

# DIFFUSE HORMONAL SYSTEMS

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## ABSTRACT

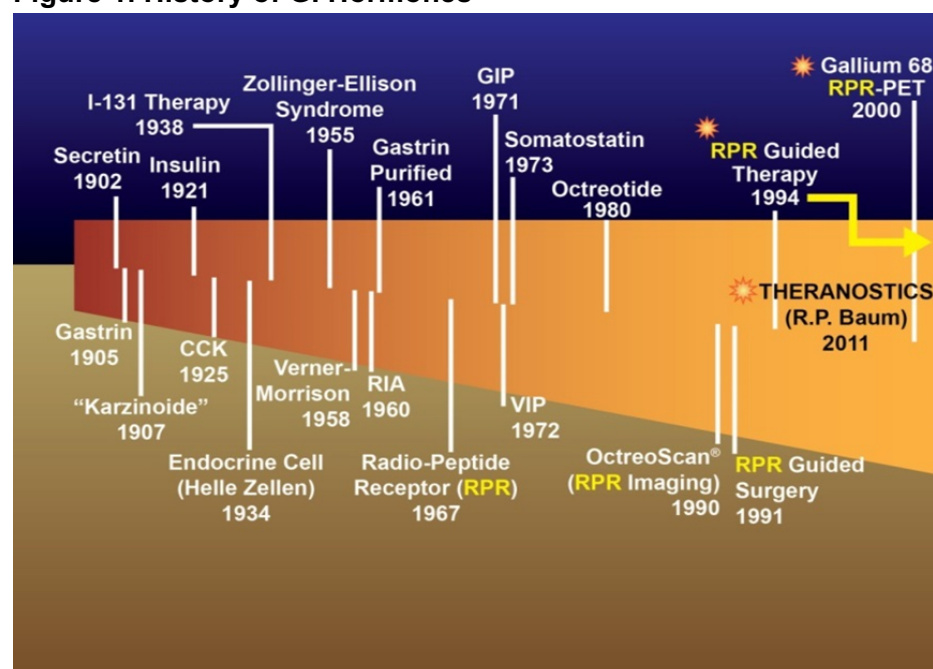
A plethora of gut hormones have been discovered and are linked to clinical syndromes. The proliferation and totipotentiality of the enterochromaffin cell (EC) is responsible for many of the neuroendocrine tumors. Somatostatin has a myriad of physiologic actions in the human body ranging from control of secretions, hormones, gut motility and tumor growth and proliferation. Somatostatin has five receptors conferring specificity of function. Attaching the molecule to various tracers has fostered development of radiotracers to identify the sites of tumor formation and Gallium 68 RPR-PET has a 40-100 fold greater potency than Octreoscan. Combination with lutetium or yttrium creates powerful destructive tools and there has been born a period of “theranostics” in which the same molecule enhances detection and diagnosis but also the ability to treat. When Guillemin discovered somatostatin that inhibited growth hormone secretion from the pituitary he exclaimed that it had not escaped his attention that there may be multiple targets for this peptide. I am not sure that he anticipated the Theranostic explosion that lay ahead. And beyond somatostatin we have tyrosine kinase and MTOR inhibitors and peptide receptor radiotherapy (PRRT) for the treatment of NETS.

## INTRODUCTION

The birth of endocrinology was in the gastrointestinal tract! Figure 1 shows the progression from the discovery of the first hormone secretin when Bayliss and Starling instilled acid into the denervated duodenum of a dog and observed the flow of pancreatic secretions and said this must be due to a hormone which is a word derived from the Greek to “excite”. Subsequently gastrin was identified by Edkins as a potent gastric acid secretagogue in 1905 and Zollinger and Ellison in 1955 recognized it as the principal culprit for the Zollinger Ellison syndrome due to gastric acid overproduction. These discoveries led to a focus on pancreatic and gastric secretion. In 1925 Oberg and Ivy discovered CCK which contracted the gallbladder and it took eons to recognize a clinical syndrome associated with gastric hypersecretion by Jens Rehfeld. Meanwhile Verner and Morrison discovered VIP in 1972 which identified the culprit behind the watery diarrhea , hypokalemia acidosis syndrome (WDHHA) . A flurry of activity in the 60s and 70s led to the discovery of a host of peptides including gastric Inhibitory polypeptide (GIP) by John Brown who renamed it as glucose dependent insulin releasing peptide which has conferred upon it much greater notoriety. Advances in this field were catapulted with the development of radioimmunoassay by Berson and Yalow in 1959 led to the ability of quantification of hormones in the circulation in picomolar amounts and the application of the assay to glucagon by Roger Unger. The advances in immunological techniques and protein chemistry led to intensive progress with the purification and sequencing of a host of other

peptides such as motilin, gastric inhibitory peptide somatostatin, leptin and ghrelin. Thus, grew the interest in physiologic mechanisms of action of these hormones digestive glandular secretion, gastrointestinal motility, visceral blood flow and tissue growth and proliferation as well as dedifferentiation of cells into their malignant counterparts. This era was recognized for the discovery of molecules without known biological function such as pancreatic polypeptide (PP), physiologic activity without known peptide regulators, hormones with dual function or as in the case of somatostatin discovered by Schally and Guillemin which was the second peptide captured for a role in peptide therapy. The ability to derive molecules from the parent molecule and its precursor enhanced the capacity to exploit its actions in controlling physiology as a virtual inhibitor of all secretions, to radiolabel the peptide in the development of imaging techniques such as the Octreoscan and the formation of long-acting analogs cable of restricting cell growth and proliferation. Further refinements have seen the evolution of peptide receptor radiotherapy (PRRT) and more potent Gallium DOTATOC and TATE scanning. This age has been referred to as Theranostics by Baum to reflect on the diagnostic capabilities as well as the therapeutic potential. The original recognition of Karzinoid as a tumor of the GI tract in 1907 led to the description by Feyrter of the cell type as Helle Zellen or transparent cells because of their characteristics gave birth to the recognition of the LC cell which is the grandfather of a far-reaching neuroendocrine tumor potential and expanded the role of the gut from pancreas and intestinal tract to a gut brain axis from which a number of disorders have blossomed. This theranostic era has witnessed the implications of tyrosine kinase inhibitors, MTOR involvement in tumor growth and therapy and these last few years have been party to a plethora of new discoveries of old hormones. New discoveries of new hormones and new discoveries of new functions for older peptides and new discoveries of actions outside of the GI tract for established GI hormones.

**Figure 1. History of GI Hormones**



Endocrine tumors of the gastroenteropancreatic (GEP) axis consist of cells that are capable of

amine precursor uptake and decarboxylation and therefore have been named APUDomas (1). The morphologic similarity of the APUD cells suggested a common embryologic origin, which was believed to be the neural crest but was later revised to include the neuroectoderm or, in the case of endocrine cells, the dorsal placoderm. However, most investigators agree that these tumors should be classified according to their secretory products (i.e., carcinoid, gastrinoma, insulinoma, somatostatinomas, glucagonoma, vasoactive intestinal peptide [VIPoma] and pancreatic polypeptide [PPoma] (2) (3) (4). Before presenting their clinical characteristics we will briefly review the currently held views on the embryologic origin of these cells and the factors regulating their growth, differentiation and apoptosis, that serve to maintain homeostatic balance. We will also indicate the derangements that result in tumor formation.

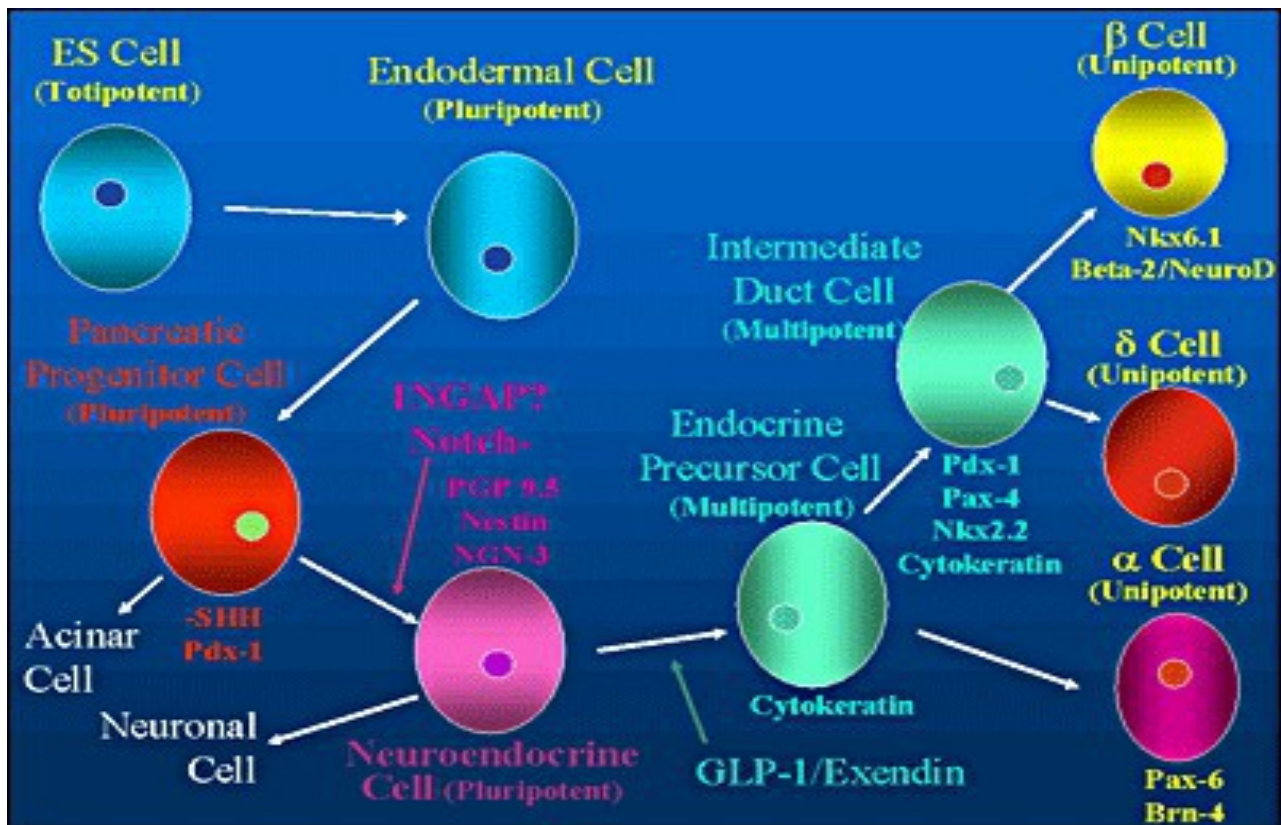
## **DEVELOPMENTAL ORIGIN OF GEP CELLS DURING EMBRYOGENESIS**

The pancreas is composed of exocrine tissue that produces enzymes for digestion, and an endocrine system designed to maintain glucose homeostasis within narrow confines. The adult endocrine pancreas contains four different cell types which produce insulin ( $\beta$  cells), glucagon ( $\alpha$  cells) somatostatin ( $\delta$  cells) and pancreatic polypeptide (PP cells). These are contained within a highly organized structure with beta cells in the interior and the remainder as a surrounding mantle. The vascular supply is elegantly organized to deliver blood to the central core of the islet and to perfuse the outer layers in a centrifugal manner from beta to alpha to  $\delta$  (synonym B (b) A (a) D ( $\delta$ )). The adult pancreas also has a sophisticated ductal drainage system that ostensibly is present as a conduit for enzymes to reach the gastrointestinal tract but appears to retain cells capable of trans-differentiation into exocrine or endocrine components upon appropriate activation. A crucial question has arisen as to whether or not the adult pancreas retains these precursor cells and if they can be identified. In recent years a molecular fingerprint of embryonic islet precursors has begun to emerge (5) and precursor cells within embryos and postnatal mice are found in the ducts (4). These ductal precursor cells can be identified by their expression of Glut 2 (6). Recently cells expressing the neuronal antigen, an intermediary filament protein, were located in pancreatic ducts of adult rats and were found to differentiate into insulin expressing cells in vitro (7), further suggesting that the study of the characteristics of embryonic development might be able to assist in the capture of the elusive precursor in the adult pancreas.

Inductive signals important in the initiation of growth and development of the pancreas to a large extent have their signals enacted or amplified by genes targeted within the embryonic stem cells or cells committed to developing into a variety of pancreatic endocrine, exocrine or ductal cells.

Pancreatic islet-specific gene expression is mostly controlled at the transcriptional level by the binding of islet enriched transcription factors to sequences in islet genes (Figure 2).

**Figure 2.**



These transcription factors are involved in the temporal expression of genes that direct pancreatic development. Cell specific and extrinsic factors present in the endoderm act in a permissive or restrictive manner to direct the formation of the islets and the various cells and structures that comprise the adult islet (8). The PDX-1 encoded homeodomain protein in mammals (STF-1, IDF-1, IDX-1) was isolated as a transcriptional regulator of insulin and somatostatin (9) (10) (11). It binds and trans-activates the insulin promoter (12). PDX was first detected in embryonic pancreatic and duodenal endoderm. It is detected in all embryonic proto-differentiated epithelial cells during pancreatic development (13). In the pancreas it becomes progressively restricted to the islets, where it is produced in >90% of beta cells, 15% delta cells and 3% alpha cells. PDX-1 defines pancreatic gene expression pattern and cell lineage differentiation (14). Mice heterozygous for PDX-1 develop normally but in homozygous PDX mice the normal branching outgrowth of the pancreas is arrested at an early stage (12) (15). Maturity onset diabetes occurred in patients heterozygous for the gene (16) (17). Diabetes develops in aging transgenic mice following suppression of PDX-1 (18). The regulation of the PDX-1 gene appears to be central to the development of the pancreatic anlage during embryonic development as well as maintaining islet mass in the adult and contributing to the regulation of insulin secretion from the adult pancreas (19). The PDX-1 gene is initially expressed in exocrine and endocrine pancreatic precursors but later becomes restricted to the beta cells in the islets. Transgenic models leading to loss of PDX-expression, either via double knockouts, dominant negative control or elimination of the target binding protein leads to

pancreatic agenesis in the case of the double knockout and with haplo-insufficiency, to defects in glucose-stimulated insulin secretion in mice and in humans (12) (17). Abolition of PDX-1 in differentiated  $\beta$  cells in mice results in loss of the  $\beta$  cell phenotype, and impaired expression of Glut 2, glucokinase required for  $\beta$  cell production of insulin in response to glucose (12). PDX-1 is also found where  $\beta$  cell neogenesis is occurring as in duct ligation model of neogenesis (20), partial pancreatectomy (21), overexpression of TGF alpha (22), or interferon gamma (23). In all instances the formation of new  $\beta$  cells is preceded by expression of PDX-1. It has been reported that stimulation of the initiation of trans-differentiation of adult stem cells with INGAP is associated with increased expression of PDX-1 in both ducts and subsequently newly formed islets (24) (25). This endorses the notion that cell differentiation in the adult can recapitulate normal fetal ontogeny. Further support for this notion derives from the observation that trans-differentiated cells stained positive for the neuronal antigen PGP 9.5. PGP 9.5 is an isoform of ubiquitin carboxy-terminal hydrolase (UCTH-LI) and is a marker for neurons and neuroendocrine cells in the skin (26-28) as well as the pancreas (29). It was also found in ductal cells during embryonic islet morphogenesis and in our studies on duct ligation of the hamster pancreas (30) (25). Thus, the combination of PDX-1 and PGP 9.5 suggest evolution from the ductal phenotype to a cell precursor en route to neoislet formation.

Various studies have shown that the hepatic nuclear transcription factors (HNFs) form a hierarchy of transcription factors that exert positive and negative influences on pancreatic islet growth and development (31) (32). Of particular relevance to islet development is the interpolation of HNF 3 b, a member of the forkhead/winged helix family of transcription factors, between inductive signals for  $\beta$  cell development and the expression of PDX-1 (33). Similarly, HNF1 a binds to a regulatory domain of PDX-1 and knockouts have reduced expression of PDX-1 (33). Cell specific and extrinsic factors are expressed during fetal development that determine the region of the endoderm destined to form the pancreatic bud (34-37). The initiation of the pancreatic program requires that signals specify the pancreatic region within the developing endoderm. Sonic hedgehog and Indian hedgehog genes dictate an intestinal differentiation, and for pancreatic development to occur these genes must be excluded. Candidate factors for excluding these genes are Activin- $\beta$  and fibroblast growth factor (38). The dorsal and ventral buds may develop differently and the LIM homeodomain protein Isl-1 may be an important determinant of pancreatic development (39). Lateral specification of pancreatic development is mediated by Notch signaling by specifying a particular pathway in a field of initially equivalent cells. Notch signaling controls the choice between differentiated endocrine and progenitor cell fates in the developing pancreas and a block in activation of the Notch receptor resulting in high Neurogenin 3 expression and promotes an endocrine fate. These cells upon differentiation migrate into the adjacent mesenchyme where they cluster and upon receiving an inductive signal, for example INGAP; generate distinct endocrine cell types depending on the inductive milieu. This in turn activates PDX-1 which appears to act upstream of fibroblast growth factor (FGF) signaling (12) and induces the FGF1-5 ligands. This is necessary for full maturation of the glucose sensing mechanism of the  $\beta$  cell including expression of the low affinity glucose transporter, Glut 2, and the proinsulin processing machinery, the proinsulin convertase PCI/3 and PC2 responsible for converting proinsulin to insulin. This appears to be conserved between mice and men (34) (35) (37). HNF3 b is a

candidate for initiating the positive response to the inductive signal and is expressed in the mouse fetus prior to the expression of PDX-1 at embryonic day 8 (E8.0) in the dorsal endoderm of the fore/midgut before the appearance of the insulin and /or the glucagon expressing cells (19). These primordial cells lack  $\beta$  cell specific markers. Around E13 the number of endocrine cells starts to increase and develop the characteristics of endocrine clusters destined to develop into the organ of Langerhans (4). The primordial cells not yet committed to develop into pancreatic islet cells express a number of neuronal markers including Neurogenin 3, (40), PGP 9.5, and of Nestin (41). Cells destined to become islet cells appear to express the glut 2 transporter prior to development of hormone secretory capacity and this has been used as a marker for these committed cells in the pancreatic ductal system (6). The organization into individual  $\alpha$ ,  $\beta$ ,  $\delta$  and PP islet cells is dependent upon appropriately timed expression of a number of other genes including PAX 4, PAX 6 and PDX-1 (for a detailed review see (42) (25) and is complete by day 18, but further refinements and development of glucose sensing occurs in the 2 week postnatal period in mice (4). Although HNF-3 b may be necessary for the response to inductive factors in embryonic development, it appears that HNF-1 $\alpha$  is necessary to maintain the islet specific expression pattern and is required throughout adult life (43).

Preliminary data suggest that embryonic stem cells can be differentiated into insulin secreting cells *ex vivo*, but these cells do not achieve terminal differentiation and have a low insulin content and poor response to glucose. Their growth is unbridled and despite production of  $\beta$  cells, they fail to cure diabetic mice (44). Israeli scientists found insulin-producing cells in embryoid bodies formed spontaneously from embryonic stem cells (ESCs) when they stop growing, but these too do not make sufficient insulin (45). Soria and colleagues used gene-trapping techniques to isolate insulin-producing cells and transfected an antibiotic resistant gene adjoined to the insulin promoter. When these cells formed three-dimensional structures the cells increased insulin to therapeutic levels but this of course remained unregulated (46). Others have created long-lived cell lines from  $\beta$  cells (47), while others have engineered beta cells from non- $\beta$  cells (48). These have lacked the necessary ingredients of expandability, and physiologic regulation including glucose sensing and an off mechanism in the absence of glucose.

Rather than struggle with the propensity of non-pancreatic stem cells with their reversion to their former state and the difficulties of identifying the necessary control mechanisms for transitioning ESCs into pancreatic stem cells, some researchers have looked to the pancreas as a source of more mature stem cells. Peck and colleagues in a multi-step process, identified islet producing stem cells and transformed these into islet progenitor cells. These grew into islet like structures which increased pancreatic mass 10,000 fold but the cells never fully matured (7). Bonner-Weir and colleagues have applied growth promoting substances to ductal cells in culture and stimulated these to grow and express the IPF-1/PDX-1 protein, the transcription factor necessary for endocrine cell development. At this stage a switch to differentiation factors induces the cells to form cultivated human islet buds which produce a small amount of insulin in response to glucose. The single biggest limiting factor of course was the limited capacity for forming the number of cells required to reverse diabetes (49). Starting

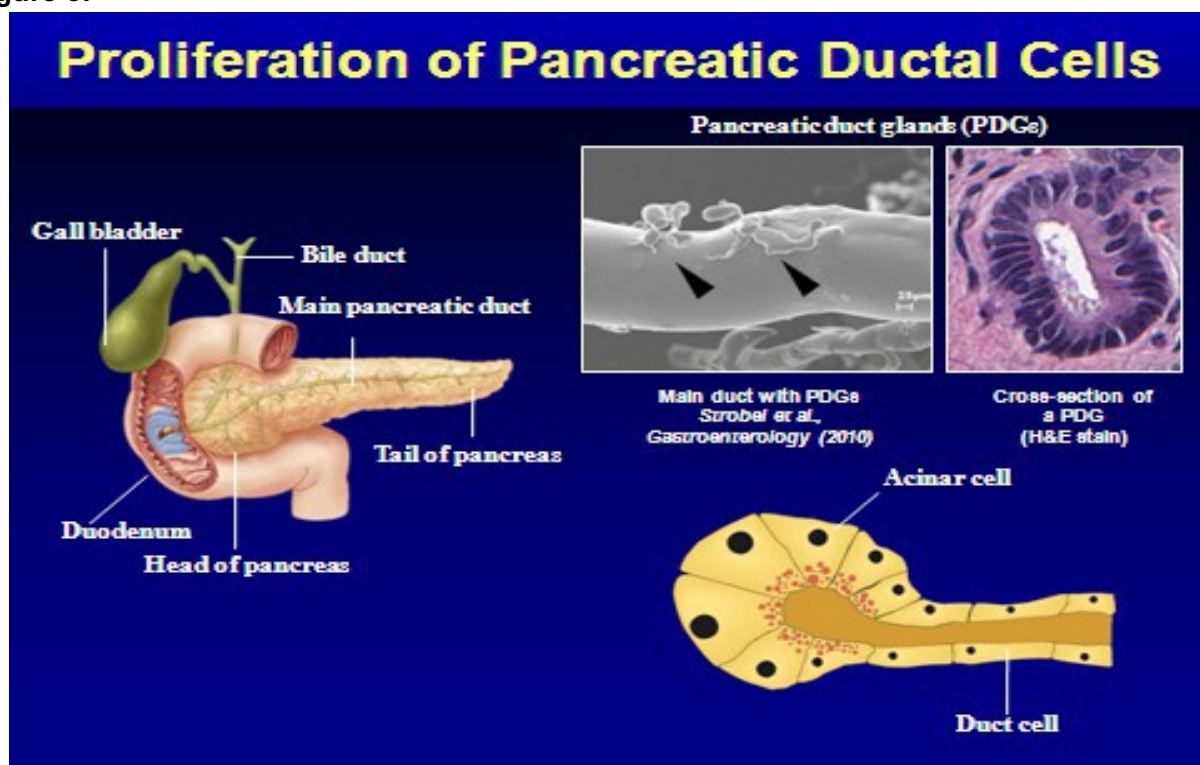
with adult human  $\beta$  cells, Levine and colleagues immortalize them by transfection with the SV40 T antigen and the K-ras oncogene to stimulate growth. Cells are induced to transdifferentiate by transfection with PDX-1 and formation of the three dimensional complexes with cell-to-cell contact conducive to insulin production. With the appropriate application of a growth- inducing stimulus these constructs are now capable of secreting insulin in response to glucose. However, these structures are not stable. When implanted they metastasize like tumors and lose their insulin secretory capacity (50) (51).

Others and we have elected to utilize the factors resident in the pancreas to stimulate islet cell growth and proliferation as an alternate to the above approaches (42) (52). It has been known for years that factors present in the pancreas mesenchyme may have an important role in islet integrity (4). More recently the close association between islets and their ducts of origin has been established by electron microscopy of pancreases using cytokeratin 20 markers of duct cells and islet hormone marker(53). The close contact between the islets and duct system has raised interesting possibilities. For example, the open nature of insulin and somatostatin cells allows secretion of hormones into the intestinal lumen, a feature we named "Lumone" many years ago (54) and indeed insulin, serotonin, gastrin, somatostatin and members of the Reg family of peptides have been found in the intestinal lumen and pancreatic juice (55-59). Receptors for insulin have also been found on the luminal surface of duct cells (60-62). The reciprocal relationship may have greater consequence for  $\beta$  cell function. Acinar cell proteins such as Reg are found in pancreatic juice (63-67) and their target may be the stimulation of growth and proliferation of duct cell proliferation and differentiation (63-67). Okamoto and colleagues established a model for islet regeneration in 90% depancreatectomized rats by the islets underwent considerable hypertrophy. They screened the islet derived cDNA library and found the novel regenerating gene and named it Reg. The rat Reg cDNA encoded a 165 amino acid protein with a 22 amino acid signal peptide. Subsequently they isolated the human counterpart which is 165 amino acids, with 68% homology to that of the rat Reg protein. The recombinant forms of Reg have been shown to expand  $\beta$  cell mass by inducing hypertrophy of existing islets and limited replication (68). They then isolated several Reg and Reg-related genes from human rat and mouse and grouped members of the family into three subclasses. Group I encodes a  $\beta$  cell growth factor and some of the type 111 (a, b, and g ) targets neuronal cells and cells of the epithelial alimentary tract where it is found extensively. In the process of ordering these genes (69) a novel form of Reg, Reg III  $\delta$ , was found with 6 exons, spanning about 3Kb, encoding a 175 amino acid protein with 40-52% of homology to other Reg proteins. Unlike Reg I and Reg II which are expressed in hyperplastic islets, Reg III delta was expressed predominantly in the exocrine pancreas. This mouse form of Reg may be the counterpart of hamster and human INGAP gene that is found almost uniquely in the exocrine pancreas, appearing with islet neogenesis and responsible for stimulating proto-differentiated cells in the ductal system to proliferate, differentiate into islets and function physiologically to reverse diabetes (70). However, Sasahara and colleagues (71) cloned a novel cDNA from mouse pancreas having a 72% homology to hamster INGAP cDNA and 47-52% homology to other members of the Reg family including the different forms of Reg and pancreatitis associated protein (PAP) and pancreatic thread protein of rat, mouse and man. They refer to this protein as INGAP related protein (INGAPrP). In contrast to INGAP, which is expressed during neogenesis, INGAPrP was abundantly expressed in the normal mouse pancreas. Roman and



colleagues (72) to determine whether islet angiogenesis and VEGFA production/release participate in the mechanism by which INGAP-PP enhances  $\beta$ -cell function and mass used two models: a) in vivo (normal rats injected with INGAP-PP for 10 days) and b) in vitro (normal islets cultured for 4 days with INGAP-PP, VEGFA, Rapamycin, and the specific VEGF-Receptor inhibitor, SU5416). INGAP-PP administration enhanced insulin secretion, b-cell mass, islet vascularization, and angiogenesis without affecting glucose homeostasis. Normal islets cultured with INGAP-PP and VEGFA increased insulin and VEGFA secretion while apoptosis decreased. INGAP-PP-induced effects were prevented by both Rapamycin and SU5416. INGAP-PP effects on b-cell mass and function were significantly associated with a positive effect on islet angiogenesis and VEGFA production/release. VEGF-A possibly potentiates INGAP-PP effect through mTORC pathway.

**Figure 3.**



The developing pancreas appears as a protrusion from the dorsal surface of the embryonic gut (4). Figure 3 shows the normal anatomy of the pancreas and duodenum in the adult. What is shown is the capability of proliferation duct glandular structures (PDGs) (73) with the capability of transformation to endocrine cells.

The different islet-cell types appear sequentially during development in vivo. Therefore, it seems reasonable to propose that coordinated growth depends on the specificity of growth factors.

Rosenberg and Vinik (74) used a model for new islet formation (i.e., nesidioblastosis) and



showed that pancreatic ductal cells are capable of differentiating on stimulation into adult endocrine cells that are capable of secreting insulin in a fully regulated manner. This has led to the notion that endocrine tumors derive from a toti-potential stem cell in the gut that is capable of differentiating into any one of a variety of cells that may be responsible for the clinical syndromes. In HIP rats treated with Sitagliptin, a dipeptidyl peptidase 1V inhibitor prevents the catalytic breakdown of glucagon like peptide 1 (GLP-1) thereby increasing endogenous GLP-1 inducing ductal metaplasia.

Human GLP-1 receptor is expressed in the ductal system in humans and upon stimulation with incretins like Exenatide or other GLP-1R agonists markedly increase the expression of GLP-1 receptor (Figure 3) leading to the formation of intraductal neoplasms called PanINs. Butler et al (75) showed expansion of exocrine and endocrine pancreas with Incretin therapy in humans with increased exocrine pancreas dysplasia and the potential for glucagon producing tumors. Pancreases from Type 2 Diabetes organ donors on Incretin therapy (n=8), other therapies (n=12) and Diabetic Controls (n=14) were examined. In diabetic patients beta cell mass was reduced 60%. Incretin treatment increased islet mass by 40%. However, 3/8 developed glucagon microadenomas and 1 developed an alpha cell NET accompanied by exocrine cell proliferation and pancreatic intraepithelial neoplasia (PanIn) (Figure 3). Co-staining for insulin and glucagon increased in DM, and was even greater in Incretin treated patients. They concluded that Incretins expand exocrine and endocrine pancreas with proliferation, dysplasia and a cell hyperplasia with possible adenoma formation. While this data was found in postmortem specimens and there is little clinical evidence in thousands of patients treated with incretins, it raises an interesting possibility on the formation of adenomas and the role that GLP-1 may play (76). Figure 4 demonstrates the appearance of glucagon cells in the ducts of a patient who had been treated with an incretin (77). The suggestion is that, with the correct genetic predisposition, use of incretins may have the capacity to induce malignant transformation of cells with formation of neuroendocrine tumors.

A great deal of interest is now being focused on the factors responsible for the initiation of growth proliferation and differentiation into adult endocrine cells, and, in neuronal systems, for growth cessation and cell maintenance. Several models of pancreatic regeneration and tumor formation have been established (63) (78-87).

## **GROWTH FACTORS AND THE DEVELOPMENT OF NEOPLASMS OF THE GASTROENTEROPANCREATIC AXIS (GEP-NETS)**

Multiple growth factors and receptors are frequently expressed in GEP tumors. These growth factors may include insulin-like growth factor-1, platelet-derived growth factor, transforming growth factors (TGF)  $\alpha$  and  $\beta$ , basic fibroblast growth factors, nerve growth factor (88) (89) and GLP-1 (77). The frequent co-expression of TGF- $\beta$  and its corresponding receptor, the epidermal growth factor receptor, suggests the presence of autocrine regulatory mechanisms in these tumors (89). TGF- $\beta$  has been implicated in the desmoplastic reaction associated with carcinoid tumors (89) (90). Overall, the precise role of these growth factors and their importance in the growth and progression of GEP tumors is unknown.

Apoptosis (i.e., programmed cell death) has been shown to be an important process that may occur under normal physiologic conditions, including embryonic growth and development, the differentiation of  $\beta$ -cell populations, and the involution of cells deprived of necessary growth factors (91). Apoptosis may be induced by a variety of chemotherapeutic drugs and cytokines (92). Several growth factors and substances that are secreted by neuroendocrine tumors, including TGF- $\beta$  (93), glucocorticoids, and somatostatin (94), have been shown in other model systems to induce apoptosis. The importance of apoptosis in the normal growth and differentiation of neuroendocrine tissues, however, and the importance of apoptosis in the response of GEP tumors to chemotherapy remain unknown.

## **GENETIC FACTORS PREDISPOSING TO DEVELOPMENT OF NETs**

The genetics of neuroendocrine tumorigenesis have yet to be elucidated. Although small familial clusters of midgut carcinoids have been described, there are no known genetic cancer syndromes associated with them. Tumors have clustered in several small families without MEN I, and multiplicity of tumors is a feature on one quarter of isolated cases. Among sporadic midgut carcinoids, several studies using comparative genomic hybridization or microsatellite markers have shown frequent allelic deletion of chromosome 18 (95) (96). On an epigenetic level, midgut NETs have been found to have global hypomethylation (97). There is little data about genetic aspects in NETs of the appendix or cecum. Tumor multiplicity is much less frequent in the appendix and cecum than the ileum.

The multiple endocrine neoplasia (MEN) characterized by the combined occurrence of tumors of the pituitary, pancreas, and parathyroid glands is associated with the loss of a tumor suppressor gene on chromosome 11q13 (98) (99). This is the same chromosome on which the insulin gene has been located (100). It has been linked to nesidioblastosis in certain families and parathyroid mitogenic activity can be identified in the plasma of patients with MEN-1 (101) (102). All of this suggests a genetic predisposition to tumor formation based on elaboration of a growth factor. Data from cell lineage analysis of pancreatic islet cells suggest that progenitor cells, which contain catecholamines, are present in pancreatic ducts and give rise to the glucagon and insulin cells of adult islets (103). These can be stimulated to grow by plasma from patients with MEN-1. Patients with MEN-1 also might elaborate into their plasma mitogenic circulating growth factor, involved in the initiation of GEP tumor growth (104). It has been suggested, but not proven, that allelic losses in the MEN-1 tumor suppressor gene located in the 11q13 region also might be responsible for sporadic parathyroid, pituitary, and neuroendocrine tumors of the stomach, pancreas, and intestine (105). The few cases of carcinoid tumors studied have not shown losses in this region.

In addition, MEN-2a (106) (107), MEN-2b, (108) (109) and familial medullary thyroid carcinoma are associated with mutations of the RET proto-oncogene, which is a conventional dominant oncogene located on 10q11.2. Although mutations in this region have been associated with sporadic medullary thyroid carcinoma, the role, if any, of this gene in sporadic GEP tumors is not known.

New molecular profiles of gastrointestinal (GI-NETs) and pancreatic neuroendocrine tumors

(pNETs) have now been reported (110) (111). Frequent chromosomal gains occur on chromosomes 7 and 20, former also associated with metastases, together with losses on chromosomes 2, 6q, 21q, and Y in pNETs. Comparative genomic hybridization studies of GI-NETs show frequent gains on chromosomes 17 and 19, while frequent loss has been detected on chromosome 18. These findings indicate different molecular genetic background of these two tumors (112) (113). Therefore, molecular profiling of GEP-NETs demonstrates that pNET and GI-NET tumors display different genetic changes and should be considered different tumor entities; thereby, also differently managed clinically (114) (115).

Of great interest is the demonstration of the possible utility of the genomic information for treatment. In 68 pNETS (116) (117) reported mutations of genes involved in chromatin assembly were reported, as well as MEN-1 gene in > 44%, DAXX 25%, ATRX 17.6%, and MTOR pathway >14%, suggesting that these mutations may predict, for e.g., responses to the newly developed MTOR inhibitors and possibly others. More importantly these mutations have survival prediction. Mutations survive 10y while in patients without mutations > 60% died in 5 years.

## **THE ROLE OF INFLAMMATORY CYTOKINES IN NETs**

Several pro-inflammatory cytokines have been implicated in the development of carcinoid tumors (61-66) and may be prognostic in metastatic carcinoid (67) as well as host anti-tumor immunity (68) (69). TNF- $\alpha$  and IL-2 are associated with GEP-NET development (118) (119). Proinflammatory cytokines have been found in pNET tissue (120) (121) (122). IL-6 and IL-1 $\beta$  may be involved in pNET development. According to SNP analyses, IL-6-174 CG and GG genotypes carriers and IL-1 $\beta$ -511/ + 3954 CTCC carriers were at risk of developing non-functional pNETs (118) (119), while IL-1 $\beta$ -511/ +3954 CTCT carriers were prone to development of functional pNETs (123) (84). Moreover, IL-6 GG genotype correlated with IL-6 serum levels that were significantly higher in patients with non-functioning pNETs. It now appears that cytokines may be important modifying factors in development, progression and prognosis of malignant tumors. In addition, many new antineoplastic drugs have been developed to target these specific genetic mutations.

## **CHARACTERISTICS OF NEUROENDOCRINE CELLS**

A number of peptides originally isolated from gut endocrine tissues have been shown to occur in nerves. These include gastrin, cholecystokinin, vasoactive intestinal polypeptide (VIP), and substance P (SP). As a corollary, peptides that have been found primarily in nervous tissues have now been identified in gut endocrine cells and include somatostatin, enkephalins, SP, neurotensin, and thyrotropin-releasing hormone (TRH) (124-126). Because many of these peptides occur both in endocrine cells and nerves, "endocrine" tumors of the gut may, in fact, be endocrine or neurocrine. Unique to the GEP axis is the ability of the endocrine cell to secrete a variety of peptides and amines. Hormonal peptides not only have been found within the same cell (e.g., motilin and serotonin in the enterochromaffin [EC] cell), but they have also been localized to the same secretory granule. Whether these act within the secretory granule in a paracrine manner or are co-regulated in some way is not clear. At any one point in time

several hormones and amines are co-secreted and the symptom complex derives from one or more of the peptides and amines produced and cannot simply be ascribed to a single factor. Thus, a tumor may secrete one peptide, recur, and secrete yet another, and its metastases may secrete still other peptides. In the British National Supra-Regional Survey of National Health Service Hospitals, 58% of 353 patients with neuroendocrine tumors had increased serum levels of two or more hormones at diagnosis. Nine percent of patients had clinical symptoms related to different hormones, and four patients developed new symptoms from secretion of a second hormone after diagnosis (127).

Rick Lloyd has recently reviewed the use of various markers to identify neuroendocrine characteristics (128). Although there are many broad-spectrum neuroendocrine markers, chromogranin and synaptophysin are the principal ones used in diagnostic pathology. He has added to the armamentarium different keratins in the differential diagnosis and particularly the low molecular weight keratins such as CAM 5.2 to avoid false negative results in the workup of some neuroendocrine tumors. For low levels of expression he emphasizes the need for in situ hybridization to establish the presence of the message if not the protein.

The chromogranin/secreotogranin (Cg/Sg) family is composed of several acidic proteins present in secretory granules of neuroendocrine cells. The three major Cg/Sg proteins are currently designated as chromogranin (Cg) A and B and secretogranin 11 (Sg11). Others include Sg111, Sg1V and Sg V. The distribution of CgA has now been studied extensively. It is present in most neuroendocrine cells and neoplasms. A few neoplasms with only a few endocrine secretory granules such as the small cell carcinoma of the lung and Merkel cell carcinomas do not react strongly with CgA. The widespread distribution and high degree of specificity of Cg/Sg make these excellent markers for endocrine cells and their neoplasms. Cg A is endocrine specific but has limited sensitivity; for example, in hindgut carcinoids it is only positive for 25-50% of carcinoids, and adding CgB will increase the sensitivity for these tumors.

Synaptophysin, a 38kDa protein molecule is a component of the membrane presynaptic vesicles. It is widely distributed in neurons, neuroendocrine cells and their neoplasms and is a good broad spectrum neuroendocrine marker. Synaptophysin can be examined in formalin fixed tissues, which allows tumors to be revisited if initially not thought to be neuroendocrine. Although present in synaptic vesicles in tumors, it is found diffusely in the cytoplasm of the cell. It has however been found in adrenal cortical adenomas and carcinomas so, although sensitive, is not very specific. It therefore should always be used in conjunction with CgA. Synaptophysin belongs to a family of synaptic proteins that include synaptogranin (p65), SNAP-25, SNAP receptor (SNARE), Syntaxin and Rab3A. However, the utility of these proteins in routine diagnostic pathology has not been established to date.

The pro-convertases (PC) are enzymes that process pro-peptides into active peptides within cells. Some of these including PC1/PC3 and PC2 are highly specific for neuroendocrine cells and tumors and can be used as specific markers. Other such as PC4 is present in the tests whereas PC5/6 is more prevalent in the gastrointestinal tract.

Neuron Specific Enolase (NSE) is a very sensitive, but not very specific marker for

neuroendocrine cells and tumors. It is commonly found in nerves, and neuroendocrine cells, but some non-neuroendocrine cells react with antisera to NSE. Therefore, NSE should only be used as a broad spectrum marker in the diagnosis of these tumors.

Bombesin, which is a tetrapeptide originally isolated from amphibian skin, is present in many endocrine cells as well as neurons. Gastrin releasing peptide (GRP), the mammalian analog of Bombesin, is found in many lung tumors and gastrointestinal endocrine tumors and can also be used as a broad-spectrum marker.

PGP-9.5 is a soluble protein that was originally isolated from the brain. It has now been shown to be a general marker for neuronal and neuroendocrine tissues. Interestingly about 50% of melanomas stain for PGP9.5 whereas these are negative for Cg/Sg.

Peptidylglycine Amidating Monooxygenase (PAM): Amidation is an important step in the maturation of neuropeptides. PAM catalyzes the post-translational modification of many neuropeptides. The PAM proteins are usually released along with other peptides during exocytosis whereas membrane bound PAM remains in association with the cell. PAM expression is found in all neuroendocrine cell types (128-131). Scopsi found a close correlation between PAM expression and at least one of the three principal Cg/Sg proteins (CgA, CgB or Sg11). It is not clear that this protein provides additional information (132).

Pancreatic endocrine tumors are usually positive for cytokeratins in more than 90% of cases (133). The low molecular weight keratins such as CAM 5.2 are more sensitive for neuroendocrine tumors than the keratin cocktails such as AE1/AE3 and thus should be added to any regime that routinely examines pancreatic neoplasms to preclude misdiagnosis of an adenocarcinoma as for a neuroendocrine tumor. The latter has a much more benign prognosis.

Pulmonary tumors include typical and atypical carcinoids and large and small-cell carcinomas. About 85% are reactive with cytokeratins. Chromogranins are usually positive in carcinoids, atypical carcinoids and large-cell neuroendocrine carcinomas, while only about 50% of small cell carcinomas are positive. However other broad spectrum markers of neuroendocrine cells are positive in these tumors (134). While this may be helpful in delineating endocrine function of these tumors it is not clear that this alters treatment strategies or dictates a different prognostic value.

## **CHARACTERISTICS OF NETS**

Neuroendocrine tumors (NETs) are rare, slow growing neoplasms characterized by their ability to store and secrete different peptides and neuroamines (121). Some of these substances cause specific clinical syndromes (135) while others are not associated with specific syndromes or symptom complexes. There is no “ideal neuroendocrine tumor marker, (136)” but according to the presentation, the sensitivity and specificity of each marker varies and it is possible to choose those of greatest value for each clinical syndrome.

## **DEFINITION OF NETS:**

- Neuroendocrine tumors (NETs) are neoplasms that arise from cells of the endocrine (hormonal) and nervous systems. Many are benign, while some are malignant
- They share common features, such as looking similar, having special secretory granules, and often producing biogenic amines and polypeptide hormones (121)
- They arise from various neuroendocrine cells whose normal function is to serve at the neuroendocrine interface. Neuroendocrine cells are present not only in endocrine glands throughout the body that produce hormones, but also diffusely in all body tissues (135).
- Enterochromaffin cells, give rise to carcinoid tumors, were identified in 1897 by Kulchitsky (136) and their secretion of serotonin established in 1953
- NETs show amine precursor (L-DOPA and 5-hydroxytryptophan) uptake and decarboxylation to produce biogenic amines such as catecholamines and serotonin.

The current view of NETs has changed somewhat,

- Neuroendocrine cells reside throughout the body in all tissues and can de-differentiate into tumor cells.
- NETs include:
  - tumors of the gastrointestinal tract
  - the pancreatic islet cells (121)
  - thymus and lung tumors
  - medullary carcinoma of the parafollicular cells of the thyroid (121)
  - tumors in the pituitary, parathyroid, and adrenomedullary glands and paraganglion cells (137)
  - NETs may be functioning or nonfunctioning but there is now a newly recognized entity of secretory tumors which are asymptomatic for a variety of reasons and may represent the largest category of NETs (138)

The annual incidence of neuroendocrine tumors (NETs) has risen to 40-50 cases per million; due to better diagnostic tools including the availability of highly specific and sensitive ways to measure tumor products and improved immunohistochemistry techniques for tumor detection. The perceived increase in incidence may be a false positive one. In a review of the SEERS database it has now been shown that the prevalence of NETS in the USA is about >100,000 cases which is twice the prevalence of gastric and pancreatic cancer combined. The great majority (56%) of these tumors are carcinoids and the remainder are pancreatic neuroendocrine (pNETS)

## **ANATOMIC DISTRIBUTION**

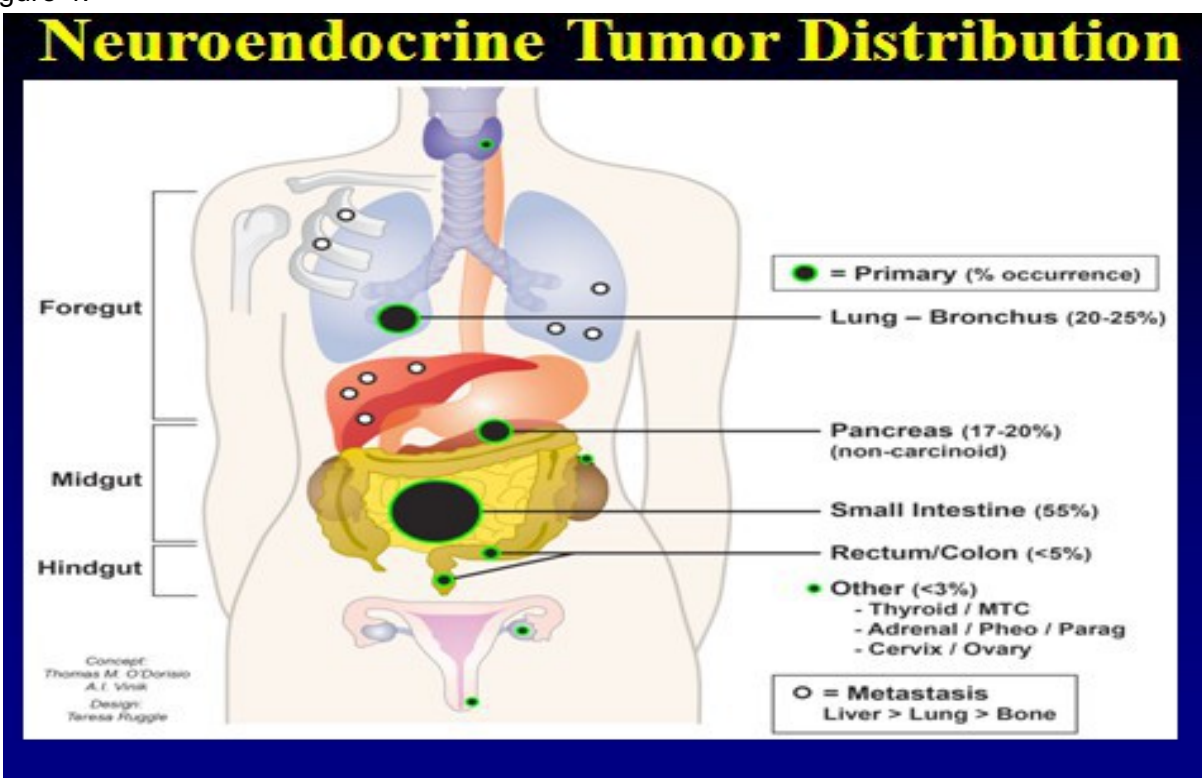
More than 50% of neuroendocrine tumors in clinical practice are of the so-called carcinoid variety and are found incidentally at operation, after metastasis has occurred, in the small intestine (especially the appendix). The remaining fraction comprises approximately 50% gastrinomas, 30% insulinomas, 13% VIPomas, 5 to 10% glucagonomas, and, rarely, less than 5% neurotensinomas, somatostatinomas, and ectopic hormone-secreting tumors.

Nonsecretory tumors were thought to make up the bulk of pancreatic tumors. However, with better immunohistochemical stains for endocrine cells, especially for neuron-specific enolase (NSE), chromogranin, synaptophysin, and receptors for somatostatin (139) there is increasing recognition that tumors masquerading as carcinomas of liver, small cell carcinoma of the lung, and others, are in reality neuroendocrine tumors. Most of these nonsecretory tumors actually store and secrete pancreatic polypeptide (PP), but because it has so little, if any, in the way of biologic activity, the tumor often remains silent until it is quite large.

Approximately 60% of pancreatic gastrinomas are concentrated in Pasarro's Triangle, an area subtended by the head of pancreas, gastric antrum, and first portion of the duodenum. Other neuroendocrine tumors may be distributed more evenly across the pancreas or in ectopic sites such as the adrenal medulla, whereas carcinoid tumors most frequently occur in the appendix and small intestine.

The tumors are proliferative in nature and may take the form of hyperplasia or neoplasia (adenoma, adenomatous hyperplasia, microadenomatosis, nesidioblastosis, or carcinoma). Hyperplasia is relatively uncommon in benign sporadic tumors, but it is the rule in MEN-1 syndrome and often is present in the area of the pancreas surrounding a benign tumor.

Figure 4.



The tumors may be further subdivided into (a) orthoendocrine, when they secrete the normal product of the cell type (e.g., alpha cell glucagon), and (b) paraendocrine, when they secrete a peptide or amine that is foreign to the organ or cell of origin. Paraendocrine tumors are found in



the adrenal medulla, kidney, lymph nodes, or liver and as a part of MEN-1 when a variety of peptides or amines are secreted. When tumors metastasize, they do so to local lymph nodes, liver, peritoneum, and, rarely, to bone, but this seems to be increasing in frequency as the natural history of these tumors changes with aggressive treatment. Metastases are notoriously highly vascular, which is a telltale sign of a GEP tumor. The occurrence of MEN-1 syndrome may be as frequent as one-third of the cases of GEP tumors, depending on the endemic area. In high-risk areas, measurements of ionized calcium, prolactin, and PP are important. Nonetheless these tumors are rare and slow growing. As Moertel once said, the study of neuroendocrine tumors of the gut is like an Odyssey in the land of slow growing tumors. Their characteristics are shown in Table 1.

**Table 1. Characteristics of Neuroendocrine Tumors**

- Rare
- Usually small, <1 cm
- Slow growing, months to years, “cancer in slow motion”
- Usually metastasize before becoming symptomatic, often when tumor is >2 cm
- Expression is episodic, may be silent for years
- Symptoms mimic commonplace conditions and often are misdiagnosed
- Complex diagnosis, rarely made clinically, requiring sophisticated laboratory and scanning techniques

Table 2 lists the common clinical syndrome, the tumor types, the sites and the hormones or peptides/amines that are produced. The sections that follow focus on the specific syndromes that are ascribed to GEP hyperfunction.

**Table 2. The Clinical Presentations, Syndromes, Tumor Types, Sites and Hormones (139).**

Clinical Presentation	Syndrome	Tumor Type	Sites	Hormones
Flushing	Carcinoid Medullary Carcinoma of Thyroid Pheochromocytoma	Carcinoid C cell tumor Tumor of Chromaffin cells	Mid/ foregut Adrenal medulla Gastric Thyroid C cells Adrenal and Sympathetic Nervous system	Serotonin GCRP Calcitonin Metanephrine and Normetanephrine
Diarrhea, abdominal pain and dyspepsia	Carcinoid, WDHHA, ZE, PP, MCT	Carcinoid, VIPoma, Gastrinoma, PPoma, Medullary carcinoma thyroid, mastocytoma	As above Pancreas, mast cells, Thyroid	As above, VIP, gastrin, PP, calcitonin
Diarrhea/ Steatorrhea	Somatostatin Bleeding GI tract	Somatostatinoma, neurofibromatosis	Pancreas Duodenum	Somatostatin
Wheezing	Carcinoid	Carcinoid	Gut/pancreas/lung	SP, CGRP, serotonin
Ulcer /dyspepsia	Zollinger Ellison,	Gastrinoma	Pancreas/ Duodenum	Gastrin
Hypoglycemia	Whipple's triad	Insulinoma, sarcoma, hepatoma	Pancreas, retroperitoneum Liver	Insulin, IGF1, IGF2.
Dermatitis	Sweet Syndrome Pellagra	Glucagonoma Carcinoid	Pancreas Midgut	Glucagon Serotonin
Dementia	Sweet syndrome	Glucagonoma	Pancreas	Glucagon
Diabetes	Glucagonoma Somatostatin	Glucagonoma Somatostatinoma	Pancreas Pancreas	Glucagon Somatostatin
DVT, Steatorrhea, Cholelithiasis Neurofibromatosis	Somatostatin	Somatostatinoma	Pancreas Duodenum	Somatostatin
Silent, liver metastases	Silent	PPOMA	Pancreas	PP

Table 2 summarizes the approach to diagnose a NET based upon the clinical presentation, the tumor type, their sites of origin and the possible means of diagnosis and the biochemical markers that should be measured. Abbreviations: CGRP: Calcitonin gene-related peptide.

**Table 3. Clinical presentation, syndrome, tumor type, sites and the hormones produced.**

Clinical Presentation	Syndrome	Tumor Type	Sites	Hormones
Acromegaly	Acromegal, Gigantism	NET, PNET, Pheo	Pancreas islet	GHRH
Cushings	Cushings	NET, PNET, Pheo	Pancreas islet, LUNG, PHEO,	CRH, ACTH
Pigmentation	Pigmentation	NET	Pancreas islet	MSH
Anorexia, nausea, vomiting, abdominal pain	Hypercalcemia	NET, PNET, Pheo	Pancreas islet, Pheo	PthRP, Pth,TGFb, IL, 25 OHD, 1,25 OHD – bone alk phos, NTx b = $\beta$
Hypoglycemia	Autonomic and CNS symptoms of hypoglycemia	NET, PNET	Pancreas Carcinoid	IGF, IGF2 and proIGF, GLP-1, GLP-2
Weakness, lethargy, apathy	Hyponatremia, SIADH	NET, PNET, Pheo	Lung, pancreas, pheo	ADH, ANP
Hyperandrogenism, gynecomastia, hyperthyroidism		PET	Pancreas	LH, FSH, Prolactin, TSH
Hypertension	Malignant hypertension	PET, Pheo, Paraganglioma	Paraganglioma, NET	Renin, pro-renin, aldosterone

**Abbreviations:**

PET = pancreatic NET

NET = neuroendocrine tumor

SIADH = syndrome of inappropriate secretion of antidiuretic hormone

Pheo = pheochromocytoma

MTC = medullary thyroid carcinoma

GHRH = growth hormone releasing hormone

CRH = corticotrophin releasing hormone

ACTH = adrenocorticotrophin

PthRP = parathyroid hormone related peptide

25 OHD = 25 hydroxy vitamin D

1,25 OHD = 1, 25 dihydroxy vitamin D

IGF = insulin like growth factor

ADH = antidiuretic hormone

ANP = atrial naturetic peptide

Alks phos = alkaline phosphatase

NTx = N telopeptide,

TSH = Thyrotropic stimulating hormone

LH – luteinizing hormone

FSH = follicle stimulating hormone

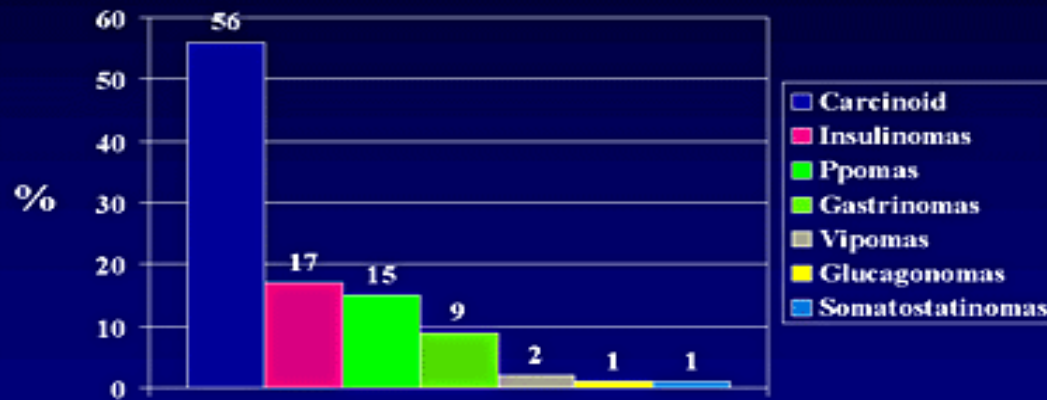
**Table 4. Specific Biochemical Markers for each Tumor Type (140)**

Site	Tumor Type	Marker	Specificity
All		CgA and B PP, NSE, Neurokinin, Neurotensin HCG $\alpha$ and $\beta$	High Intermediate Low
Thymus	Foregut Carcinoid	ACTH	Intermediate
Bronchus	Foregut Carcinoid, Small Cell Lung Carcinoma.	ACTH, ADH, Serotonin, 5- HIAA, Histamine, GRP, GHRH, VIP, PTHrp	Intermediate Low
Stomach	Foregut Carcinoid, Gastrinoma, Ghrelinoma.	Histamine, Gastrin Ghrelin	Intermediate Low
Pancreas	Gastrinoma, Insulinoma, Glucagonoma, Somatostatinoma, PPoma, VIPoma.	Gastrin, Insulin, Proinsulin, Glucagon, Somatostatin C-peptide, Neurotensin, VIP, PTHrp, Calcitonin	High Low
Duodenum	Gastrinoma, Somatostatinoma.	Somatostatin, Gastrin	High
Ileum	Midgut Carcinoid	Serotonin, 5-HIAA Neurokinin A, Neuropeptide K, Substance P	High Intermediate
Colon and Rectum	Hindgut Carcinoid	Peptide YY, Somatostatin	Intermediate
Bone	Metastasis	Bone Alkaline Phosphatase, N- Telopeptide  PTHrp	High (blastic lesions), Modest (lytic lesions)  Intermediate
Cardiac Involvement	Carcinoid	BNP	Intermediate

Table 4 shows the specific biochemical markers used for each tumor and their specificity. CgA and B: Chromagranin A and B; PP: pancreatic polypeptide; NSE: neuron-specific Enolase; HCG: human chorionic gonadotropin; ACTH: adrenocorticotrophic hormone; ADH: anti diuretic hormone; 5-HIAA: 5 hydroxyindoleacetic acid; GRP: gastrin releasing peptide; GHRH: growth hormone releasing hormone; VIP: vasointestinal peptide; PTHrp: parathyroid hormone related peptide; BNP: brain natriuretic peptide

**Figure 5.**

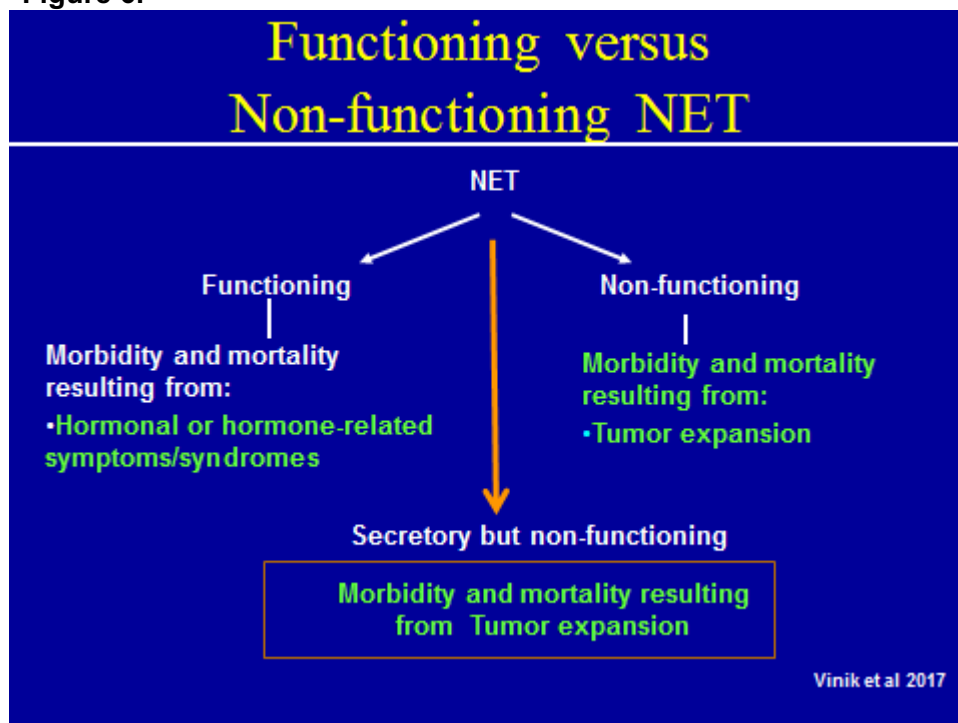
## Neuroendocrine Tumors of the Gastrointestinal Tract : Annual Incidence 10 cases per million



Vinik, A.L., Perry, R.R. Neoplasms of the Gastroenteropancreatic Endocrine System, Chapt 103. In: *Cancer Medicine*, Fourth ed. Vol. 1. Edited by Holland JF, et al Baltimore: Williams & Wilkins, pg. 1605-1641, 1997.

The great majority of the symptomatic tumors are carcinoid tumors accounting for more than half of those presenting each year (Figure 5). Insulinomas, gastrinomas and PPomas account for 17, 15 and 9%, while the remainder are around the 1% mark. These tumors are what is known in common parlance as “Zebras” because of their rarity, but physicians are fascinated by their complexity and the unusual nature of their presentations. For the most part the endocrinologist makes his living not by diagnosing one of these and treating it, but by excluding conditions that masquerade as a neuroendocrine tumor. For this reason it is probably more appropriate to consider the clinical presentations rather than the tumor types. By far the most frequent clinical manifestations found in practice are flushing and diarrhea (Table 3), which are the cardinal presentations of the most common tumor syndrome, carcinoid, and this will therefore be discussed first in the next Chapter. However, a new era is dawning wherein it has become increasingly recognized that tumors may be secretory but do not produce a clinical syndrome as indicated in Figure 6.

**Figure 6.**



There have been major strides in the therapeutic options for patients with NETS. Studies that have come to fruition in the last decade include the CLARINET trial which evaluated lanreotide on tumor progression free survival in patients with non-functioning NETs; the ELECT trial (140) which showed that lanreotide was capable of controlling the major symptoms of flushing and diarrhea; The RADIANT-2 and RADIANT-4 studies which evaluated the MTOR inhibitor Everolimus in functioning and non-functioning NETS of the gastrointestinal tract and lungs alone and in combination with somatostatin, the Telectar study which evaluated telotristat ethyl for control of symptoms of flushing and diarrhea by blocking serotonin synthesis and the tyrosine kinase inhibitor Sunitinib on secretory midgut NETS which demonstrated improvement in PFS (141) (142) in addition to improving quality of life (142) and most recently the <sup>177</sup> Lu-DOTOTATE in NETs of the small intestine and proximal colon (midgut) showing remarkable impact on PFS and to some extent overall survival (143). Perhaps as shown by Vinik and colleagues (144) quality of life was improved and the improvement was shown to be dependent on a change in the bulk of the tumor, progression free survival and the biomarkers secreted. In the earlier Vinik studies (144) the surprising findings were the intimate link of quality of life on the secretory product, the tumor bulk and the peptide or amine secreted. These remarkable advances amongst others have instigated NANETS to develop a Consensus statement on the current recommendations for the management of NETs (see the position statement and consensus guidelines) (145). In the ensuing pages we will entertain the reader to the many advances that have occurred in the neuroendocrine tumor world particularly the new syndromes, recognition of the importance and value of biomarkers in diagnosis, prediction of tumor behavior and the ramifications for patient survival and quality of life and mortality and welcome addition of

new biologic agents, better and more powerful means of tumor identification and peptide targeted therapies including the scope for peptide radioactive receptor targeting (PRRT).

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