domains and subsequently hetero-oligomerise through the D domains from their N-terminal extremities (Van Klinken et al, 1998). The Cys domains are believed to bring another level of complexity to the oligomerisation process via intermolecular disulphide bond formation. As the composition of gel-forming mucins differs among tissues
and MUC4/Y, present a growth factor-like architecture and are thought to be involved in fetal and tumour development. However, the lack of specific antibodies makes it difficult to perform appropriate functional studies.

**ABNORMAL EXPRESSION OF MUCIN GENES IN PC**

Of particular interest, the pattern of mucin expression within the pancreas varies depending on the pathophysiologic conditions.
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Table I Mucin gene expression in different pancreatic physiologic conditions

| Gene  | Fetus | Normal pancreas | Pancreatitis | IPMT | PanIN | Tissue | Cell line |
|-------|-------|-----------------|--------------|------|-------|--------|-----------|
| MUC1  | −/+   | +               | ++           | +    | −     | −      | −/+       |
| MUC2  | −     | −               | −            | −    | ND    | + to +++| +/+       |
| MUC3  | ±     | ±               | ±            | ± ND | ND    | ±     | ±/−       |
| MUC4  | −     | −               | −            | −    | ND    | −      | −/−       |
| MUC5AC| −     | +               | −/+          | ++   | ND    | −/−   | −/−       |
| MUC5B | −     | +               | ++ +/+++     | ++   | ND    | +/+    | +/+       |
| MUC6  | +     | +               | ++ +/+++     | ++++ | ND    | ++++   | −/+       |
| MUC11/12 | ND | −/+           | ND           | ND   | ND    | ND      | ND        |
| MUC16 | ND   | ND              | ND           | ND   | ND    | ND      | ND        |
| MUC17 | ND   | ND              | ND           | ND   | ND    | ND      | +         |

= negative; ± = low; + = moderate; +++ = intense; ND = not determined; −/+ = from negative to positive depending the sample; ± = negative or positive depending the reports; IPMT = intraductal papillary-mucinous tumours; PanIN = pancreatic intraepithelial neoplasias.

MUCINS FOR PC DIAGNOSTIC

The pancreas is the second largest gland of the digestive system following the liver. It lies retroperitoneally in the upper abdominal cavity, with its head enclosed by the curve of the duodenum and its tail reaching to the spleen. It performs both endocrine and exocrine functions. The exocrine component, constituting about 95% of the mature pancreas, is made up of 85% acinar cells and 10% of secreting ductal cells. The endocrine cells are believed to occupy just 1–2% of the total pancreatic volume in adults.

Adenocarcinomas of the ductal phenotype constitute over 85% of PC, and other tumours of ductal type, such as mucinous cystic tumours, serous cystic tumours and IPMTs make up another 5–7%. A number of factors, including hereditary, environmental, occupational, and social factors are now recognised as potential contributors to the development of PC (Michaud et al, 2003). Pancreatic cancer is an international problem because of its increasing incidence worldwide. The incidence and age-adjusted mortality rates are almost equal, underscoring the aggressive nature of the disease. It is a daunting challenge for modern medicine as the survival rates for patients diagnosed with metastatic PC range from 4 to 6 months on average. The lethality of the disease is best illustrated by its poor 5-year survival rate of a mere 5%. The highest cure rate only occurs if the tumour is truly localised to the pancreas; however, this stage of disease accounts for fewer than 20% of all cases. For those patients with localised disease and small tumour size (<2 cm) with no lymph node metastases and no extension beyond the ‘capsule’ of the pancreas, complete surgical resection can yield actuarial 5-year survival rates of 18–24% (Yeo et al, 1997, 1999). Unfortunately, the signs of early stage PC are vague and often attributed to other problems by both patients and physicians. More specific symptoms tend to develop after the tumour has grown to invade other organs or blocked the bile ducts. Patients are usually diagnosed at an advanced stage, with a high incidence of associated metastases, spread all over the body. The inability to diagnose PC at an early, localized, and curable stage has contributed to poor prognosis. The silent course of PC and its explosive fatal outcome have hindered studies of identification of early biochemical and genetic alterations that could help us diagnose the disease at a curable stage and develop successful therapeutic strategies. Thus, PC remains a dismal disease and early diagnostic markers and therapeutic targets are urgently needed.

Early symptoms of PC are difficult to detect and are often ignored. There are no tumour-specific markers for PC; markers such as serum CA 19-9, DUPAN-2, and CA125 that are being used as potential targets have low specificity (McLaughlin et al, 1999; Rhodes, 1999). For over two decades, the structures of these antigens (CA 19-9, DUPAN2, or CA 125) have been heavily
investigated for the development of serum-based immunoassays to detect early cancers. These antigens contain oligosaccharide structures that are being recognised by monoclonal antibodies. Further, these saccharide epitopes are present on the O-glycosidic chains harboured by the apomucin backbones. For examples, MUC1 carries CA19-9 (Burdick et al, 1997) and DUPAN-2 (Khorrami et al, 2002) epitopes, and MUC16 carries CA 125 epitope (Yin et al, 2002). At this time, CA19-9 remains the only Food and Drug Administration (FDA)-approved marker to monitor PC. The CA 19-9 recognises a mucin-type glycoprotein sialosyl leu...ab/ negative, the maximum sensitivity of this marker is of 95%.

Aberrent glycosylation occurs in essentially all types of experimental and human cancers and has been associated with tumorigenicity and metastasis. In fact, many glycosyl epitopes constitute tumour-associated antigens (TAAs) and have been used as a target for immunotherapy and diagnosis. The nature of aberrant glycosylation as a result or a cause of cancer remains enigmatic. Many recent studies have indicated that some, if not all, types of aberrant glycosylation are a result of initial oncogenic transformation, as well as a key event in induction of invasion and metastasis.

The mucin-type O-glycans are attached to the glycoproteins through O-glycosidic linkages between N-acetylgalactosamine and serine or threonine amino-acid residues in the apomucin moieties. O-glycans are assembled by a series of reactions catalysed by glycosyltransferases and sulphotransferases in the Golgi compartment. In cancer cells, the expression pattern of these enzymes is dysregulated and leads to tumour-specific glycanc epitopes. Depending on the glycosyltransferases expressed, several hundred different O-glycan structures have been described and classified according to their core structures. All of the cores have the N-acetylgalactosamine, linked to the serine or threonine residues that represents the Tn antigen in common. When sialylated, this antigen forms the sialyl-Tn (sTn) epitope reported to be expressed on the surface of mucin cores. Indeed, sTn is detected at the surface of MUC1 overexpressed by pancreatic adenocarcinoma cells (Burdick et al, 1997). It has been proposed that the appearance of the sTn antigen might result from MUC1 overexpression. The abundance of acceptor sites may saturate the post-translational modification (Burdick et al, 1997). The sTn antigen is recognised by the mouse monoclonal antibody CC49, which is being extensively investigated for the development of radio-immunotherapeutic protocols.

Alternatively, the Tn antigen can be elongated to form one of the eight distinct cores and terminated with sulphate, sialic acid, fucose, galactose, N-acetylgalactosamine, and N-acetylgalactosamine. Depending on the physiologic conditions, the peripheral sugar may vary and gives rise to tumor-associated antigens, such as Leα (Lewisα), Leα, Leβ, Leβ, sLeα, sLeβ, Leα, and sLeβ. The CA 19-9 recognised previously recognises the sLeα and DUPAN-2 recognises the sLeβ.

**IMPLICATION OF MUCINS IN THE PATHOGENESIS OF PC**

As described previously, both the glycosylation and the expression of mucins are deregulated during the development and progression of pancreatic adenocarcinoma. The main mucins that present the most deregulated expression patterns are MUC1 and MUC4, two mucins that belong to the membrane-anchored mucin subfamily. Therefore, this review will focus on the known functions of MUC1 and MUC4. Both MUC1 and MUC4 play a key role in the development of PC as well as in its progression (invasion and metastasis). As indicated earlier in this paper, the high incidence of metastases in PC is the major cause of its lethality. MUC1 and MUC4 are implicated in almost all of the steps associated with the development of metastases.

MUC1 and MUC4 possess antiadhesive properties. The negative charge of the O-glycosidic chains carried by their central repetitive domain provides a extended conformation to MUC1 and MUC4, with a size up to 500 nm and 2.12 μm (Moniaux et al, 1999), respectively. Moreover, MUC1 and MUC4 are not only upregulated in PC but their upregulation is also accompanied by the loss of their strictly apical localisation. The steric hindrance caused by the overexpression of these two extended glycoproteins disturbs the cell–cell and/or cell–matrix interactions (Komatsu et al, 1997). This physical mechanism favours the release of cancer cells into the circulation. MUC1 also interacts directly with β-catenin via an SXXS motif (PSGL-1 motif) present within its cytoplasmic tail (Yamamoto et al, 1997). β-Catenin plays important functions in the formation of the cell–cell junction via E-cadherin interaction (Hulsken et al, 1994). β-Catenin also binds to adenomatous polyposis coli (APC) (partner in the Wingless/Wnt-1 signal pathway). The Wnt-1 intracellular pathway is directly implicated in the development of the central nervous system. Complex binding to β-catenin is a mutually exclusive process. APC overexpression reduces the level of free cytoplasmic β-catenin, and thus reduces the formation of β-catenin/E-cadherin complexes and also decreases intercellular adherence. The formation of these complexes is regulated by the phosphorylation of the cytoplasmic tail of each partner by GSK3β. After phosphorylation, β-catenin is degraded. GSK3β is also able to phosphorylate the β-catenin–binding site on the MUC1 cytoplasmic tail (Li et al, 1998). The phosphorylation at the serine residue of the cytoplasmic tail of MUC1 by GSK3β was shown to decrease the binding of MUC1 to β-catenin (Li et al, 1998). The relative level of MUC1, E-cadherin, β-catenin, GSK3β, and APC seem to be critical for maintaining epithelium integrity. The overexpression of MUC1 leads to an increase in the interaction between MUC1 and β-catenin, thereby inhibiting β-catenin/E-cadherin interaction and disrupting cell–cell contacts, which facilitate the release of the tumour cell from the tissue. The cytoplasmic tail of MUC1 is also phosphorylated at tyrosine residue. In vitro, tyrosine phosphorylation of the MUC1 cytoplasmic domain increases recolonisation and promotes changes in cell–cell adhesion (Quin and McGuckin, 2000). Interestingly, both src and EGFR induce tyrosine phosphorylation and cooperate in the anchorage independence between MUC1 and β-catenin (Li et al, 2001; Schroeder et al, 2001).

The expression of mucin-associated carbohydrate antigens, sLeα and sTn, is associated with higher-grade PanIN lesions (Park et al, 2003) and is thought to result from a shift in the expression of glycosyltransferases. These mucin-associated antigens are known to bind endothelial cells through the P- and E-selectins, and the cell-adhesion molecule, ICAM-1 (Regimbald et al, 1996). The P-selectin ligand (PSGL-1) (Sako et al, 1993) presents a structure similar to MUC1 and MUC4 and carries within its repetitive domain O-glycosidic chains with terminal sugars comparable to those of MUC1 and MUC4 in tumoral situations. Therefore, in addition to favouring the release of PC cells, MUC1 and MUC4 also facilitate their extravasation into and/or from the circulation (Burdick et al, 1997). MUC4 is known to induce tumour killing by lymphokine-activated killer cells (Komatsu et al, 1999).

Information regarding the role of MUC1 and MUC4 in the growth of primary pancreatic tumours has remained scarce until recently. Both mucins have been reported to serve as potential modulators of the receptor tyrosine kinase signalling pathways. Indeed, both MUC1 and MUC4 have been referred to as the heterodimeric partners of EGFR/HER1 (Li et al, 2001; Schroeder et al, 2001) and HER2 (Carraway et al, 2002), respectively. When MUC1 interacts with EGFR, the cytoplasmic tail of MUC1 becomes phosphorylated and leads to the activation of c-Src (Li et al, 2001). Moreover, the formation of the complex activates the mitogen MAP kinase pathway (Schroeder et al, 2001). For MUC4, its
membrane-bound subunit acts as a ligand for HER2, activating this growth factor receptor, and in synergy with neuregulin, potentiates the phoshorylation of HER2 and HER3. Phosphorylation of HER2 occurs at residue Tyr1248 after binding with MUC4 and leads to the upregulation of the cell-cycle inhibitor, p27kip (Jepson et al, 2002). However, in presence of neuregulin, MUC4/HER2 activation downregulates p27kip but activates the protein kinase B/Akt via HER3. Therefore, MUC4 appears to be a modulator of cell proliferation. Inhibition of MUC4 expression using antisense or short-interfering RNA (siRNA) oligonucleotides specific to MUC4 results in a decreased tumorigenicity and dissemination of cancer cells (Singh et al, 2004). We believe that MUC4 is implicated in tumour growth and metastasis by directly altering the tumour cell properties (adhesion/aggregation and motility), and/or in part, via modulating HER2 expression.

CONCLUSIONS AND PERSPECTIVES
Pancreatic cancer is an international problem because of its increasing incidence worldwide. The incidence and age-adjusted mortality rates are almost equal, underscoring the aggressive nature of the disease. Although efforts are being made to unveil the principles governing the initiation and progression of this cancer, and to identify the factors that confer its particular aggressiveness, the exact succession of molecular events underlying the development of this devastating malignancy has remained unsolved. The management of PC is, therefore, an ongoing challenge. Mucins have been implicated in the pathogenesis and progression of PC. Differential glycosylation, aberrant expression, and alternative splicing of mucins are being investigated in PC. MUC1 and MUC4 are finding unique functions in the early diagnosis and progression of the disease. The potential use of these mucins in the targeted therapy of pancreatic and other cancers is under active investigation.

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