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Review Article

The Role of Tobacco-Derived Carcinogens in Pancreas Cancer

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The extremely poor outcome from pancreas cancer is well known. However, its aetiology less well appreciated, and the molecular mechanisms underlying this are poorly understood. Tobacco usage is one of the strongest risk factors for this disease, and this is a completely avoidable hazard. In addition, there are well described hereditary diseases which predispose, and familial pancreas cancer. We have sought here to summarise the role of tobacco-derived carcinogens and the mode of their tumorigenic action on the pancreas. There is compelling evidence from animal and human studies (laboratory including cell line studies and epidemiologic) that tobacco derived carcinogens cause pancreas cancer. However, the manner in which they do so is not entirely apparent. There is also compelling evidence that synergism with genetic and other life-style factors—like diet obesity—results in a multifactorial causation of the disease. Ascertaining the role of tobacco carcinogens in the development of this cancer and their interaction with other risk factors will enable novel therapeutic and preventative strategies to improve outcome from this appalling malignancy.

1. Introduction

Adenocarcinoma of the pancreas is a devastating disease, and only a small proportion of sufferers achieve an attempt at curative surgical treatment which leads to a median survival of about 12 months [1]. In spite of advances in surgical technology, perioperative care, and adjuvant treatments the improvement in outcome from this disease has been minimal. Improving survival could be the result of an understanding of the biology of the cancer, and its risk factors with a view to detecting it early—possibly in high-risk individuals with secondary prevention strategies in selected patients and also devising novel modes of interfering with its initiation and progression.

There have been numerous lines of evidence implicating tobacco smoking as a risk factor for pancreatic cancer and this has been well recognised in the field of pancreatology. Realisation of this in the wider healthcare community, however, had been limited until the publication of the 2004 US Surgeon General's report on health consequences of Smoking [2]. Tobacco usage is the single largest preventable

cause of disability disease and death in the developed world and probably also plays a great role in morbidity and mortality amongst people within the developing world.

A recent meta-analysis [3] demonstrated the significant strength of the association between cigarette smoking and pancreas cancer and calculated that the population attributable risk secondary to tobacco use for the malignancy was about 20%. Genetic factors play a role in about 10% of incident cases. However, the exact etiological cause for the vast majority of these cancers continues to remain speculative.

Tobacco smoking is the strongest risk factor for pancreas cancer, but the mechanism of disease causation has not been elucidated although the various steps in the sequence of development of the malignancy have been described—beginning from PAN-IN 1 to invasive adenocarcinoma [4]. On a background of this recent meta-analysis summarising the evidence linking tobacco use with pancreatic cancer, we have reviewed the available laboratory and experimental data, providing a summary of the current knowledge of tobacco-driven pancreas carcinogenesis.

2. Search Methods

Established medical databases including PUBMED, MEDLINE, SCOPUS, and INDEX MEDICUS were searched for a variety of different combination of the terms *pancreas, pancreatic, cancer, adenocarcinoma, tobacco, use, smoking, and carcinogens* to identify peer-reviewed publications exploring the relationship between tobacco smoking and pancreas cancer. After excluding duplicate results, a total of 235 publications were initially identified. They were subjected to careful scrutiny and we excluded case-control, cohort studies and other cross-sectional/longitudinal studies published up until 2008. This was due to an excellent and comprehensive meta-analysis summarising the epidemiology of tobacco use and pancreas cancer (vide supra) published in 2008. All publications dedicated to laboratory, experimental and clinical consequences of tobacco carcinogen effect on the pancreas or development of pancreas cancer were identified and the full-text was carefully scrutinised. We also examined epidemiological papers published after 2008. Thus for the purposes of this paper 115 publications were reviewed in detail.

3. Review

Nicotine is the major psychoactive substance in tobacco and is responsible for tobacco dependence and addiction. It is thought to induce a euphoric state in users by the activation of the mesolimbic dopaminergic reward system in the nucleus accumbens of the brain [5], and this may be related to the highly addictive properties of the drug [6].

Individuals have genetically based differences in their ability to metabolize nicotine as well as genetic differences in the psychological reward pathways that may influence individual response to smoking initiation, dependence, addiction and cessation. While nicotine itself has some cancer-promoting abilities which we will discuss later, most of the health consequences of tobacco use are secondary to the other chemicals within it. Some are nicotine metabolites, whilst the others are unrelated.

3.1. Tobacco-Derived Carcinogens. Tobacco smoke contains 4000 compounds and 50 carcinogens as compared to 3000 compounds and 30 carcinogens in processed unburnt tobacco [7]. Both mainstream and sidestream smoke are harmful and have differing proportions of carcinogens. These carcinogens include polynuclear aromatic hydrocarbons (PAH), tobacco-specific nitrosamines (TSNA), aromatic amines, aza-arenes, and aldehydes, other organic compounds like benzene, inorganic compounds like hydrazine, and various metals [8] (reviewed by Hecht and Hoffmann). Seven compounds have been identified in the family of TSNA's—NNN (*N'*-nitrosoornicotine), NNK (4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone), NNAL (4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol), NAT (*N'*-nitrosoanatabine), NAB (*N'*-nitrosoanabasine), iso-NNAL [iso 4-(methylnitrosamino)-4-(3-pyridyl)-1-butanol] and iso-NNAC [iso 4-(*N*-methylnitrosamino)-4-(3-pyridyl)butyric acid]. NNN, NNK, and NNAL are the most

powerful carcinogens. Nitrosation of nicotine during tobacco processing and cigarette smoking leads to the formation of tobacco-specific nitrosamines, of which 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK) [9] is the most notorious and is now classified by the International Agency for Research on Cancer as a Group 1 carcinogen. In the context of pancreatic cancer TSNA's, NNK and NNAL are particularly important, as they demonstrate organ specificity towards the pancreas. They are present in large quantities in both burnt and unburnt tobacco.

TSNA's are procarcinogens. Following exposure, they need to undergo a series of steps uptake, metabolic activation, and DNA and protein adduct formation which subsequently leads to altered growth kinetics in the target organ and development of neoplasia. These metabolic pathways of NNK and NNN have been demonstrated *in vivo* in mice [10], rats, and hamsters [11] and in subcellular fractions, cultured cells and tissues from animals [12] and humans [13].

NNK can undergo hydroxylation, oxidation and carbonyl reduction to yield numerous metabolites which include diazoxides, formaldehyde, NNK-N-oxide, and NNAL. These metabolites react with DNA and protein resulting in adducts formation. In mice and rats, NNK-derived electrophiles react with nucleophilic centers in DNA to yield a variety of products including O⁶-methylguanine which causes miscoding of DNA during replication [14]. This production of O⁶-methylguanine and O⁶-ethylguanine had also been confirmed histochemically in pancreatic duct cells *in vitro* [15].

Until recently, nicotine had been considered to be responsible for only the addictive property of tobacco only; however, of late it is being increasingly recognised that nicotine might independently possess cancer facilitating properties causing the metastasis of tumours preinitiated by tobacco carcinogens [16] in rat models of lung cancer. This effect is thought to be mediated through nicotine stimulation of nAChR (nicotinic acid acetyl choline receptors). Nicotine can also induce epithelial-mesenchymal transition in cultured lung, breast and pancreatic cancer cells [17]. This is an essential part of the invasion—metastasis sequence and therefore it appears that while nicotine has only limited capacity to initiate tumour formation, it can induce invasion and metastasis in preexistent tumours.

3.2. Tobacco-Derived Carcinogens and Pancreatic Tumours in Animals. Numerous animal models of pancreas ductal cancer have been developed, and these have proved invaluable in elucidating the kinetics of the carcinogen within physiological systems and pathogenesis of ductal cancer of the pancreas. In 1988, the important role of tobacco derived carcinogens in extrapulmonary cancers including the pancreas was highlighted in a commentary by Hecht and Hoffmann. The same commentary also concluded that two of the nicotine-derived nitrosamines, NNK and NNN, are strong carcinogens in laboratory animals and that they could induce tumors both locally and systemically. Also, the magnitude to the total doses of NNK and NNN required to produce cancer in laboratory animals is similar to the total estimated doses which long-term snuff-dippers or heavy smokers are exposed life time [8].

In F-344 rats, NNK and NNAL cause development of not only lung but also pancreatic adenocarcinoma. The doses of carcinogens to body weight needed to cause these neoplasms in rats were similar to lifetime exposure of these chemicals in heavy smokers (40 cigarettes/day). This was the first example of pancreatic tumour induction by a constituent of tobacco smoke. NNAL appeared to be the proximate pancreatic carcinogen of NNK as it induced more tumours than NNK [18]. They are the only carcinogens to induce pancreatic adenocarcinoma in animal models when given systemically [18, 19]. Also, in F-344 rats, there is evidence that following oral NNK administration, there is preferential metabolism of NNK to (S)-NNAL followed by its extensive retention in various target tissues including the pancreas of NNK-orally treated animals [20]. Treatment of rats with TSNA's also resulted in the induction of pancreatic acinar cell and ductal cell neoplasms [21].

In rodents it has been shown that NNK and NNAL are excreted in the bile in significant concentrations [22]. If this is true in humans, it may be the route through which activated carcinogens reach the head of pancreas (carcinogen containing bile refluxing into the pancreatic duct). This theory is attractive given that the pancreatic head is the most frequent site for adenocarcinoma [23–25]. A study in rhesus monkeys ($n = 4$), however, found that biliary excretion of the NNK metabolites was significantly less than predicted from rat experiments. Very limited experiments have been performed on this route of TSNA excretion.

3.3. Tobacco Carcinogens in Humans and Their Relevance to Pancreatic Cancer. Most animal studies have been extrapolated to humans and the assumption is that the metabolism and physiological distribution kinetics of tobacco derived carcinogens is similar to that in rats and rodents. However, there will be differences in the manner in which our species handles these carcinogens, and a few studies have tried to elucidate this by various means. Essentially, what has been achieved is to show that the pancreas is exposed to these chemicals and that these metabolites bind to pancreatic ductal cell DNA and result in mutations there and that various phenotypic changes occur there including cancer. However the exact mechanism by which these carcinogens turn a normal ductal cell into a malignant one has not been described.

TSNA's (NNK and NNAL) have been detected in the pancreatic juice of smokers in significantly higher quantities as compared to nonsmokers confirming that the pancreas is exposed to these carcinogens [26]. It has been shown that aromatic amines and nitroaromatic hydrocarbons are metabolically activated in the human pancreas [27]. This confirmed that the pancreas is exposed to TSNA's and that these carcinogens may play a role in carcinogenesis at this site [22].

Although a strong correlation had been suggested between cigarette smoking and pancreatic cancer, studies on pathological changes in the pancreas of smokers are infrequent. Tomioka et al. performed a comparative autopsy study on 73 pancreases obtained by autopsy from 42 heavy

cigarette smokers and 31 nonsmoker patients. Although the incidence of pancreatic cancer in smokers was higher than in nonsmokers, the difference was statistically not significant. Ductal changes, including mucinous or squamous cell metaplasia and papillary hyperplasia, were found with equal frequencies in both groups of patients and the authors concluded that the type and the incidence of these ductal alterations were not related to smoking but to the age. There were significant limitations of this autopsy study including limited number of the sections of the pancreas examined, as well as exclusion of other important variables, such as alcohol, diet and diabetes weaken the value of this study [28]. Another autopsy study obtained purified DNA from human lung, liver, bladder, pancreas, breast and cervix of 13 men and 6 women and analysed it for DNA adducts using the nuclease P1 modification of the ³²P postlabelling technique. Relatives were asked to provide information on smoking history for deceased subjects. All tissues examined except the breast had detectable adducts. In lung, bladder and pancreatic tissue a characteristic pattern of adducts was seen which had previously been reported as typical of cigarette-smoke-induced damage; diagonal reactive zone [29]. Smokers and former smokers tended to have higher adduct levels than nonsmokers in the tissues examined but this was only significant for the lung. These results confirmed the finding that cigarette smoking is associated with DNA damage in the lung and suggested that similar damage may be related to tobacco-induced neoplasms of other tissues [30]. TSNA's adducts have been found in the pancreas and the levels have correlated with dose and time related to exposure [31].

3.4. Mechanism of Tobacco-Induced Carcinogenesis in the Pancreas. Over the past 10–15 years extensive work into the development of pancreatic cancer has been carried out. A model of stepwise progression from normal to malignant cells, and the molecular alterations involved in these has been described [32].

Very similar to the adenoma-carcinoma sequence in the colon, there is neoplastic progression in the pancreatic ducts [33–36]. This progression from a normal pancreatic ductal cell to an infiltrating carcinoma involves sequential multiple genetic alterations. The genetic changes include activating point mutations in K-ras, overexpression of HER-2neu, and inactivation of p16, p53 DPC4, and BRCA2. A gate-keeper gene for the initiation of pancreatic neoplasia has not been identified and the cause of the ignition of change in a normal ductal cell towards neoplasia is under investigation.

Several mechanisms have been proposed in regard to how tobacco smoking might be involved in pancreatic carcinogenesis such as tobacco-carcinogen-induced adducts resulting in the mutation of the K-ras oncogene and initiating tumorigenesis and subsequent promotion occurring by other factors. However, this is not yet clear, and other mechanisms such as the autonomic nervous system and its various pathways, lipid peroxidation, and synergistic molecular damage by other environmental, occupational, and other factors may play an important role.

3.4.1. K-ras Mutations, DNA Adducts, and Tobacco in the Initiation of Pancreatic Cancer. K-ras mutations have been identified in various malignancies, including pancreas cancers. A number of animal studies have been performed examining the hypothesis that tobacco smoking-induced K-ras mutations and that these were the beginnings of the malignancy [15, 37, 38]. In one of these models, an in vitro transformation of immortal hamster pancreatic duct cells was studied after exposure to NNK for varying lengths of time. Analysis of pancreatic DNA for K-ras mutation at codons 12, 13, and 61 showed G→A transition at codon 12 of the K-ras oncogene in tumour cells after 1 and 3 days of NNK treatment. However, no mutation was detected in tumour cells developing 5 and 7 days after NNK treatment [15]. One and 3 day NNK-treated cells were able to grow in the absence of growth factors and serum immediately after the treatment. Also, the tumorigenicity of these transformed cells was determined in nude mice, and the cells treated for 1 and 3 days produced well-differentiated neoplasms, while those that were treated for longer durations did not. Thus, it appeared that although K-ras mutation at codon 12 of pancreatic adenocarcinoma was an early event, it was not necessarily required for the development and/or progression of the tumours in nude mice.

Numerous studies have been performed in humans to ascertain the role of K-ras in pancreas development with conflicting results. Two key studies reporting on this issue and had divergent results—Nagata et al. observed a negative association [39], whilst Hruban et al. found a positive association [40]. In a population-based case-control study, where information on smoking and other life-style factors was obtained at direct patient interview, no significant association between K-ras mutation and smoking was identified [41]. A meta-analysis of 8 studies investigating K-ras mutations in various cancers including pancreas adenocarcinoma [42], explored the hypothesised association lifetime history of tobacco consumption. No significant association between the frequency of K-ras mutations (OR = 1.26; 95% CI = 0.82–1.94) and tobacco usage was identified. Subsequently, the PANKRAS 2 study group authors reported a case-case study [43], where they did not find any association between acquisition of K-ras mutations and tobacco smoking. In combination, these studies have contributed to the conclusion that while both smoking and K-Ras mutations are important in the development of pancreas cancer, they are independent of one another.

3.4.2. Promotion. Recent studies have demonstrated over-expression of cyclooxygenase and 5-lipoxygenase receptors in exocrine pancreatic carcinomas [44]. Following on from this, Weddle et al. demonstrated high basal levels of arachidonic acid release and expression of m-RNA for β adrenergic receptors (1 and 2) in two human cell lines derived from exocrine ductal pancreatic carcinomas. Notably, exogenous NNK promoted DNA synthesis in these cells [45]. This study therefore underlined the importance of β -adrenergic mechanisms in pancreas carcinogenesis (as had previously been reported for lung cancer [46, 47]).

NNK reportedly binds with high affinity to adrenergic and nicotinic receptors and activates downstream signalling pathways, inducing cellular proliferation cancer cell lines derived from human pancreas, breast and lung malignancies [48]. In a hamster model of exocrine pancreatic cancer induced by transplacental exposure to ethanol and the tobacco-carcinogen NNK [49], Schuller et al. reported a reduction in the development of pancreatic cancer in offspring who had been given the arachidonic acid pathway inhibitors, ibuprofen or MK886. Tumour development was reduced by 50% or 30%, respectively [49]. The reduction was not a result of an interaction with the drugs on NNK metabolism or cancer initiation events, as the NNK was administered as a single dose on day 15 of gestation, while the preventive treatments started 4 weeks later, when the offspring were weaned from their mothers. Of note, no mutations in the Ki-, N-, or H-ras or p53 genes were found in these tumours.

There is also recent evidence indicating that NNK is an agonist for nicotinic acetylcholine receptors (nAChRs), and in hamsters, NNK-induced alterations in regulatory nAChRs may contribute to the development of smoking-associated PAC and PDAC by disturbing the balance between cancer-stimulating and inhibiting neurotransmitters [50].

In combination, these findings suggest that NNK is a β -adrenergic agonist. β -adrenergic, AA-dependent regulatory pathways in pancreatic cancer are a possible novel target-dietary or pharmacologic for cancer intervention strategies [51] in an effort towards the prevention and clinical management of pancreatic cancer.

3.5. Synergistic Cofactors Contributing to Tobacco Related Pancreatic Carcinogenesis? While we are beginning to understand some of the key factors involved in pancreatic carcinogenesis, of which smoking is one, the primary etiology of the disease remains poorly understood. Other epidemiological factors may also be important and a genetic predisposition to the disease, supported by reported familial occurrences of the disease [52–54] has long been suspected. As reviewed here, investigators have struggled to show that tobacco contributes directly to the development of acquired mutations in the commonly reported oncogenes and tumour suppressor genes. However, there may well be a more subtle association, with innate or inherited genetic variation, which increases an individuals exposure to damaging agents, or possibly that individuals ability to repair induced DNA damage. There may also be interplay here, as with all polygenic diseases, with other environmental factors.

Certainly, there is a lot of individual variation in the metabolism of the known tobacco-derived carcinogens. Metabolically activated NNN and NNK bind not only to DNA but also to the protein moiety of haemoglobin resulting in globin-carcinogen adducts. Mass-spectroscopic studies have detected a significant overlap of the globin-carcinogen adduct levels between smokers and nonsmokers, suggesting that individuals vary in their ability to activate TSNA's [55]. As previously mentioned, there is also considerable variation in adduct levels in the pancreas at autopsy among smokers,

which could not be accounted for by duration or daily consumption level [30]. While the evidence for a synergistic role between smoking and other factors is limited, the key suspects are mentioned here.

(a) *Dietary Factors.* Various groups of researchers have explored the interaction of tobacco smoke with dietary and other factors in animal models in an attempt to replicate the scenarios found in humans, and there is evidence that some dietary factors act synergistically with these carcinogens. Coadministration of sinigrin (a glucoside found in some plants of the Brassica family such as brussels sprouts, broccoli, and seeds of black mustard) with NNK, for example, resulted in a significant incidence of pancreatic tumors in rats [56]. In a long-term bioassay (24 months) exploring the interaction of dietary fat and tobacco carcinogens, F344 rats were given NNK, in the drinking water. In addition, one group of rats was given a high-corn oil diet and the second group received a low-corn oil diet. There were control groups with similar diet and on plain tap water only. The NNK + high corn oil group gained more weight and developed more number of pancreas tumours as compared to the NNK + low corn oil group. There was no such effect on development of lung cancers in the animals. This elegant and simple bioassay provided supplementary evidence to corroborate epidemiological studies which had suggested a link between daily fat intake and pancreas cancers in smokers [57].

(b) *Obesity.* Obesity is now recognised as a risk factor in development of all cancers, but this is particularly so for pancreatic cancer. Wang et al. reported a 2.6 fold increase in relative risk of a pancreatic cancer associated death in individuals with a body mass index greater than or equal to 35. The animal study above, in which the fatter NNK group fed corn oil developed more pancreatic cancers, supports this although the actual cause is as yet unclear. A further study demonstrated that body mass index was positively correlated to the levels of DNA, lipid peroxidation related adducts and the total aromatic adducts in pancreatic tumour tissues [58]. These observations support the hypothesis that DNA damage related to a combination of carcinogen exposure and lipid peroxidation may be involved in human pancreatic carcinogenesis.

(c) *Alcohol.* A key dietary factor worthy of independent mention is alcohol. Alcohol has long been suspected of contributing to pancreatic cancer development [59, 60], but a synergistic role with tobacco exposure has also been considered. In pregnant animal models, NNK can cross the placenta following tracheal administration and cause its carcinogenic effect-pancreas cancer on the foetus. Concomitant administration of ethanol can greatly potentiated this effect [61], but other than recommending that pregnant women neither drink nor smoke, the human relevance of these findings is unclear. The PANKRAS 1 study investigated the presence of K-Ras mutations in patients who either smoked, or drank alcohol, or did both. The information in this study was taken from patient notes rather than a questionnaire,

but reported a higher risk only in those who did one or the other, rather than both [62]. As discussed previously, the frequency of K-Ras mutations is probably not the best tool to assess the impact of suspected carcinogens, and the true impact of smoking in combination with alcohol on pancreatic carcinogenesis has yet to be determined.

(d) *Genetic Factors.* A genetic predisposition is frequently alluded to in reviews of the aetiology of pancreatic cancers [63, 64] and certainly there are genetic disorders, such as Hereditary pancreatitis [65, 66], the Liefraumeni syndrome [67], Peutz-Jeghers syndrome [68] and Hereditary nonpolyposis colon cancer syndrome [69]. Familial atypical melanoma mole syndrome [70] where pancreatic cancer is a major feature. Furthermore, familial pancreatic cancer is a well recognised entity [71–73]. A recent retrospective cross-sectional cases-only study suggested an increased risk for pancreas cancer when multiple environmental risk factors (including tobacco smoke exposure) were present on a background of a family history of pancreas cancer [74]. This study has again emphasised the role of environmental factors in modulating the genetic risk for development of pancreas cancer.

When considering potential synergy between innate susceptibility and tobacco derived carcinogens, we are beginning to look toward genetic variability in the ways in which tobacco derived compounds or metabolites interact with targets, are metabolised, or even the ways in which the damage incurred is repaired. Polymorphisms in genes coding for dopamine receptors and transporters, nicotinic receptors and serotonin receptors, neurotransmitters and transporters [75] may be relevant, and certainly understanding the genetic factors involved in addiction may ultimately result in more effective tobacco cessation programs reducing the incidence of tobacco related diseases, including pancreatic cancer. In addition, however, we are beginning to understand individual variability of susceptibility to damage at a more molecular level.

Both the quantity and duration of exposure to carcinogens may determine adduct formation or the capacity to cause damage. The carcinogens themselves may be metabolised at different rates in individuals. In human pancreatic tissues, there is individual variability in the capacity for, and stereoselectivity of, carbonyl reduction of NNK. In individuals whose microsomes metabolize NNK at a lower rate but form predominantly (S)-NNAL, “stereoselective localization of (S)-NNAL” in the human pancreas might occur, similar to the rat lung, where S-NNAL gets retained resulting in higher incidence of cancers there [76].

One family of proteins with an important role in the metabolism of foreign compounds and drugs, and, therefore, a key suspect in promoting cancer predisposition if relatively ineffective in some circumstances, are the cytochrome P450 (CYP) superfamily. There is a vast literature reporting various genetic polymorphism in CYPs which increase cancer susceptibility. As yet, this is largely unconfirmed, with the exception of CYP2A6 polymorphism and tobacco-induced cancer [77, 78]. The role of these in tobacco related cancer has been summarised by others [78–80] and is not discussed

in depth here. In summary, although they have significant effects on tobacco-derived carcinogen metabolism, they are not considered to play an important role in pancreas cancer causation. Phase-2 metabolising enzymes such as Uridine-diphospho-glucuronosyl transferase (UDPGT) [81], Glutathione S-transferase (GST) [82–85] have also been studied but are reported from relatively small single institution studies and need validation in large case-control molecular epidemiological studies.

As well as variability in the capacity to cause damage, those pathways involved in the repair of damage have been studied, with significant individual variation reported. In particular, the role of polymorphisms of genes coding for enzymes and proteins within key metabolic and DNA repair pathways in modulating risk for human pancreas cancer is being investigated and has been the subject of recent reviews [86–88]. Numerous small single centre studies exploring the role of gene-environment interaction and interindividual variability in susceptibility to tobacco derived carcinogen damage [77, 89–95] have recently been reported and require validation. In addition, genome wide association studies (GWAS) in large numbers of individuals with pancreatic cancer are being performed and may ultimately lead us closer to the key genetic factors involved. The first of these confirmed an earlier epidemiologic finding that blood group O results in a decreased risk for pancreas cancer [96]. Another GWAS in Japanese individuals, who have a particularly high risk of pancreatic cancer, was reported in 2010 and identified genes on chromosomes on 6, 7, and 12 [97] and a further similar but larger study has suggested other specific loci on chromosomes 1, 5, and 13 to be associated with an increased risk for the malignancy; however, the functional significance of these findings is not clear.

4. Conclusion

Tobacco, as it is used in its most prevalent form, that is, smoking, is the most important risk factor for the development of pancreas cancer. There is compelling epidemiological evidence for a disease-causation effect for this which is backed up by physiological evidence based on laboratory studies on subcellular fractions, cell lines derived from human and animal models of the disease, whole animal models and human studies. There is also significant evidence for interindividual variation in susceptibility to tobacco-derived carcinogens which is a field of intense current research. Understanding of the role of not only tobacco carcinogens, but also the possible toxic role of nicotine itself in humans needs to be emphasised in public awareness campaigns.

Further work is urgently required to explore the complex interactions between genetic, life-style/environmental factors at both laboratory and population levels to understand the disease better and enable improvement in outcome by not only earlier diagnosis, but also innovative and newer modes of intervention.

References

- [1] N. A. van der Gaag and D. J. Gouma, "PBD treatment of cancer of the head of the pancreas," *Nature Reviews Clinical Oncology*, vol. 7, no. 11, 2010.
- [2] United States. Public Health Service. Office of the Surgeon General., United States. Office on Smoking and Health, *The health consequences of smoking: a report of the Surgeon General*, U.S. Department of Health and Human Services, Public Health Service, Rockville, Md, USA, 2004.
- [3] S. Iodice, S. Gandini, P. Maisonneuve, and A. B. Lowenfels, "Tobacco and the risk of pancreatic cancer: a review and meta-analysis," *Langenbeck's Archives of Surgery*, vol. 393, no. 4, pp. 535–545, 2008.
- [4] R. H. Hruban, N. V. Adsay, J. Albores-Saavedra et al., "Pancreatic intraepithelial neoplasia: a new nomenclature and classification system for pancreatic duct lesions," *American Journal of Surgical Pathology*, vol. 25, no. 5, pp. 579–586, 2001.
- [5] R. A. Wise and P. P. Rompre, "Brain dopamine and reward," *Annual Review of Psychology*, vol. 40, pp. 191–225, 1989.
- [6] D. J. K. Balfour, "The neurobiology of tobacco dependence: a preclinical perspective on the role of the dopamine projections to the nucleus," *Nicotine and Tobacco Research*, vol. 6, no. 6, pp. 899–912, 2004.
- [7] S. S. Hecht, "Biochemistry, biology, and carcinogenicity of tobacco-specific N-nitrosamines," *Chemical Research in Toxicology*, vol. 11, no. 6, pp. 559–603, 1998.
- [8] S. S. Hecht and D. Hoffmann, "Tobacco-specific nitrosamines, an important group of carcinogens in tobacco and tobacco smoke," *Carcinogenesis*, vol. 9, no. 6, pp. 875–884, 1988.
- [9] D. Hoffmann, J. D. Adams, J. J. Piade, and S. S. Hecht, "Chemical studies on tobacco smoke LXVIII. Analysis of volatile and tobacco-specific nitrosamines in tobacco products," *IARC Scientific Publications*, no. 31, pp. 507–516, 1980.
- [10] S. S. Hecht, M. A. Morse, S. Amin et al., "Rapid single-dose model for lung tumor induction in A/J mice by 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone and the effect of diet," *Carcinogenesis*, vol. 10, no. 10, pp. 1901–1904, 1989.
- [11] S. S. Hecht, J. D. Adams, S. Numoto, and D. Hoffmann, "Induction of respiratory tract tumors in Syrian golden hamsters by a single dose of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK) and the effect of smoke inhalation," *Carcinogenesis*, vol. 4, no. 10, pp. 1287–1290, 1983.
- [12] S. E. Murphy, R. Heiblum, and N. Trushin, "Comparative metabolism of N'-nitrosornicotine and 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone by cultured F344 rat oral tissue and esophagus," *Cancer Research*, vol. 50, no. 15, pp. 4685–4691, 1990.
- [13] A. Castonguay, G. D. Stoner, H. A. J. Schut, and S. S. Hecht, "Metabolism of tobacco-specific N-nitrosamines by cultured human tissues," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 80, no. 21, pp. 6694–6697, 1983.
- [14] P. Upadhyaya, B. R. Lindgren, and S. S. Hecht, "Comparative levels of O6-methylguanine, pyridyloxobutyl-, and pyridylhydroxybutyl-DNA adducts in lung and liver of rats treated chronically with the tobacco-specific carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone," *Drug Metabolism and Disposition*, vol. 37, no. 6, pp. 1147–1151, 2009.
- [15] K. Baskaran, S. Laconi, and M. K. Reddy, "Transformation of hamster pancreatic duct cells by 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK), in vitro," *Carcinogenesis*, vol. 15, no. 11, pp. 2461–2466, 1994.

- [16] R. Davis, W. Rizwani, S. Banerjee et al., "Nicotine promotes tumor growth and metastasis in mouse models of lung cancer," *PLoS ONE*, vol. 4, no. 10, Article ID e7524, 2009.
- [17] P. Dasgupta, W. Rizwani, S. Pillai et al., "Nicotine induces cell proliferation, invasion and epithelial-mesenchymal transition in a variety of human cancer cell lines," *International Journal of Cancer*, vol. 124, no. 1, pp. 36–45, 2009.
- [18] A. Rivenson, D. Hoffmann, B. Prokopczyk, S. Amin, and S. S. Hecht, "Induction of lung and exocrine pancreas tumors in F344 rats by tobacco-specific and Areca-derived N-nitrosamines," *Cancer Research*, vol. 48, no. 23, pp. 6912–6917, 1988.
- [19] D. Hoffmann, A. Rivenson, F. L. Chung, and S. S. Hecht, "Nicotine-derived N-nitrosamines (TSNA) and their relevance in tobacco carcinogenesis," *Critical Reviews in Toxicology*, vol. 21, no. 4, pp. 305–311, 1991.
- [20] S. Zhang, M. Wang, P. W. Villalta et al., "Analysis of pyridyloxobutyl and pyridylhydroxybutyl DNA adducts in extrahepatic tissues of F344 rats treated chronically with 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone and enantiomers of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol," *Chemical Research in Toxicology*, vol. 22, no. 5, pp. 926–936, 2009.
- [21] P. M. Pour and A. Rivenson, "Induction of a mixed ductal-squamous-islet cell carcinoma in a rat treated with a tobacco-specific carcinogen," *American Journal of Pathology*, vol. 134, no. 3, pp. 627–631, 1989.
- [22] J. Schulze, E. Richter, U. Binder, and W. Zwicklenpflug, "Biliary excretion of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone in the rat," *Carcinogenesis*, vol. 13, no. 11, pp. 1961–1965, 1992.
- [23] M. Niedergethmann, M. Rexin, R. Hildenbrand et al., "Prognostic implications of routine, immunohistochemical, and molecular staging in resectable pancreatic adenocarcinoma," *American Journal of Surgical Pathology*, vol. 26, no. 12, pp. 1578–1587, 2002.
- [24] K. C. Conlon, D. S. Klimstra, and M. F. Brennan, "Long-term survival after curative resection for pancreatic ductal adenocarcinoma: clinicopathologic analysis of 5-year survivors," *Annals of Surgery*, vol. 223, no. 3, pp. 273–279, 1996.
- [25] A. Iakimov and I. Zheleva, "Pancreatic cancer. I. The age distribution and location of the tumor process in the gland (a statistical analysis based on autopsy data from the Department of Pathological Anatomy of the Biomedical Research Institute over the 25 years from 1963–1987)," *Khirurgiia*, vol. 44, no. 1, pp. 28–31, 1991.
- [26] B. Prokopczyk, D. Hoffmann, M. Bologna et al., "Identification of tobacco-derived compounds in human pancreatic juice," *Chemical Research in Toxicology*, vol. 15, no. 5, pp. 677–685, 2002.
- [27] K. E. Anderson, G. J. Hammons, F. F. Kadlubar et al., "Metabolic activation of aromatic amines by human pancreas," *Carcinogenesis*, vol. 18, no. 5, pp. 1085–1092, 1997.
- [28] T. Tomioka, A. Andren-Sandberg, H. Fujii, H. Egami, Y. Takiyama, and P. M. Pour, "Comparative histopathological findings in the pancreas of cigarette smokers and non-smokers," *Cancer Letters*, vol. 55, no. 2, pp. 121–128, 1990.
- [29] E. Randerath, D. Mittal, and K. Randerath, "Tissue distribution of covalent DNA damage in mice treated dermally with cigarette 'tar' preference for lung and heart DNA," *Carcinogenesis*, vol. 9, no. 1, pp. 75–80, 1988.
- [30] J. Cuzick, M. N. Routledge, D. Jenkins, and R. C. Garner, "DNA adducts in different tissues of smokers and non-smokers," *International Journal of Cancer*, vol. 45, no. 4, pp. 673–678, 1990.
- [31] E. Randerath and K. Randerath, "Monitoring tobacco smoke-induced DNA damage by ³²P-postlabelling," *IARC Scientific Publications*, no. 124, pp. 305–314, 1993.
- [32] J. Geradts, R. H. Hruban, M. Schutte, S. E. Kern, and R. Maynard, "Immunohistochemical p16(INK4a) analysis of archival tumors with deletion, hypermethylation, or mutation of the CDKN2/MTS1 gene: a comparison of four commercial antibodies," *Applied Immunohistochemistry*, vol. 8, no. 1, pp. 71–79, 2000.
- [33] R. H. Hruban, M. Goggins, J. Parsons, and S. E. Kern, "Progression model for pancreatic cancer," *Clinical Cancer Research*, vol. 6, no. 8, pp. 2969–2972, 2000.
- [34] M. Goggins, R. H. Hruban, and S. E. Kern, "BRCA2 is inactivated late in the development of pancreatic intraepithelial neoplasia: evidence and implications," *American Journal of Pathology*, vol. 156, no. 5, pp. 1767–1771, 2000.
- [35] R. E. Wilentz, M. Goggins, M. Redston et al., "Genetic, immunohistochemical, and clinical features of medullary carcinoma of the pancreas: a newly described and characterized entity," *American Journal of Pathology*, vol. 156, no. 5, pp. 1641–1651, 2000.
- [36] R. E. Wilentz, C. A. Iacobuzio-Donahue, P. Argani et al., "Loss of expression of Dpc4 in pancreatic intraepithelial neoplasia: evidence that DPC4 inactivation occurs late in neoplastic progression," *Cancer Research*, vol. 60, no. 7, pp. 2002–2006, 2000.
- [37] M. Tsutsumi, S. Kondoh, O. Noguchi et al., "K-ras gene mutation in early ductal lesions induced in a rapid production model for pancreatic carcinomas in Syrian hamsters," *Japanese Journal of Cancer Research*, vol. 84, no. 11, pp. 1101–1105, 1993.
- [38] M. Tsutsumi, Y. Murakami, S. Kondoh et al., "Comparison of K-ras oncogene activation in pancreatic duct carcinomas and cholangiocarcinomas induced in hamsters by N-nitrosobis(2-hydroxypropyl)amine," *Japanese Journal of Cancer Research*, vol. 84, no. 9, pp. 956–960, 1993.
- [39] Y. Nagata, M. Abe, K. Motoshima, E. Nakayama, and H. Shiku, "Frequent glycine-to-aspartic acid mutations at codon 12 of c-Ki-ras gene in human pancreatic cancer in Japanese," *Japanese Journal of Cancer Research*, vol. 81, no. 2, pp. 135–140, 1990.
- [40] R. H. Hruban, A. D. M. van Mansfeld, G. J. A. Offerhaus et al., "K-ras oncogene activation in adenocarcinoma of the human pancreas: a study of 82 carcinomas using a combination of mutant-enriched polymerase chain reaction analysis and allele-specific oligonucleotide hybridization," *American Journal of Pathology*, vol. 143, no. 2, pp. 545–554, 1993.
- [41] R. J. C. Slebos, J. A. Hoppin, P. E. Tolbert et al., "K-ras and p53 in pancreatic cancer: association with medical history, histopathology, and environmental exposures in a population-based study," *Cancer Epidemiology Biomarkers and Prevention*, vol. 9, no. 11, pp. 1223–1232, 2000.
- [42] M. Porta, M. Crous-Bou, P. A. Wark et al., "Cigarette smoking and K-ras mutations in pancreas, lung and colorectal adenocarcinomas: etiopathogenic similarities, differences and paradoxes," *Mutation Research*, vol. 682, no. 2-3, pp. 83–93, 2009.
- [43] M. Crous-Bou, M. Porta, T. López et al., "Lifetime history of tobacco consumption and K-ras mutations in exocrine pancreatic cancer," *Pancreas*, vol. 35, no. 2, pp. 135–141, 2007.
- [44] H. M. Schuller, G. Kabalka, G. Smith, A. Mereddy, M. Akula, and M. Cekanova, "Detection of overexpressed COX-2 in precancerous lesions of hamster pancreas and lungs by molecular imaging: implications for early diagnosis and prevention," *ChemMedChem*, vol. 1, no. 6, pp. 603–610, 2006.

- [45] D. L. Weddle, P. Tithoff, M. Williams, and H. M. Schuller, " β -Adrenergic growth regulation of human cancer cell lines derived from pancreatic ductal carcinomas," *Carcinogenesis*, vol. 22, no. 3, pp. 473–479, 2001.
- [46] H. M. Schuller, P. K. Tithof, M. Williams, and H. Plummer III, "The tobacco-specific carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol is a β -adrenergic agonist and stimulates DNA synthesis in lung adenocarcinoma via β -adrenergic receptor-mediated release of arachidonic acid," *Cancer Research*, vol. 59, no. 18, pp. 4510–4515, 1999.
- [47] P. G. Park, J. Merryman, M. Orloff, and H. M. Schuller, " β -adrenergic mitogenic signal transduction in peripheral lung adenocarcinoma: implications for individuals with preexisting chronic lung disease," *Cancer Research*, vol. 55, no. 16, pp. 3504–3508, 1995.
- [48] H. M. Schuller, "Neurotransmitter receptor-mediated signaling pathways as modulators of carcinogenesis," *Progress in Experimental Tumor Research*, vol. 39, pp. 45–63, 2007.
- [49] H. Schuller, L. Zhang, D. L. Weddle, A. Castonguay, K. Walker, and M. S. Miller, "The cyclooxygenase inhibitor ibuprofen and the FLAP inhibitor MK886 inhibit pancreatic carcinogenesis induced in hamsters by transplacental exposure to ethanol and the tobacco carcinogen NNK," *Journal of Cancer Research and Clinical Oncology*, vol. 128, no. 10, pp. 525–532, 2002.
- [50] H. A. N. Al-Wadei and H. M. Schuller, "Nicotinic receptor-associated modulation of stimulatory and inhibitory neurotransmitters in NNK-induced adenocarcinoma of the lungs and pancreas," *Journal of Pathology*, vol. 218, no. 4, pp. 437–445, 2009.
- [51] S. Subongkot, D. Frame, W. Leslie, and D. Drajer, "Selective cyclooxygenase-2 inhibition: a target in cancer prevention and treatment," *Pharmacotherapy*, vol. 23, no. 1, pp. 9–28, 2003.
- [52] P. Ghadirian, A. Simard, and J. Baillargeon, "Cancer of the pancreas in two brothers and one sister," *International Journal of Pancreatolgy*, vol. 2, no. 5–6, pp. 383–391, 1987.
- [53] M. Del Chiaro, A. Zerbi, M. Falconi et al., "Cancer risk among the relatives of patients with pancreatic ductal adenocarcinoma," *Pancreatolgy*, vol. 7, no. 5–6, pp. 459–469, 2007.
- [54] P. Ghadirian, P. Boyle, A. Simard, J. Baillargeon, P. Maisonneuve, and C. Perret, "Reported family aggregation of pancreatic cancer within a population-based case-control study in the Francophone Community in Montreal, Canada," *International Journal of Pancreatolgy*, vol. 10, no. 3–4, pp. 183–196, 1991.
- [55] S. S. Hecht, S. G. Carmella, P. G. Foiles, and S. E. Murphy, "Biomarkers for human uptake and metabolic activation of tobacco-specific nitrosamines," *Cancer Research*, vol. 54, no. 7, supplement, pp. 1912–7917, 1994.
- [56] M. A. Morse, C. X. Wang, S. G. Amin, S. S. Hecht, and F. L. Chung, "Effects of dietary sinigrin or indole-3-carbinol on O6-methylguanine-DNA-transmethylase activity and 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol-induced DNA methylation and tumorigenicity in F344 rats," *Carcinogenesis*, vol. 9, no. 10, pp. 1891–1895, 1988.
- [57] D. Hoffmann, A. Rivenson, R. Abbi, and E. L. Wynder, "A study of tobacco carcinogenesis: effect of the fat content of the diet on the carcinogenic activity of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol in F344 rats," *Cancer Research*, vol. 53, no. 12, pp. 2758–2761, 1993.
- [58] M. Wang, J. L. Abbuzzese, H. Friess et al., "DNA adducts in human pancreatic tissues and their potential role in carcinogenesis," *Cancer Research*, vol. 58, no. 1, pp. 38–41, 1998.
- [59] M. Voirol, F. Infante, O. Brahime-Reteno, L. Raymond, V. Hollenweger, and E. Loizeau, "Alcohol, tobacco and food consumption in pancreatic diseases. Preliminary results of a study of 1000 cases," *Schweizerische Medizinische Wochenschrift*, vol. 110, no. 22, pp. 854–855, 1980.
- [60] I. Heuch, G. Kvale, B. K. Jacobsen, and E. Bjelke, "Use of alcohol, tobacco and coffee, and risk of pancreatic cancer," *British Journal of Cancer*, vol. 48, no. 5, pp. 637–643, 1983.
- [61] H. M. Schuller, R. Jorquera, A. Reichert, and A. Castonguay, "Transplacental induction of pancreas tumors in hamsters by ethanol and the tobacco-specific nitrosamine 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol," *Cancer Research*, vol. 53, no. 11, pp. 2498–2501, 1993.
- [62] N. Malats, M. Porta, J. M. Corominas, J. L. Piñol, J. Rifà, and F. X. Real, "Ki-ras mutations in exocrine pancreatic cancer: association with clinico-pathological characteristics and with tobacco and alcohol consumption," *International Journal of Cancer*, vol. 70, no. 6, pp. 661–667, 1997.
- [63] P. D. L. M. Hall, R. E. Wilentz, W. de Klerk, and P. P. C. Bornman, "Premalignant conditions of the pancreas," *Pathology*, vol. 34, no. 6, pp. 504–517, 2002.
- [64] S. Landi, "Genetic predisposition and environmental risk factors to pancreatic cancer: a review of the literature," *Mutation Research*, vol. 681, no. 2–3, pp. 299–307, 2009.
- [65] D. C. Whitcomb and C. D. Ulrich II, "Hereditary pancreatitis: new insights, new directions," *Bailliere's Best Practice in Clinical Gastroenterology*, vol. 13, no. 2, pp. 253–263, 1999.
- [66] M. D. Finch, N. Howes, I. Ellis et al., "Hereditary pancreatitis and familial pancreatic cancer," *Digestion*, vol. 58, no. 6, pp. 564–569, 1997.
- [67] J. M. Birch, R. D. Alston, R. J. Q. McNally et al., "Relative frequency and morphology of cancers in carriers of germline TP53 mutations," *Oncogene*, vol. 20, no. 34, pp. 4621–4628, 2001.
- [68] F. M. Giardiello, J. D. Brensinger, A. C. Tersmette et al., "Very high risk of cancer in familial Peutz-Jeghers syndrome," *Gastroenterology*, vol. 119, no. 6, pp. 1447–1453, 2000.
- [69] H. T. Lynch, S. J. Lanspa, B. M. Boman et al., "Hereditary nonpolyposis colorectal cancer—lynch syndromes I and II," *Gastroenterology Clinics of North America*, vol. 17, no. 4, pp. 679–712, 1988.
- [70] H. T. Lynch, R. M. Fusaro, and W. J. Kimberling, "Familial atypical multiple mole-melanoma (FAMMM) syndrome: segregation analysis," *Journal of Medical Genetics*, vol. 20, no. 5, pp. 342–344, 1983.
- [71] M. Del Chiaro, A. Zerbi, G. Capurso et al., "Familial pancreatic cancer in Italy. Risk assessment, screening programs and clinical approach: a position paper from the Italian Registry," *Digestive and Liver Disease*, vol. 42, no. 9, pp. 597–605, 2010.
- [72] C. Shi, R. H. Hruban, and A. P. Klein, "Familial pancreatic cancer," *Archives of Pathology and Laboratory Medicine*, vol. 133, no. 3, pp. 365–374, 2009.
- [73] T. A. Brentnall, "Management strategies for patients with hereditary pancreatic cancer," *Current Treatment Options in Oncology*, vol. 6, no. 5, pp. 437–445, 2005.
- [74] T. P. Yeo, R. H. Hruban, J. Brody, K. Brune, S. Fitzgerald, and C. J. Yeo, "Assessment of "gene-environment" interaction in cases of familial and sporadic pancreatic cancer," *Journal of Gastrointestinal Surgery*, vol. 13, no. 8, pp. 1487–1494, 2009.
- [75] S. L. MacLeod and P. Chowdhury, "The genetics of nicotine dependence: relationship to pancreatic cancer," *World Journal of Gastroenterology*, vol. 12, no. 46, pp. 7433–7439, 2006.
- [76] Y. Lao, N. Yu, F. Kassie, P. W. Villalta, and S. S. Hecht, "Formation and accumulation of pyridyloxobutyl DNA adducts

- in F344 rats chronically treated with 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone and enantiomers of its metabolite, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol," *Chemical Research in Toxicology*, vol. 20, no. 2, pp. 235–245, 2007.
- [77] S. Kadlubar, J. P. Anderson, C. Sweeney et al., "Phenotypic CYP2A6 variation and the risk of pancreatic cancer," *Journal of the Pancreas*, vol. 10, no. 3, pp. 263–270, 2009.
- [78] A. Rossini, T. D. A. Simo, R. M. Albano, and L. F. R. Pinto, "CYP2A6 polymorphisms and risk for tobacco-related cancers," *Pharmacogenomics*, vol. 9, no. 11, pp. 1737–1752, 2008.
- [79] H. Bartsch, U. Nair, A. Risch, M. Rojas, H. Wikman, and K. Alexandrov, "Genetic polymorphism of CYP genes, alone or in combination, as a risk modifier of tobacco-related cancers," *Cancer Epidemiology Biomarkers and Prevention*, vol. 9, no. 1, pp. 3–28, 2000.
- [80] C. Rodriguez-Antona, A. Gomez, M. Karlgren, S. C. Sim, and M. Ingelman-Sundberg, "Molecular genetics and epigenetics of the cytochrome P450 gene family and its relevance for cancer risk and treatment," *Human Genetics*, vol. 127, no. 1, pp. 1–17, 2010.
- [81] J. Ockenga, A. Vogel, N. Teich, V. Keim, M. P. Manns, and C. P. Strassburg, "UDP glucuronosyltransferase (UGT1A7) gene polymorphisms increase the risk of chronic pancreatitis and pancreatic cancer," *Gastroenterology*, vol. 124, no. 7, pp. 1802–1808, 2003.
- [82] J. D. Collier, M. K. Bennett, A. Hall, A. R. Cattan, R. Lendrum, and M. F. Bassendine, "Expression of glutathione S-transferases in normal and malignant pancreas: an immunohistochemical study," *Gut*, vol. 35, no. 2, pp. 266–269, 1994.
- [83] A. B. Ulrich, J. Standop, B. M. Schmied, M. B. Schneider, T. A. Lawson, and P. M. Pour, "Expression of drug-metabolizing enzymes in the pancreas of hamster, mouse, and rat, responding differently to the pancreatic carcinogenicity of BOP," *Pancreatology*, vol. 2, no. 6, pp. 519–527, 2002.
- [84] A. B. Ulrich, B. M. Schmied, J. Standop et al., "Differences in the expression of glutathione S-transferases in normal pancreas, chronic pancreatitis, secondary chronic pancreatitis, and pancreatic cancer," *Pancreas*, vol. 24, no. 3, pp. 291–297, 2002.
- [85] E. J. Duell, E. A. Holly, P. M. Bracci, M. Liu, J. K. Wiencke, and K. T. Kelsey, "A population-based, case-control study of polymorphisms in carcinogen-metabolizing genes, smoking, and pancreatic adenocarcinoma risk," *Journal of the National Cancer Institute*, vol. 94, no. 4, pp. 297–306, 2002.
- [86] R. Lochan, A. K. Daly, H. L. Reeves, and R. M. Charnley, "Genetic susceptibility in pancreatic ductal adenocarcinoma," *British Journal of Surgery*, vol. 95, no. 1, pp. 22–32, 2008.
- [87] R. L. Milne, W. Greenhalf, C. Murta-Nascimento, F. X. Real, and N. Malats, "The inherited genetic component of sporadic pancreatic adenocarcinoma," *Pancreatology*, vol. 9, no. 3, pp. 206–214, 2009.
- [88] Y. Lin, K. Yagyu, N. Egawa et al., "An overview of genetic polymorphisms and pancreatic cancer risk in molecular epidemiologic studies," *Journal of Epidemiology*, vol. 21, no. 1, pp. 2–12, 2011.
- [89] H. Suzuki, J. S. Morris, Y. Li et al., "Interaction of the cytochrome P4501A2, SULT1A1 and NAT gene polymorphisms with smoking and dietary mutagen intake in modification of the risk of pancreatic cancer," *Carcinogenesis*, vol. 29, no. 6, pp. 1184–1191, 2008.
- [90] R. R. McWilliams, W. R. Bamlet, J. M. Cunningham et al., "Polymorphisms in DNA repair genes, smoking, and pancreatic adenocarcinoma risk," *Cancer Research*, vol. 68, no. 12, pp. 4928–4935, 2008.
- [91] E. J. Duell, P. M. Bracci, J. H. Moore, R. D. Burk, K. T. Kelsey, and E. A. Holly, "Detecting pathway-based gene-gene and gene-environment interactions in pancreatic cancer," *Cancer Epidemiology Biomarkers and Prevention*, vol. 17, no. 6, pp. 1470–1479, 2008.
- [92] J. Ockenga, S. Strunck, C. Post et al., "The role of epoxide hydrolase Y113H gene variant in pancreatic diseases," *Pancreas*, vol. 38, no. 4, pp. e97–e101, 2009.
- [93] R. R. McWilliams, W. R. Bamlet, M. de Andrade, D. N. Rider, J. M. Cunningham, and G. M. Petersen, "Nucleotide excision repair pathway polymorphisms and pancreatic cancer risk: evidence for role of MMS19L," *Cancer Epidemiology Biomarkers and Prevention*, vol. 18, no. 4, pp. 1295–1302, 2009.
- [94] D. Zhao, D. Xu, X. Zhang et al., "Interaction of cyclooxygenase-2 variants and smoking in pancreatic cancer: a possible role of nucleophosmin," *Gastroenterology*, vol. 136, no. 5, pp. 1659–1668, 2009.
- [95] B. Mohelnikova-Duchonova, D. Vrana, I. Holcatova, M. Ryska, Z. Smerhovsky, and P. Soucek, "CYP2A13, ADH1B, and ADH1C gene polymorphisms and pancreatic cancer risk," *Pancreas*, vol. 39, no. 2, pp. 144–148, 2010.
- [96] L. Amundadottir, P. Kraft, R. Z. Stolzenberg-Solomon et al., "Genome-wide association study identifies variants in the ABO locus associated with susceptibility to pancreatic cancer," *Nature Genetics*, vol. 41, no. 9, pp. 986–990, 2009.
- [97] S. K. Low, A. Kuchiba, H. Zembutsu et al., "Genome-wide association study of pancreatic cancer in Japanese population," *PLoS ONE*, vol. 5, no. 7, Article ID e11824, 2010.