

# We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index  
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?  
Contact [book.department@intechopen.com](mailto:book.department@intechopen.com)

Numbers displayed above are based on latest data collected.  
For more information visit [www.intechopen.com](http://www.intechopen.com)



---

# Thiamine and the Cellular Energy Cycles — A Novel Perspective on Type 2 Diabetes Treatment

---

Saadia Shahzad Alam and Samreen Riaz

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/59224>

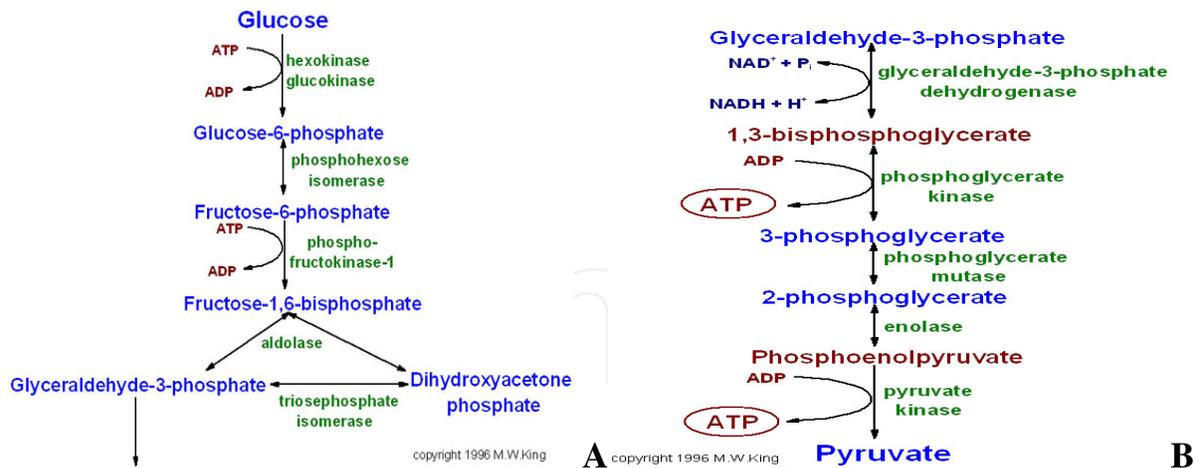
---

## 1. Introduction

Cellular survival is dependant upon the energy pathways ingrained within them. Their comprehension is imperative in understanding the role of their component enzymes in type 2 diabetes treatment and the inextricable linkage of a few of them to thiamine. The Glycolytic pathway is an ancient metabolic, cytosolic pathway that converts glucose into pyruvate under anaerobic conditions and further into lactate or ethanol. The free energy released from this forms high energy compounds ATP and NADH. Under aerobic conditions CO<sub>2</sub> and substantially more ATP is produced [1]. The pathway of glycolysis comprises of 2 clear divisions (Fig 1). After glycolysis, further aerobic processing of glucose is conducted through the Krebs Cycle, synonymous with tricarboxylic acid or citric acid cycle (Fig 2). Intracellularly the mitochondria serve as site of citric acid cycle and oxidative phosphorylation activities.

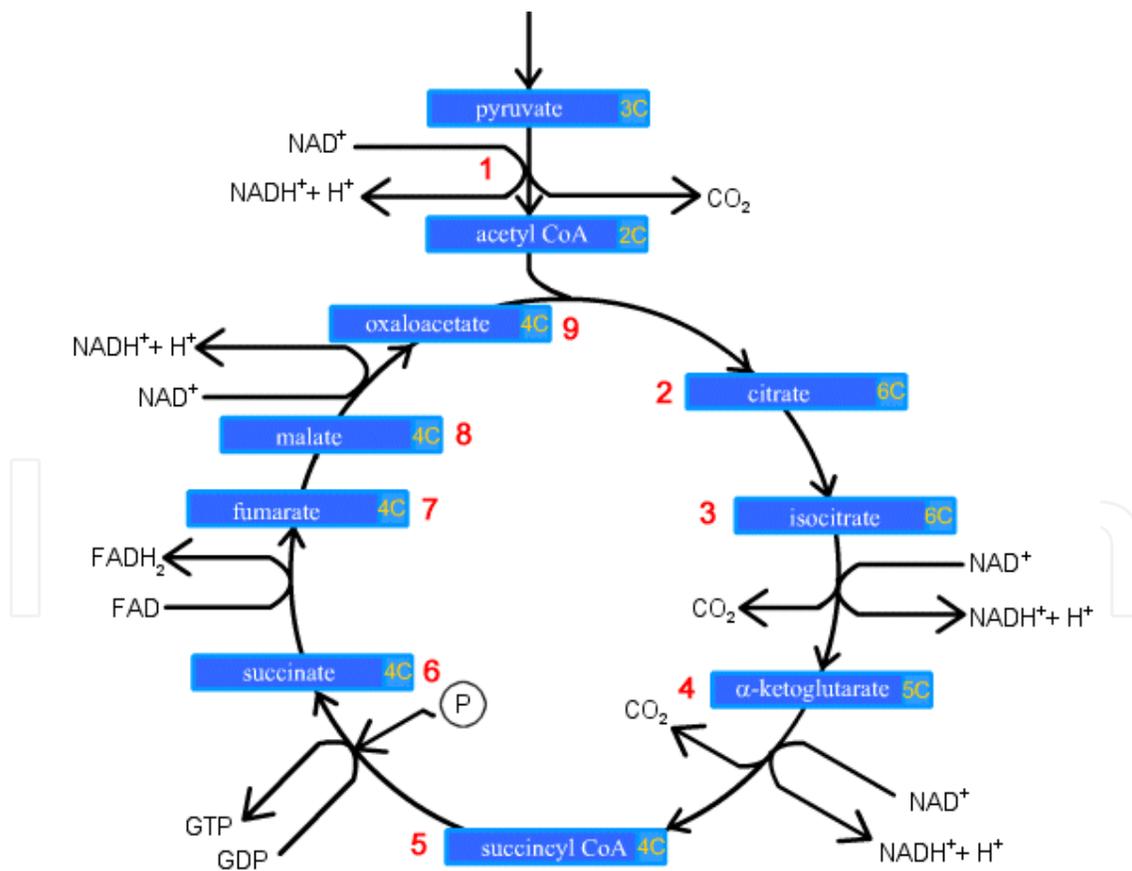
The overall chemical reaction of the tricarboxylic acid cycle is:





Adapted from Michael W. King, Ph.D / IU School of Medicine / miking at iupui.edu / © 1996–2011.

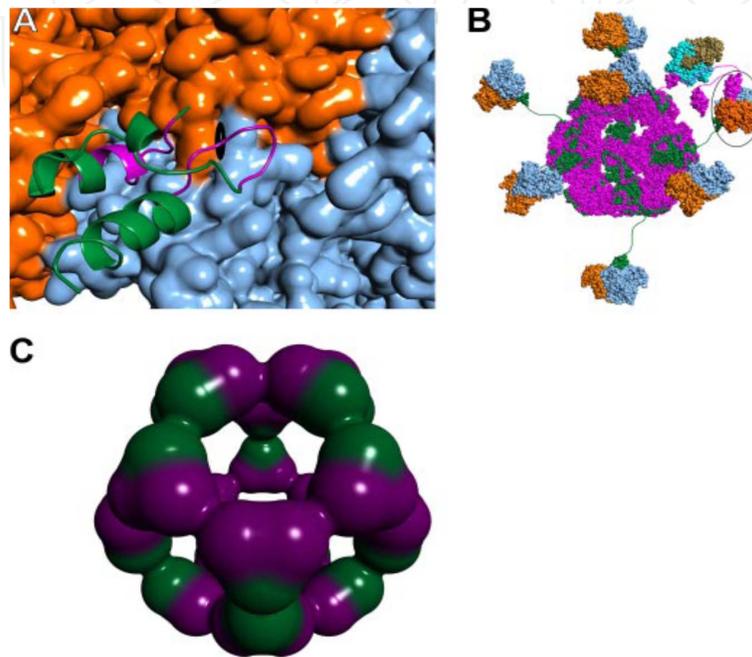
**Figure 1.** (A) Phase1 (Priming Phase) of Embden Meyerhoff Pathway; (B) Phase 2 (Energy Yielding Phase) of Embden Meyerhoff Pathway; A & B: A Schematic Pathway of glycolysis from glucose to pyruvate.and its connection to the reductive pentose pathway and citric acid cycle.



**Figure 2.** Krebs cycle (www. library.thinkquest.org)

## 2. The mitochondrial catalytic repertoire

**The pyruvate dehydrogenase complex:** Both prokaryotic and eukaryotic species carry among others, conglomeration of proteins into a mega, specifically arranged multienzyme structural complex termed (a "metabolon").



**Figure 3.** Protein-protein Interactions in the Native human PDC. Adapted from Brautigham (2006)

- a. Close-up view of E3BD (ribbons representation) bound to E3 (surface) (Brautigham 2006). One monomer of E3 is colored orange, and the other is blue. The approximate position of the dyad axis of the E3 dimer is shown by the black symbol and arrow. Most of E3BD is colored green, but those residues with atoms that would clash with a second bound E3BD are shown in purple.
- b. Schematic model of the native human PDC. The dodecahedral 60-meric core of the human PDC is modeled using the structure of the catalytic domain of *B. tearothermophilus* E2 (Izard 1999). The E2p polypeptides are colored magenta, with E3BP polypeptides colored green. The E3 dimers are shown in blue and orange, with a single E3BD bound per dimer of E3 (Brautigham 2006), as indicated by the data. In this model, it is possible for 20 E3 dimers to bind; only 7 are shown for clarity. A single E1p heterotetramer docked to the E1pBD of E2p is represented, subunits shown in tan and cyan. The structure of the human versions of E1p bound to E1pBD is unknown; shown here is the structure from *B. stearrowthermophilus* (Frank 2004). The circled E3 has an LBD of *E. coli* E2p docked to the active site. E2p and E3BD are therefore noncovalently cross-linked via their mutual interaction with E3.

- c. Possible arrangement of E2p and E3BP components in a 40/20 core. Shown is a dodecahedral arrangement of 20 heterotrimers composed of 2 E2p proteins (purple) and one E3BP (green) (Brautigham 2008). Of these enzyme complexes of the metabolon, the pyruvate dehydrogenase complex is highly evolutionarily conserved mitochondrial  $\alpha$ -ketoacid dehydrogenase complex, along with the branched-chain  $\alpha$ -ketoacid dehydrogenase complex (BCKDC), and the  $\alpha$ -ketoglutarate dehydrogenase complex (KGDC) [4, 5]. The complex has 3 main components with multiple subunits and multiple names. (Fig 3)

The heterotetramer **PDE1 p PYRUVATE DEHYDROGENASE (EC1.2.4.1)** comprises of 2 alpha and 2 beta subunits [6]. Its alpha 1 subunit is designated as PDE1A-2, (pyruvate dehydrogenase (lipoamide) alpha2). Its gene PDHA2 is located on chromosome 4 having length of 1383 bp/460 aa [7, 8] Whereas the alpha 2 subunit is designated as PDH E1-A type1 (i.e.) synonym PHE1A. Its gene PDHA1 is located on chromosome X which has length of 15922 bps [9] and a mol.wt of 160KDa. The Pyruvate dehydrogenase E1 component subunit beta, or pyruvate dehydrogenase (lipoamide) beta mitochondrial, synonym, PDE1-B, has gene located on chromosome 3 having length of 6198 bp [10-12]. The key function of the complex E1alpha subunit containing the active site is to be the rate limiting enzyme, unidirectionally funneling intermediate metabolites from glucose breakdown to either the oxidative metabolic pathways or fatty acid and cholesterol synthesis [13]. **PDE2p** contains **dihydrolipoyl transacetylase enzyme activity (EC2.3.1.12)** encoded by DLAT Dihydrolipoamide acetyl transferase gene, present on human chromosome 11 band q23.1. It has mol wt 200 KDa [14]. Interestingly, this long arm region of chromosome 11 often presents with translocations in cellular genetic abnormalities [15]. **PDE3/GCSL/LAD/PHE3 (EC 1.8.1.4)** component contains the dihydrolipoyl dehydrogenase activity. E3 activity is encoded by the DLD located on chromosome 7 and length 28799 [16]. It has a mol.wt of 110 KDa. This protein has four different sites: the flavin adenine dinucleotide binding site, the nicotinamide adenine dinucleotide binding site, the centre site and the interface site. The protein forms a homodimer with the FAD and NAD binding regions on one unit and the interface domain of the other unit forming the active centre [17].

### 2.1. Structural association of the 3 units

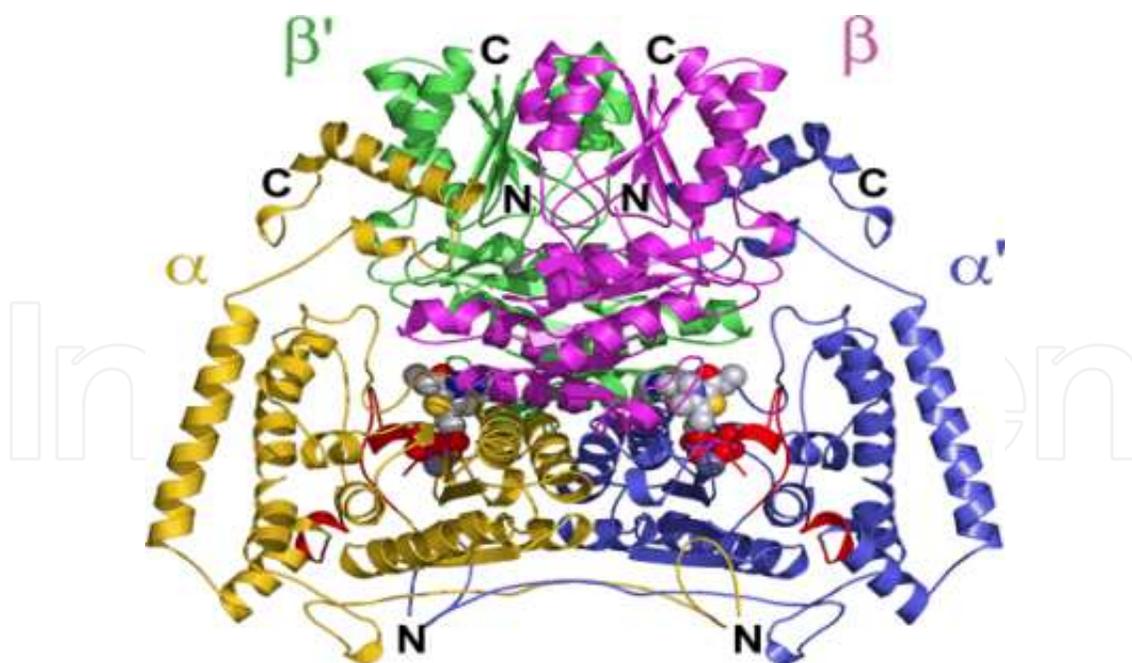
The human pyruvate dehydrogenase multi enzyme complex (PDC) is a nuclear encoded mitochondrial matrix 9.5 megadalton catalytic organization of copies of three catalytic components i.e. heterodimeric pyruvate dehydrogenase (E1p 30copies) (thiamine diphosphate (ThDP) dependant), homodimeric dihydrolipoyl transacetylase (E2p 12 copies) and dihydrolipoamide dehydrogenase dimer (E3) (FAD containing) residing in the inner mitochondrial membrane [4] (Fig. 3). The (E1p) and E3 subunits surround a 60-meric dodecahedral core of 40 copies of E2p and 20 copies of a monomeric non catalytic component, E3-binding protein (E3BP), which specifically tethers E3 dimers to the pyruvate dehydrogenase complex [18]. Each E2p subunit contains two consecutive lipoic acid-bearing domains (LBDs), termed as L1 and L2, one subunit binding domain (SBDp) which binds E1p and the inner-core/catalytic domain containing the E2 p active site responsible for the self assembly of the core which connects with the other independent domains by

unstructured linkers [3](Fig.3). Similarly, each E3BP subunit consists of a single LBD (referred to as L3), the E3-binding domain (E3BD) and the noncatalytic inner core domain. It is presumed that the lipoyl bearing domains LBDs (L1, L2, and L3) and 60 subunits of the transacetylase seem to form a free circulation of lipoyl groups among which the acetyl groups are freely exchanged [18] and shuttle between the active sites of the three catalytic components of the PDC during the oxidative decarboxylation cycle [19]. Unspecified copies of each PDC regulatory enzyme pyruvate dehydrogenase kinases and pyruvate dehydrogenase phosphatases are also strung non-covalently to the core by the LBD2 [5, 20].

The active site synchronization over a distance of 20 Angstroms via proton wire through an acidic tunnel in the protein, keeps the active sites in an alternating activation state [22]. Phosphorylation of the heterotetrameric ( $\alpha_2\beta_2$ ) E1p component is essential for the inactivation of the human PDC which occurs at 3 serine residues of the alpha subunit. Two of these sites are located in the conserved phosphorylation loop A [6] which forms one wall of the active site channel and helps to anchor ThDP to its active site. Site 3 is in the phosphorylation loop B which provides coordination to magnesium is chelated by the ThDP potassium. Phosphorylation of any of the 3 sites inactivates E1p and drastically reduces the affinity for pyruvate [24]. Disordered loops of E1p arise from phosphorylation and result in downregulation of the PDC activity. Binding of the cofactor ThDP induces ordering of both the loops which then can mediate decarboxylation and reductive acetylation of the pyruvate. Phosphorylation of PDC is crucial in regulating carbohydrate and lipid metabolism [14, 25]. Starvation and diabetes increase phosphorylation that inactivates PDC, leading to impaired glucose oxidation [26, 27]. On the other hand prevention of PDC phosphorylation by specific PDK inhibitor, dichloroacetate increases reactive oxygen species levels in the mitochondria leading to cellular apoptosis and the inhibition of tumour growth [28, 29]. Therefore the regulation of PDC flux by reversible phosphorylation is a potential target for obesity and cancer [30, 31]. Finally the expression of PDK2 and PDK4 is down regulated by insulin in the long term [32, 33]. In the animal model, downregulation of skeletal muscle pyruvate dehydrogenase in the rat model before and after the onset of diabetes mellitus has been observed [34]. Dephosphorylation/activation of the PDC is ascribed to two Mg and Ca dependant genetically and biochemically distinct isoforms of pyruvate dehydrogenase phosphatase PDP heterodimeric (PDP1&PDP2), which are important regulators of PDC activity. PDP1 has both a catalytic (PDPc) subunit bound to the inner mitochondrial membrane and a regulatory (PDPr) subunit [35]. Both PDP1 components are targeted by insulin which enhances PDPc activity and lessens PDPr negative control resulting in enhanced overall PDP1 efficiency. These effects are at the core of insulin signaling of PDH [36]. PDP2, recently discovered in rat tissues consists of a catalytic subunit insensitive to Ca, 10 fold less sensitive to Mg than PDP c is also considered a target in insulin signaling [37, 38]. In humans too, down regulation of PDP in obese subjects is a malfunction that signals insulin resistance [39].

## 2.2. Diseases produced by defective PDC

As the PDC has prime significance in intermediary metabolism, mutations in the genes encoding for PDC subunits produce severe clinical phenotypes [40]. Congenital defects in E1p in the X linked gene lead to lactic acidemias, encephalopathies, neuronal dysfunction in infancy [40]. Mutations in the E2, E3BP cause primary biliary cirrhosis leading to liver failure [41, 42], autoimmune hepatitis [43] and neurodegenerative conditions such as Alzheimer's disease. Combined enzyme deficiencies of  $\alpha$ -ketoacid dehydrogenase complexes pyruvate dehydrogenase complex, BCKDC and ketoglutarate dehydrogenase complexes have been observed due to genetic changes in human E3 [44] resulting in lactic acidemias and maple syrup urine disease [45-47]. Other anomalies of the PDC include autoantibodies leading to paediatric biliary cirrhosis [47]. Additionally, the aberrant down-regulation of pyruvate dehydrogenase complex activity by reversible phosphorylation has been shown to be contributory to hyperglycemic states observed in type-2 diabetes [25], increasing the chances of pyruvate dehydrogenase complex as a therapeutic target for a 150 million people affliction i.e. diabetes). Failure of functioning of the pyruvate dehydrogenase complex and specially of its E1p subunit due to lack of thiamine vitamin B1 would therefore inevitably lead to poor handling of glucose and its substrates and could manifest as deleterious effects in type 2 diabetics. The human 2 ketoglutarate dehydrogenase complex while extensively studied has not yet been reconstructed in vitro and reliance on other mammal models persists [5, 48](Fig 4).



**Figure 4.** Representative Model for Human 2 Ketoglutarate Dehydrogenase Complex: All figures of molecular structures were created with the program PyMol (DeLano Scientific, San Carlos, CA). Jun Li. The Journal of Biological Chemistry, 2007;282, 11904-913.

### 2.3. Structure of alphaketoglutarate dehydrogenase complex

This 4 to 10 mega Dalton supramolecular complex is organized around a polyhedral form of a cubic core of 24/60 lipoate bearing dihydrolipoyl succinyltransferase E2 subunits (8 trimers) arranged with octahedral (432) symmetry [5] associated with non covalently attached multiple copies of dihydrolipoamide E1k and dihydrolipoamide E3K individually held via its E1/E3 binding domains which serve as scaffolds for the E2 core. There is also biochemical evidence of E3 binding to the aminoacid terminal region of E1 terminal allowing for separation of a stable E1-E3 submolecular complex from the E2 core [49]. Also attached are regulatory kinase and phosphatase units [50]. Further lipoyl bearing domains LBDs of the E2 core are attached serving as swing arms impart substrate channelling by sequentially visiting the different active sites in each of the three E1, E2 and E3 catalytic components [51] to transfer acyl groups to the active site of E2 leading to oxidative decarboxylation of the alpha ketoacids [51]. The complex has 3 main enzymatic components with multiple subunits & copies and varied names: oxoglutarate dehydrogenase (lipoamide); EC: 1.2.4.2 (E1k), dihydrolipoamide S-succinyltransferase; EC:2.3.1.61 (E2k) and dihydrolipoamide dehydrogenase; EC:1.8.1.4 (E3k) [52].

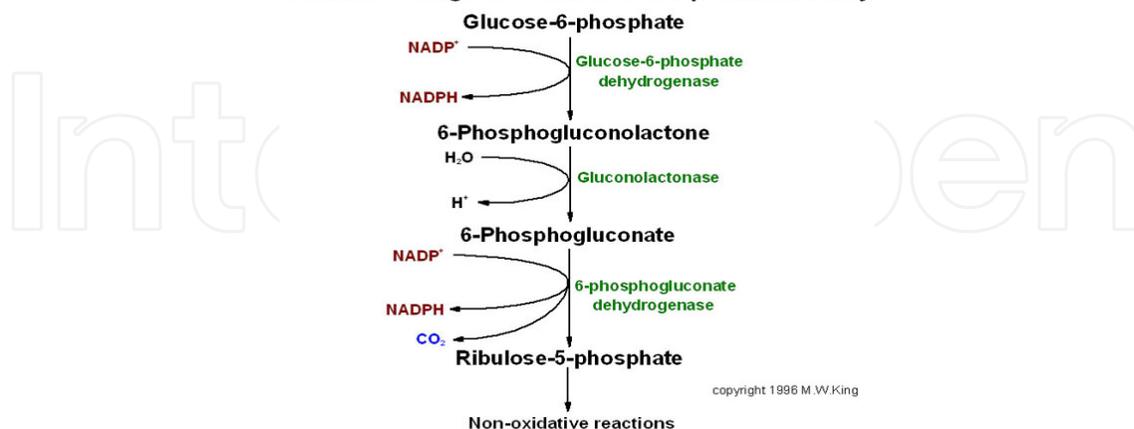
1. **Alpha ketoglutarate dehydrogenase/2 oxoglutarate dehydrogenase E1k heterotetramer** (2 alpha and 2 betachains) (53) component has 6 copies (lipoamide) polypeptide enzyme having mol wt 115.94 kDa (from nucleotide sequence) and sequence length 34160 aminoacids. It is encoded by the OGDH gene localized on chromosome 10, 54290aa & 7 at p13-p14 [54] containing 22 exons spanning 102483 bpairs [55, 56]. It contains a thiamine diphosphate cofactor and catalyzes thiamine diphosphate dependant decarboxylation of 2 oxoglutarate and subsequent reductive acylation of the oxidized lipoyl moiety LBD (lip-LBD-S2) which is covalently bound to the E2 component dihydrolipoamide succinyl transferase [5]. Thiamine diphosphate is tightly but not covalently bound to the 2-oxoglutarate dehydrogenase component [57] ThDP remains an essential cofactor and alphaketoglutarate dehydrogenase complex in the form of homo dimers alpha<sub>2</sub>, homo tetramers alpha<sub>4</sub> or heterotetramers alpha<sub>2</sub> beta<sub>2</sub> contain ThDP binding pockets that constitute two or four active sites for this enzyme which operate independently without an obligatory alternating mechanism in the E1b component [58] and overall activity is abolished at 50% phosphorylation (1 of 2 sites) within each active channel similar to PDC [59].
2. **Dihydrolipoamide S-succinyltransferase E2k** core has 24 /60 copies containing lipoyl active site as well as active sites for E1 and E3 subunits based on similar mammalian PDC structural studies and molecular wt of 64.5 KDa [5]. It is encoded in gene DLST located on chromosome 14 q24.2-q24.3 with a length of 21815 base pairs [60]. This inner core plays an essential role in mediating the E1 catalyzed decarboxylation of 2 oxoglutarate and reductive acylation of the lipoyl moiety and E3 catalyzed reoxidation of the dihydrolipoyl moiety.
3. Located in the mitochondrial lumen, **Dihydrolipoamide dehydrogenase E3k** or E3 component a flavoprotein (dimer) has 12 copies, a sequence length of 28796 aminoacids and is 54.15kDa in weight. It is encoded in the DLD gene localized to 7q31-q32 [61], its function is to catalyze the transfer of electrons from dihydrolipoamide to NAD<sup>+</sup> and bears close

structural and functional approximation to the PDE3 component of pyruvate dehydrogenase and its full complex contains 6 dimers [5].

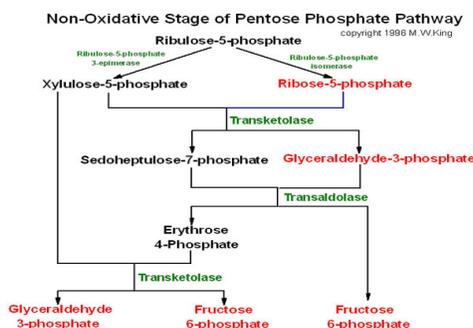
The  $\alpha$ -ketoglutarate dehydrogenase complex EC 1.2.4.2 also termed as oxoglutarate dehydrogenase complex, acts on  $\alpha$ -keto-glutarate/2 oxoglutarate a key intermediate in the krebs cycle converting to succinyl co A, produces NADH and CO<sub>2</sub> in an irreversible reaction [62] KGDHC catalyzes a vital step in the Krebs cycle, which is also a step in the metabolism of the potentially excitotoxic neurotransmitter glutamate. It allows amino acids to enter the citric acid cycle and produce energy; this is a reversible reaction in which glucose which enters the cycle can leave it to make amino acids thus linking amino acid pathways to the citric acid cycle. It also participates in lysine degradation and tryptophan metabolism.  $\alpha$ -KGDH is vital for maintaining NADH supply to the respiratory chain and is limited only when  $\alpha$ -KGDH is also inhibited by ROS. In addition being a key target, it is also able to generate ROS during its catalytic function which is regulated by the NADH/NAD<sup>+</sup> ratio [63]. Its cofactors are TPP bound to E1, lipoic acid covalently bound to lysine on E2 which accepts the hydroxyethyl carbanion from TPP as an acetyl group, coenzyme A which is substrate for E2 and accepts the acetyl group from it, FAD bound to the E3 subunit reduced by lipoamide and NAD which is substrate for E3 and reduced by FADH<sub>2</sub> [64]. Basic short term regulation of KGDHC is through adenosine diphosphate ADP, P (i) and Ca<sup>2+</sup>; these positive effectors increase manifold the affinity of ketoglutarate dehydrogenase complex to  $\alpha$ -ketoglutarate. While KGDHC inhibitors are NADH, adenosine triphosphate, succinyl-CoA, and thioredoxin protects KGDHC from self-inactivation during catalysis [65].  $\alpha$ -KGDH is also sensitive to oxidative stress and a number of metabolites modify the activity of KGDHC, including inactivation by 4-hydroxynonenal. In the human brain, comparison of KGDHC activity to other enzymes of energy metabolism like aconitase, phospho-fructokinase and the electron transport complexes shows it to be lower than all of them. Therefore impairment of KGDHC function is likely to disturb brain energy metabolism and result in brain disease [66]. In Wernickes encephalopathy there is AKGDH and thiamine deficiency associated with increased oxidative stress markers, lipid peroxidation resulting in neuronal cell death in pons, thalamus and cerebellum [67, 69]. In general, the clinical manifestations of KGDHC deficiency relate to the severity of the deficiency. A range of disorders have been recognized: varying from psychomotor retardation in childhood, to intermittent neuropsychiatric disease with ataxia and other motor disabilities, such as Friedreich's and other spinocerebellar ataxias [70], as well as neural diseases where mental deficits are also visible such as Parkinson's disease, and Alzheimer's disease (AD) [70] In Parkinsons Disease which has been deeply investigated, KGDHC Activity is reduced, coupled to elevated levels of monoamine oxidase B [71] and cytosolic accumulation of cytochrome c which inturn activates other pathways, including cell death cascades and enzyme inhibition which alters Ca<sup>2+</sup> homeostasis [72] The KGDHC enzyme is further a target for ubiquitination-dependent degradation in mitochondria by binding of Siah2, the RING finger ubiquitin-protein isopeptide ligase 2, encoded by gene siah2 [73]. Diabetes mellitus, thiamine dependent megaloblastic anaemia and sesorineural deafness associated with deficient  $\alpha$  ketoglutarate dehydrogenase activity have also been reported [74]. There exist 2 wings, oxidative and reductive of the pentose phosphate pathway (Fig 5). The oxidation steps, utilizing glucose-6-phosphate (G6P) as the substrate, occur at the beginning of the pathway and generate 2 moles

of NADPH. The reactions catalyzed by glucose-6-phosphate dehydrogenase (G6PD) and 6-phosphogluconate dehydrogenase are essential for the conversion of hexoses to pentoses [75].

#### Oxidative Stage of Pentose Phosphate Pathway



#### A) Digrammatic Representation of the Oxidative Stage of Hexose Monophosphate Shunt



#### B) Reductive or Non Oxidative Stage of the Hexose Monophosphate Shunt

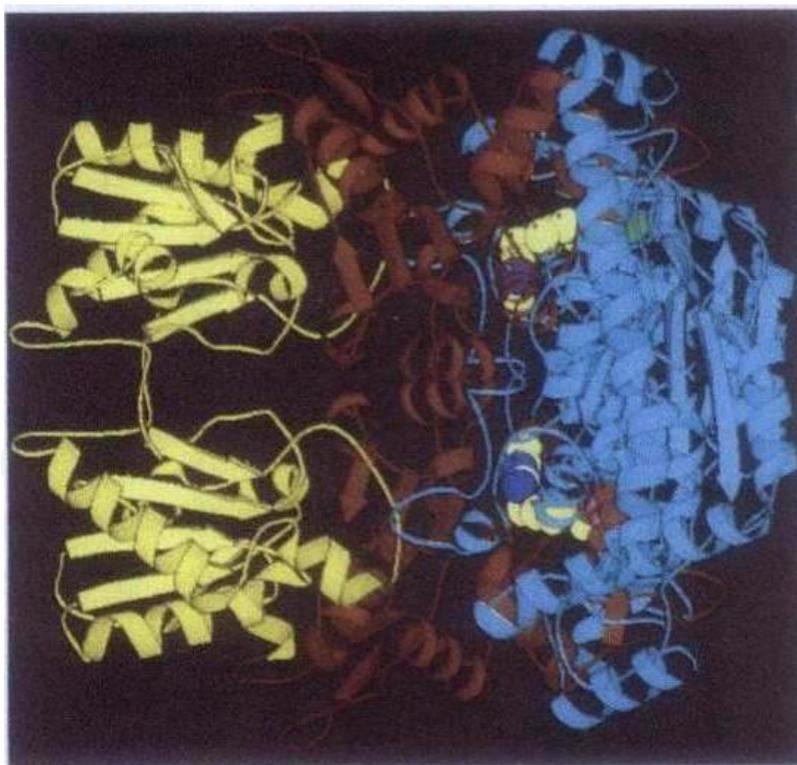
**Figure 5.** (A): Digrammatic Representation of the Oxidative Stage of Hexose Monophosphate Shunt and (B) Reductive Stage of the Hexose Monophosphate Shunt

The non-oxidative reactions of the pentose phosphate pathway are mainly functioning to produce ribose 5 phosphate, and equally significantly to convert dietary 5 carbon sugars into both 6 (fructose-6-phosphate) and 3 (glyceraldehyde-3-phosphate) carbon sugars which can then be utilized by the pathways of glycolysis [76].

#### 2.4. Functions of the pentose phosphate pathway in normal and diseased conditions

The Pentose phosphate pathway (PPP) is primarily energy forming, and non mitochondrial with only a cytoplasmic enzymatic presence entrusted to utilizing 6 carbon sugars, and producing in turn 5 carbon sugars for the synthesis of nucleotides, nucleic acids and reducing equivalents in the form of NADPH. The pentose phosphate pathway is a metabolic redox estimator and regulates transcription during the anti-oxidant response, as a shift from primary carbon metabolism, is fastest in oxidative stress [77]. NADPH cofactor serves as reducing equivalent in the endoplasmic reticulum lumen for fatty acid and steroid biosynthesis in

hepatic and, adipose tissue, adrenal cortex [78]. High levels of PPP enzymes are in neutrophils and macrophages as they utilize NADPH to produce ROS to destroy engulfed microbes in a process termed as respiratory burst [79]. G6PD deficiency effects red blood cell viability dependent on PPP generated NADPH, a glutathione reducer, the absence of which results in hemolysis seen with certain drugs and diseases like malaria which cause oxidative stresses [80]. Cancer cells are known to access successfully the glucose flux in the pentose phosphate pathway supporting NADPH and reactive oxygen species production and glutathione reduction [81] responding to both incremental and decremental reactive oxygen species [82]. Electron leakage from the mitochondrial electron transport remains essential (through the action of ribonucleotide reductase) in generating deoxyribonucleotides from nucleotides as well producing ROS in collusion with oncogenes [83] and molecular oxygen [84] promoting genetic damage in normal cells and therapy resistance in cancerous cells [85]. Malignant cells also use reduced glutathione [81] or NADPH to combat oxidative stress and to support the oxidation of fatty acids in detached cells [86]. **Transketolase** is the premier cytosolic enzyme of the reductive pentose phosphate pathway. Its 3 genes TKT, Transketolase like TKTL1 and Transketolase like TKTL2 encode for proteins with transketolase activity. All of them participate in the reductive pentose pathway reactions catalyzing transfer of a 2 carbon fragment from a ketose donor to an aldose (acceptor substrate) [87].



Adapted from Kochetov2005, Lindquist 1992

**Figure 6.** Schematic View of Transketolase Dimer Showing its Different Components. The 3 components are colour differentiated: N terminal domain, light blue, middle domain, light brown & C terminal domain yellow. The bound cofactor ThDP is shown as a CPK model and Ca<sup>++</sup> ion in green

**Transketolase:** synonymous with TKT1 & TK is composed of and encoded by the TKT gene located on chromosome 3 (30390 bp) [89-91]. **Transketolase like protein 1:** named as TKT2, TKR, TK 2, Transketolase 2, Transketolase-related protein has molwt of 60-70 KDaltons depending on splice variation encoded by the TKTL1 gene located on chromosome X Length: 25052 bp [92, 93]. **Transketolase like protein 2** termed TK is composed of 913 aminoacids encoded by gene TKTL2 located on chromosome 4 having length of 2742 bp [94].

**TKT Structure:** Transketolase (TK) is a homodimer [95] (Fig 6) and the least structurally complicated member of thiamine diphosphate (ThDP)-dependent enzymes group containing PDHC & OGDHC [96]. Each monomer consists of three distinct regions the N terminal or PP binding region, the middle or pyrimidine binding region and C terminal region [87]. The first 2 regions are associated with coenzyme binding while the role of the third remains unknown [85, 97].

**Thiamine Binding Site:** TKT has two active centres with one THDP molecule attached to a binding motif [98, 99] and a bivalent cation (Ca affinity more than Mg [100]) tightly bound at each centre by noncovalent interactions [101]. Thiamine binding site is located within a deep furrow which allows only the C2 atom of the thiazolium ring to be exposed to the donor substrate [101]. A highly conserved starter sequence glycine-aspartate-glycine GDG and concluding sequence asparagine-asparagine (NN) represent this site between residues 154 and 185 [101]. Further the interactions of the non-covalently bound coenzyme ThDP-magnesium with the protein component are at five critical sites containing arginines (Arg 101, Arg 318, Arg 395, Arg 401 and Arg 474 and Asp155) [101] contribute to dimer formation, stability or catalytic activity [102, 96]. The dimerization process involves initial binding of magnesium to the aspartate in the starter sequence which in turn interacts with the pyrophosphate molecule of the thiamine diphosphate through hydrogen bonding [101], followed by one transketolase monomer engaging the pyrophosphate moiety and the other with the thiazolium and pyrimidine rings of ThDP [88, 97]. The importance of this interaction is reflected in the noticeable refractoriness in Wernickes encephalopathy to thiamine treatment alone in hypomagnesemic alcoholics [103]. This enzyme has a 2 stage catalytic cycle central to which is the TPP molecule, initiated by the deprotonation in its thiazolium ring due to interaction with Glu 418 of apotransketolase.

## 2.5. Role of transketolase in disease and therapy

Transketolase enzyme genetic variants and depreciated enzyme activities have been noted in neurodegenerative diseases like Wernickes Korsakoff syndrome and Alzheimers disease [104]. Upregulation of the TKT L1 gene has been found in a number of malignant disorders resulting in enhanced total transketolase activity and cellular proliferation in human colon cancer [105], thyroid [106], cervical [107], ovarian cancer [108], nephroblastoma and adenocarcinoma. Its increased expression is found to be a potential diagnostic biomarker for breast cancer [109] and prognostic biomarker for nasopharyngeal [110] and laryngeal squamous cell carcinoma [111]. The reason may lie in the role of transketolase in the reductive pentose pathway which remains a source of carbons such as in ribose required for nucleotide synthesis, NADPH and reduced glutathione in addition to aromatic acids and fatty acids required for cellular growth

in general and explosive growth in particular. Transketolase has begun to emerge as a target in the cellular immune response in multiple sclerosis [112]. Human transketolase can be used in structure-based drug design as target for inhibition in the treatment of cancer [113] and in the search for new transketolase inhibitors as non permanently charged thiamine analogs, which are substrates for the thiamine activator thiamine pyrophosphokinase. These pyrophosphate analogs antagonize the ability of transketolase in vitro [113]. In diabetes mellitus type 2 experimental model, the role of transketolase in the reductive pentose pathway and its activation by administration of lipid soluble thiamine derivative benfotiamine is well documented and undeniable [114] and further clinical research is ongoing.

## 2.6. Pharmacotherapeutics of type 2 diabetes

Treatment is done using 4 categories of oral antidiabetic drugs.

1. Insulin secretagogues: Sulfonylureas, meglitinides, D-phenylalanine derivatives
2. Those reducing insulin resistance:
  - i. Biguanides
  - ii. Thiazolidinediones (glitazones)
3. Those decreasing carbohydrate absorption from the gut: Alpha Glucosidase inhibitors.

## 2.7. Insulin secretagogues

### i. Sulfonylureas:

These act by stimulating insulin release from pancreatic B cells. Sulfonylureas may also act by decreasing hepatic insulin clearance [115]. They increase insulin concentration often failing to improve first phase insulin release in response to a glycemic challenge. There is secondary failure and tachyphylaxis to sulfonylurea therapy following prolonged use. Their adverse effects are hypoglycaemia, GIT disturbances, cholestatic jaundice, agranulocytosis, aplastic and hemolytic anemia, generalized hypersensitivity and dermatological reactions [116]. There is also a debate on associated cardiovascular mortality – due to blockage of KATP channels of the hearts and vascular tissues [117]. Second generation sulfonylurea glimepiride is useful as single therapy in previously drug naïve patients and also in combination with non-secretagogue medication [118]. Glimepiride may be linked to lower incidence of hypoglycaemia [119] and may improve insulin sensitivity [120]. It also has an insulin sparing action [121].

### ii. Meglitinides:

Like the sulfonylureas, meglitinides also stimulate insulin secretion.

### iii. D-phenylalanine derivatives:

Netaglinide is the latest insulin secretagogue to become available. It selectively enhances early insulin release providing excellent meal time glucose control while reducing total insulin exposure [122]

**iv. Biguanides:**

These agents don't cause hypoglycemia and are thus called euglycemic agents. Current proposed mechanisms of biguanides include glycolysis stimulation in tissues, reducing glucose absorption from GIT with increased glucose to lactate conversion, reduced hepatic and renal gluconeogenesis, in the GI tract and reduction of plasma glucagon levels [123]. Most frequent toxicity are gastrointestinal (anorexia, nausea, vomiting, abdominal discomfort and diarrhea). It is contra indicated in patients with hepatic disease or in conditions predisposing to tissue anoxia because of risk of lactic acidosis [124].

**v. Thiazolidinediones (glitazones):**

They are also considered to be euglycemic and are effective in 70% users. Three drugs have been used clinically from this group (Troglitazone, Rosiglitazone and Pioglitazone). Troglitazone a severely hepatotoxic and its removal from public use is well known. These are selective agonists for nuclear peroxisome proliferator – activated receptor – gamma (PPAR GAMMA) whose activation enhances insulin responsive genes that regulate carbohydrate and protein metabolism [125]

**vi. Alpha Glucosidase Inhibitors:**

Competitive inhibitors of intestinal alpha glucosidases namely acarbose and miglitol decrease the post meal digestion and assimilation of simple and complex carbohydrates such as starch and disaccharides [126]. These are effective also in prediabetic individuals and successfully restored  $\beta$  cells function. Therefore, diabetes prevention may be a further indication for their usage [127].

### **3. New drugs for type 2 diabetes**

#### **3.1. Currently available**

The Incretin hormones released by the gut, gastric inhibitory peptide (GIP) and Glucagon like peptide1 (GLP-1) (liraglutide) stimulate insulin secretion upon nutrient entry into the gut, suppression of glucagon release, slow gastric emptying and decrease food intake [128, 129]. Therefore, they have an antidiabetogenic potential. Incretin mimetics e.g. Exenatide LAR from exendin 4 is currently in use and most resistant to DPP4 degradation. GIP has also been shown enhancing  $\beta$  cell proliferation and inhibiting apoptosis in islet cell lines [130, 131]. Additionally functional GIP receptors have been identified on adipocytes and shown to stimulate glucose transport, accelerating fatty acid synthesis and stimulating lipoprotein lipase activity in animal models [131, 133, 134]. Several novel GIP analogues have been developed which act as stronger GIP agonists, showing resistance to degradation by Dipeptidyl Peptidase-4 (DIPP-4) [135] and demonstrating increased insulinotropic and blood glucose lowering activity [135]. Dipeptidyl peptidase Inhibitors (vildagliptin & sitagliptin) suppress breakdown of Glucagon like peptide1 (GLP-1) show great potential and are undergoing clinical testing. Antihyperglycemic synthetic analogs of amylin a hormone which are produced by the pancreas to lower blood sugar levels

are available in injectable form and require close monitoring. Dapagliflozin a renal glucose reabsorption inhibitor reduces glycaemic reabsorption independent of insulin, promises to be a new drug for type 2 diabetes treatment [136]. Testosterone replacement therapy in diabetic hypogonadal men decreases insulin resistance [137] probably by protective effect on pancreatic beta cells through its action on inflammatory cytokines [138].

### 3.2. Experimental new drugs

A vanadium and allixin based drug [139] and macrophage migration inhibitory factor MIF blocking inhibitory synthetic oral drug reducing blood sugar levels was tried in the mouse model and found to be effective in both the type 1&2 diabetic model [140]. Lisofylline, a fat metabolism inhibitor which prevents buildup of ceramide a by product of fat metabolism in mouse skeletal muscle decreased the insulin resistance and thus appears to be a novel new approach for type 2 diabetes [141]. It also has the ability to protect insulin producing cells by inhibiting cytokines produced by immune cells leading to apoptosis and cellular dysfunction and is thus effective in type1 diabetes [142]. LXR agonists have shown potential and require further testing in human and model systems [143]. Growth factors and protein kinase C inhibitors may act as innovative therapies for diabetic retinopathy [144].

### 3.3. Surgical interventions

Recently a type of gastric bypass surgery has been successful in normalizing blood sugar in a small number of normal to moderately obese type 2 diabetics [145, 146]. This surgery may possibly reduce death rate by 40% from all causes in morbidly obese people [147].

### 3.4. Micronutrient approaches to treatment of diabetic complications

People with diabetes have reduced antioxidant capacity which lays the basis for usage of antioxidant vitamins such as  $\beta$  carotene or vitamin C or E. A reduced level of ascorbic acid (Vitamin C) leaves the body more at mercy of the detrimental effects of aldose reductase, an enzyme responsible for many diabetic complications, such as cataracts and peripheral neuropathy [148]. Quercetin is another powerful aldose reductase inhibitor. It has been shown to inhibit aldose reductase by upto 50% [149]. Vitamin E is a free radical scavenger. It may play a preventive role in diabetic retinopathy by decreasing DAG levels, normalizing protein kinase C activation, normalizing blood flow in retinal and renal microvasculature and restoring NO mediated endothelium dependent relaxation [150, 151]. Renal and retinal vascular flows and responses were normalized in individuals who had diabetes of less than 10 years duration with high dose oral vitamin E therapy given for short periods while unchanged glycaemic control was observed [152].

Magnesium and chromium deficiency have been associated with poor diabetic control, insulin resistance, macro vascular disease and hypertension [153] and decreased glucose tolerance respectively [154]. Reduction of neuronal damage in diabetics by inhibiting glutamate dehydrogenase via vitamin B6 therapy has also been observed [155]. N-Reduced glutathione precursor NAcetyl Cysteine is a gene expression and cellular metabolism modulating antiox-

identant and its role in prevention of  $\beta$  cell oxidatory damage by acting as NFKB (a genetic regulator) inhibitor and subsequent deintensification of inflammatory responses is well documented [156]. Trace element vanadyl sulfate that behaves like insulin normalized hyperglycemic levels in diabetic animals and decreased the insulin need by upto 75% [157]. In human with Type 2 diabetes, low doses of vanadyl sulfate enhanced insulin responsive glucose uptake, glycogen production and decreased endogenous glucose formation. This resulted in reduced lipid oxidation and plasma free fatty acids levels [158]. Alpha lipoic Acid has powerful antioxidant activity, insulinomimetic action and provides protection from insulin resistance linked diabetic stress while improving glucose utilization [159]. Hyperglycemia reduction in diabetic rats was observed along with improvement in GSH levels with selenium therapy [160]. Calcium AEP has benefited both type 1 and type 2 diabetics as it is alpha cell membrane integrity factor required for cellular membrane function. The hormone dehydroepiandrosterone (DHEA) undergoes a decrease in levels with aging that many researchers have linked to impair glucose metabolism. It was found to be as effective in reducing body fats and maintaining insulin responsiveness as exercise [161]. Thiamine is also now showing potential as therapy for type 2 diabetes.

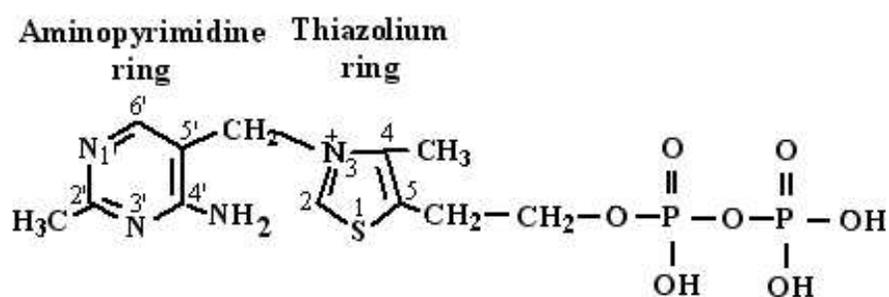


Figure 7. Structure of thiamine diphosphate molecule.

Thiamine (termed aneurin or antineuritic vitamin initially) was the premier discovery of the B vitamins and thus ranked vitamin B1 (Fig 7). It has relative temperature, acid stability and water solubility containing a pyrimidine ring and a thiazole nucleus linked with a methylene bridge. Thiamine is an essential micronutrient with a dietary reference intake (DRI) for normal healthy subjects of 1.1 mg/day for females and 1.3 mg/day for males [162]. Found in range of foodstuffs such as cereal grains. Its rich sources are brown rice, bran, oat meal, flax, poultry, egg yolks, beef, pork, liver, nuts, fruits and vegetables such as oranges, asparagus, kale, cauliflower, potatoes [163]. UK law demands compulsory fortification of flour with thiamin of not less than 0.24mg/100g flour to replace losses during milling. In Pakistan no compulsory fortification is done and the general public consumes milled white flour which is easily available and probably thiamine deficient. Thiamine is naturally found in 4 forms in varying degrees of phosphorylation in TMP thiamine monophosphate, TPP thiamine pyrophosphate or diphosphate and TTP=thiamine triphosphate. It is commercially available as salt in its mononitrate HCl (also natural byproduct) and relatively inaccessible semi lipid soluble form S-acyl derivative benfotiamine and truly lipid soluble thiamine disulphide derivatives

sulbutiamine and fursultiamine. Out of these, Thiamine HCl is the water soluble, easily accessible and commonly used vitamin supplement available with the trade name Benerva.

### 3.5. Pharmacokinetics

#### 3.5.1. Thiamine absorption in normal conditions

Thiamine is released from its administered form by phosphatase and pyrophosphatase in the proximal part of the small intestine, following which absorption occurs mainly from this site with some from the stomach and the colon; thiamine absorbed in the colon may originate from intestinal microflora. Its absorption is hindered by alcohol consumption and folic acid deficiency [164]. High affinity organic anion transporters THTR1 [165], THTR2 for thiamine and reduced folate transporter RFC-1 transports both folic acid thiamine monophosphate (TMP) intracellularly [166, 168] at normal physiological concentrations. At high expression levels RFC1 also transports TPP out of the cells [167]. At higher concentrations thiamine crosses cell membranes in its open unionized form of the thiazolium ring even by passive diffusion. THTR2 is placed on the luminal surface of the gastrointestinal epithelial cells and THTR1 is on the basolateral surface mainly but not exclusively [169]. THTR1 is expressed widely in human tissues with particular high expression in skeletal muscles, placenta, heart liver and kidney [168, 170]. Mutations in the SLC19A2 (D93H, S143F and G172D) cause malfunctioning of the thiamine transporter THTR1, thiamine deficiency and thiamine responsive megaloblastic anaemia (TRMA) [171, 172]. THTR2 is widely expressed most abundantly in placenta, kidney and liver [173]. Also highly expressed RFC-1, is in human tissues including mitochondrial membranes [168, 174]. It has affinities for TMP and TPP of 26 $\mu$ M and 32 $\mu$ M respectively [167, 168]. Cellular efflux is the probable reason for the presence of thiamine in plasma and cerebrospinal fluid [175-177]. Thiamine in the glomerular filtrate is reabsorbed by the renal brush border membrane high affinity transporters where influx is increased by an outward directed H<sup>+</sup>-gradient [178] RFC-1 is expressed on the apical and basolateral surface of the proximal tubular epithelial cells [179]; it may mediate the reuptake of TMP and provide a solution to the normal absence of TMP in the urine. Proton antiport membrane transport may operate in both intestinal and renal proximal tubular thiamine uptake [180]

#### 3.5.2. Assessment of thiamine status

Erythrocytes contain approximately 90% of total thiamine in the blood and therefore conventionally their transketolase levels have generally been considered to be the measure of thiamine status in the body [181]. Thiamine deficiency is assessed conventionally by measuring the percentage below complete saturation of the thiamine dependant enzyme transketolase (TK) in RBCs-“thiamine effect”. The normal value of the thiamine effect in human subjects is in the range 0-15%, mild deficiency is 15-25% and severe thiamine deficiency >25% [182]. Latest research has however questioned its reliability as thiamine transporters THTR1 and RFC1 in erythrocytes are upregulated in thiamine deficiency and RBC TK levels are not decreased in tandem [183]. Furthermore it doesn't account for changes in TK expression in RBC and other precursor cells. The expression of TK is decreased in thiamine deficiency [184]. Currently

assessment of mononuclear TK activity and plasma thiamine concentration determination using HPLC fluorimetric determination with respect to normal healthy controls gives greater insight into thiamine status [185-187]. More recently in capillary enzyme reaction and capillary electrophoresis methods are emerging as potential alternative monitoring and determining techniques for thiamine in samples [188].

### 3.5.3. *Thiamine metabolism within the cells*

When TMP enters cells by RFC-1 it is hydrolyzed to thiamine by phosphatases [168]. Thiamine deficiency decreased the activity of TPPK [189] and was implicated in decreased hepatic levels of TPP with normal levels of thiamine in STZ diabetic rats [190]. Within mitochondria TPP is slowly hydrolyzed to TMP by phosphatases which may leave the mitochondria via the same transporter. High concentrations of thiamine monophosphate inhibit thiamine pyrophosphokinase activity noncompetitively [191] and inhibit the entry of TPP into the mitochondria competitively [189]. A small amount of TPP is further phosphorylated to thiamine triphosphate (TTP) by thiamine pyrophosphate kinase and hydrolyzed to TPP by TPPphosphatase [192] [168]. Plasma half life is relatively short (2days) [193] but its tissue half life is approximately 9-18 days [194]. Thiamine is stored largely in skeletal muscle and the highly perfused organs such as heart, brain, liver and kidneys [163]. Subcellularly only 10% of total TPP is available for binding to transketolase most of it is associated with the mitochondria [185]. Thiamine and its acid metabolites are excreted primarily in the urine [195].

## 4. Pharmacodynamics of thiamine

Thiamine diphosphate binds to a evolutionarily highly conserved domain located in a deep cleft in the active sites of the thiamine dependant enzymes resulting in the activity of these enzymes [196]. The physiological function of thiamine is mainly fulfilled by TPP (TDP). Structurally the basis of thiamine action and activation of all ThDP-dependent enzymes lies in thiamine catalysis and deprotonation of the thiazolium ring and contribution of the aminopyrimidine side chain in this effect [197-198] while the pyrimidine ring with its dual proton donor and acceptor capability functioning as a proton transfer system. On the basis of these chemical alterations TPP functions as coenzyme for mitochondrial enzymes pyruvate dehydrogenase (PDH [199] and  $\alpha$  ketoglutarate dehydrogenase [200] of the citric acid cycle.

### 4.1. Symptoms of severe thiamine deficiency

Thiamine derivatives and thiamine dependant enzymes are universally present in all cells of the body thus a thiamine deficiency would seem to affect all organ systems especially the heart and the nervous system due to their high oxidative metabolism as witnessed in its severest form as beriberi (dry, wet or infantile) [195]. Symptoms occur rarely include tachycardia, warmth, flushing, irritability, sweating, nausea, restlessness and allergic reactions. Pharmacokinetic interactions at the level of drug metabolism include microsomal enzyme induction by prolonged anticonvulsant phenytoin resulting in decreased plasma levels of thiamin in

patients with seizure disorders such as epilepsy. The water soluble thiamine HCl form is safe in humans in oral doses less than or equal to several hundred milligrams via oral route. A UK EVM found that a small clinical trial in Alzheimers patients revealed no adverse effects of thiamineHCl at daily oral intakes of 6000 to 8000mg for five to six months. A randomized double blind placebo controlled trial was conducted in India for therapy of primary dysmenorrhea, a daily oral dose of 100mg thiamine was given to 556 females for 60-90 days and no adverse effects were noted. In extremely rare cases of allergic sensitivity were noted solely in patients using thiamine by the parenteral route and were probably due to the injection vehicle and it not been reported to be carcinogenic or mutagenic. No known genetic microsomal variations increase susceptibility to thiamine toxicity [214].

## 5. Thiamine and diabetes

Experimental evidence suggests that thiamine transport maybe abnormal in diabetes. In experimental diabetes, these was diminished intestinal absorption of thiamine and TMP. Mild deficiency of thiamine in diabetes may induce increased expression of THR1 as found in frank thiamine deficiency. In streptozocin induced diabetic rats with supportive insulin therapy to regulate hyperglycemia, 54% decreased plasma thiamine concentration was reported in contrast to normal controls [190]. This was induced in the diabetic state despite high dietary intake (9 fold) in excess of DRI for rats. The primary cause was marked increased renal clearance of thiamine which was increased by 8 fold. In streptozotocin-induced diabetic rats, there was decreased transketolase expression and activity in renal glomeruli, liver, skeletal muscle and RBCs after 12 weeks of diabetes was found associated with progressive increase in the renal clearance of thiamine and increased albuminuria with duration of diabetes, suggesting that abnormal renal handling of thiamine may occur early in the process of impairment of renal function in diabetes [190]. In experimental diabetes, similar low plasma thiamine concentration was associated with low TK activity and expression in renal glomeruli. Reduced activity of PDH was also noticed due to thiamine depletion. Similar impairment of thiamine-related metabolism may occur in the diabetic retina and peripheral nerves predisposing these tissues to the adverse effects of hyperglycaemia.

### 5.1. Effect of thiamine therapy in diabetes: On glycemc control in experimental and animal model

Thiamine therapy was found to decrease hyperglycemia in cirrhosis, insulin resistance of muscle and inadequate insulin secretion by  $\beta$  cells. In thiamine responsive megaloblastic anaemia too hyperglycemia is linked to impaired insulin secretion due to mutated high affinity thiamine transporter. Therapeutic intervention by thiamine in both cases is likely to involve improved  $\beta$  cell metabolism and insulin secretion. This effect was not noticed in permanent insulin deficiency of the STZ diabetic rat model where most of the pancreatic  $\beta$  cells are damaged or destroyed and resultantly no improvement in glycemc control is observed. It is not yet known if thiamine or benfotiamine improve glycemc control in type 2 diabetic animal model.

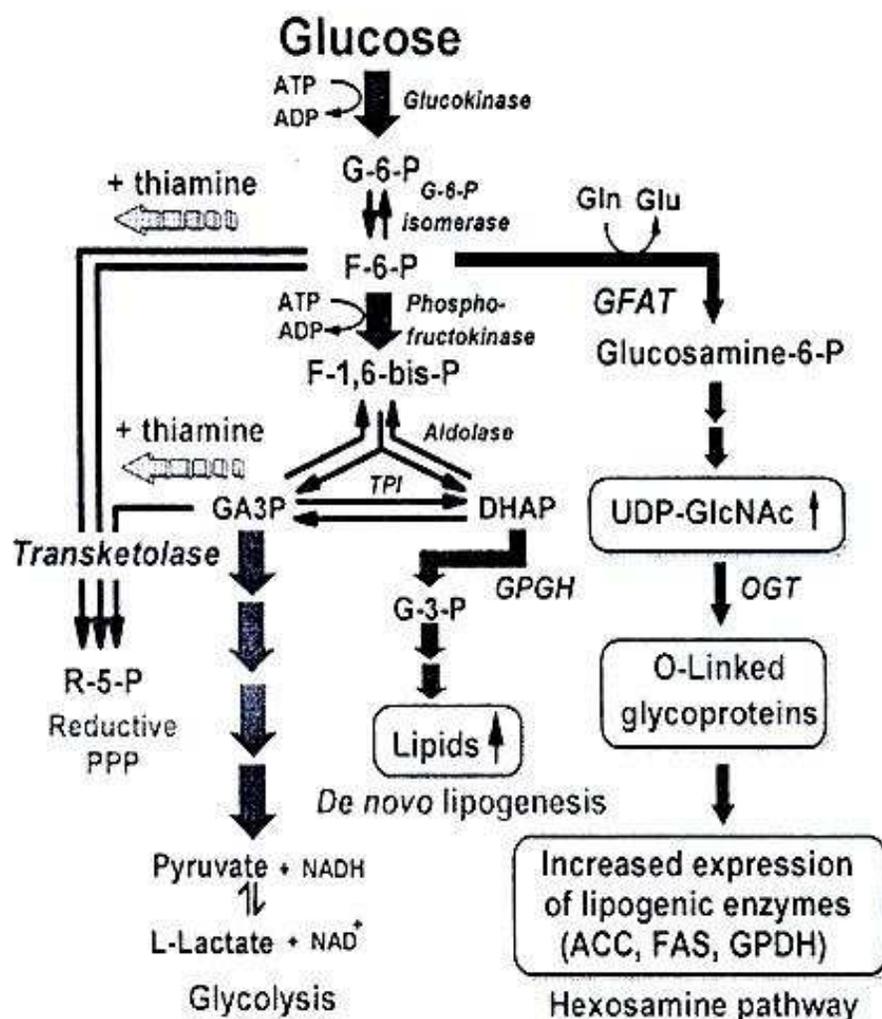
## **5.2. Mild thiamine deficiency in diabetics and improved post therapy thiamine status in clinical studies**

Mild thiamine deficiency has been observed in diabetics in different international studies. There is paucity of data on thiamine and thiamine dependant enzyme status in clinical diabetes mellitus. In Japan a study of 46 diabetic patients (7 type 1, 39 type 2) with moderate glycemic control (glycated hemoglobinA1c 9%) found lower diabetic RBC TK activity in 79% of patients and a concomitant decrease in thiamine level in 76% of diabetics. Oral thiamine supplementation 3-80mg/day increased thiamine levels (20 patients) and TK activity (15 patients). In a larger Israel study of 100 type 2 diabetic patients (glycated HbA1c 9.2%), TK activity was lower than the minimum normal range in 18% of diabetics. A smaller Italian study of 10 type 1 diabetic children with normal renal function found plasma thiamine concentration to be decreased by 34% with respect to normal healthy controls and was normalized in a placebo controlled intervention with lipophilic thiamine derivative benzoxymethyl thiamine (50mg/day).

## **5.3. Intervention of high dose thiamine therapy in biochemical dysfunction in diabetes and the prevention of microvascular dysfunction, neuropathy, dyslipidemia complications**

Microvascular disease (nephropathy, retinopathy and neuropathy) a common debilitating manifestation of chronic diabetes mellitus, has no effective therapy. Hyperglycaemia in diabetic subjects is an essential element for development of both microvascular and macrovascular complications risk factor DCCT 2003. High doses of thiamine and its derivative S-benzoylthiamine monophosphate (Benfotiamine) are proposed as a new therapy to counteract biochemical dysfunction leading to the development of microvascular complications [114]. High dose thiamine and Benfotiamine may counter the development of microvascular complications by activation of the reductive pentosephosphate pathway. Interestingly by activation of the hexosamine pathway the glucose-mediated induction of lipogenic enzymes, glycerophosphate dehydrogenase (GPDH), fatty acid synthase (FAS) and acetyl-CoA carboxylase, was stimulated in liver and adipocytes (Fig 8). In turn, this diverts metabolic flux away from the hexosamine pathway, decreased lipogenesis and correct diabetic dyslipidaemia as shown below (Fig 8).

Drugs such as cerivastatin decreased total and LDL cholesterol, triglycerides, microalbuminuria and increased HDL cholesterol in type 2 diabetic patients. However, normal levels of these metabolite were not achieved. Interestingly pharmacologically combined therapy of vit B1, B6 and B12 did not augur well in diabetics having diabetic nephropathy and substantial adverse outcomes associated with high dose vitamin B6, B9 and B12 co-supplementation in patients with advanced diabetic nephropathy was brought to light Recently concluded Diabetic Intervention with Vitamins to Improve Nephropathy (DIVINE) study produced an unexpected accelerated decline in renal function. The reasons could have been multipronged ranging from toxic accumulation of folate and B12 in patients of diabetic nephropathy with low GFR or competitive inhibition of TMP and TPP transport at the level of RFC1 transporter by high dose folate at key sites such as the kidney and vascular cells thus adversely affecting sharing of thiamine between tissues rich in thiamine and those deficient in it [183].



**Figure 8.** Metabolic Mechanism for Suppression of Hepatic Lipogenesis in Diabetes by Thiamine. Adapted from PJ Thornalley 2006

## 6. Summary

Thus final summarization of these studies indicates that high dose thiamine repletion may decrease the risk of micro and macrovascular disease and counter incipient nephropathy in diabetes. The effect of thiamine occurred independent of control of hyperglycaemia, blood pressure and statin/fibrate therapy, suggesting that high dose thiamine therapy may produce improvements in the prevention of dyslipidaemia and diabetic nephropathy in addition to those produced by current therapy for control of hyperglycaemia, blood pressure, cholesterol and lipids. Since dyslipidemia and microalbuminuria are reversible in type 2 diabetic patients, it is possible that high dose thiamine therapy might improve renal function and metabolic control through reduction in biochemical dysfunction and improvement in thiamine dependant enzyme activities in diabetic patients with existing dyslipidaemia and microalbuminuria. However, it appears that there may be noticeable variations in these parameters on the basis

of geographical, racial and pharmacogenetic factors. So the need of the hour was an indepth study as a double blind placebo controlled clinical trial to study the effect of high dose thiamine therapy on biochemical profile and activities of thiamine dependant enzymes in type 2 diabetic patients in our multiracial population in Pakistan.

## 7. Therapeutic implications

Based on the data above, the first ever randomized, double blinded, placebo controlled clinical intervention trial registered with the World Health Organization involving high dose B1 therapy was conducted by Dr.Saadia ShahzadAlam of the Pharmacology Deptt (Co-Principal Investigator 1) of Federal Postgraduate Medical Institute Lahore for a period of 5 months to study the effect of high dose thiamine therapy on biochemical profile and activities of thiamine dependant enzymes on type 2 diabetics in the Pakistani population. This trial was also pioneering internationally on the subject of diabetic nephropathy and the effect of thiamine supplementation on it. 40 type 2 microalbuminuric diabetic patients at the Diabetes Clinic of Shaikh Zayed Hospital Lahore were administered 300mg/day (100mg tablets Administration of 300mg B1 TDS) / placebo for 3 months followed by a 2 month washout period. The results of this trial were quite interesting and have been published internationally, plasma thiamine levels of both thiamine and placebo groups were significantly depleted as compared to normal controls. There were significant baseline derangements of incipient diabetic nephropathy (microalbuminuria), glycemic control parameters FBS and glycated hemoglobin, lipid profile including total cholesterol, HDL, LDL, triglycerides and VLDL in type 2 microalbuminuric diabetics as compared to healthy individuals. Following 3 months 300 mg/day thiamine administration there was significant improvement of urinary albumin excretion, and preservation of glomerular filtration rate suggested that these occurred due to thiamine replenishment and decreased glycated hemoglobin and LDL cholesterol levels were observed in the washout period as a delayed effect. Additionally following thiamine therapy significant reduction in plasma levels of sVCAM-1, noticeable and an inverse linkage between thiamine therapy and vWF was apparent in this group as compared to placebo, suggested noticeable benefit with reduction in the risk factors of type 2 diabetes. Significant changes in other serum and urinary biomarkers profile were also observed in type 2 diabetics following thiamine therapy in a simultaneously carried out proteomic study. Three thiamine dependant enzymes PDE3, PDE1 $\beta$ , AKGDHE1 and Transketolase were determined to be dysfunctional at baseline in type 2 microalbuminuric diabetic patients in comparison to normal healthy controls, and improved in both activity and gene expression with high dose thiamine therapy While importantly no hepatic or renal adverse effects were encountered prior, during therapy or as a residual effect, post washout thus fortifying the previously established human safety track record of thiamine. [200] We hope that these findings would contribute to knowledge regarding the role of thiamine therapy at 300mg/day dosage on biochemical profile and molecular aspects of those vital thiamine dependant enzymes and help in providing improved, safe and more effective treatment for type 2 diabetic patients with incipient nephropathy, dyslipidemia with expected decrease risk of heart disease and kidney failure.

## Acknowledgements

I am grateful to Higher Education Commission of Pakistan for funding the project, Prof. M. Waheed Akhtar principal investigator of the project and co-supervisor, Prof. Paul J Thornalley, Dr. Naila Rabbani as Co Principal Investigator 2 of the project and Prof. Abdul Hameed Khan my Ph.D supervisor.

## Author details

Saadia Shahzad Alam<sup>1\*</sup> and Samreen Riaz<sup>2</sup>

\*Address all correspondence to: saadia.pharma@gmail.com

1 Pharmacology Department, Federal Postgraduate Medical Institute, Lahore, Pakistan

2 Department of Microbiology and Molecular Genetics, University of the Punjab, Lahore, Pakistan

## References

- [1] Jeremy M. Berg, John. L. Tymoczko. The Glycolytic Pathway. Biochemistry 6<sup>th</sup> Edition 2006, 435-57.
- [2] David L. Nelson, Michael M. Cox. The Citric Acid Cycle. Lehninger Principles of Biochemistry 5<sup>th</sup> edition. 620-35.
- [3] Brautigam CA, Wynn RM, Chuang JL et al. Structural insight into interactions between dihydrolipoamide dehydrogenase (E3) binding proteins of human pyruvate dehydrogenase complex. Structure, 2006; 14(3): 611-21.
- [4] Patel MS, and Roche T.E. Molecular biology and biochemistry of pyruvate dehydrogenase complexes. FASEB J, 1990; 4: 3224-33.
- [5] Reed RL. A trial of research lipoic acid to alpha-keto acid dehydrogenase complexes. J Biol Chem, 2001; 276(42): 38329-336.
- [6] Cizak EM, Korotchkina LG, Dominiak PM, Sidhu S, and Patel MS. Structural basis for flip-flop action of thiamine pyrophosphate-dependent enzyme relevelated by human pyruvate dehydrogenase. J. Biol. Chem, 2003; 278:21240-246.
- [7] Dahl NH, Brown RM, Hutchison WM, Maragos C, Brown GK. A testis-specific form of the human pyruvate dehydrogenase E1 alpha subunit it coded for by an intronless gene on chromosome 4. Genomics 1990; 8(2):225-32.

- [8] Fitzgerald J, Hutchison WM, Dahl HH. Isolation and characterization of the mouse pyruvate dehydrogenase E1 alpha genes. *Biochem Biophys Acta* 1992; 1131(1); 83-90.
- [9] Borglum AD, Flint T, Hansen LL, Kruse TA. Refined alpha localization of the pyruvate dehydrogenase E1 alpha gene (PDHA1) by linkage analysis. *Hum Genet*, 1997; 99:80-82.
- [10] Weimann S, weil B, Wellenreuther R, Gassenhuber J, Glassl S et al. Toward a catalog of human genes and Proteins: sequencing and analyzing of 500 novel complete protein coding human cDNAs. *Genome Res* 2001; 11(3):422-35.
- [11] Koike K, Urata Y, Koike M. Molecular cloning and characterization of human pyruvate dehydrogenase beta subunit gene. *Proc Natl Acad Sci USA*, 1990; 87:5594-97.
- [12] Koike K, Urata Y, Matsuo S, Koike M. Characterization and nucleotide sequence of the gene encoding the human pyruvate dehydrogenase alpha subunit. *Gene*, 1990; 93: 307-11.
- [13] Brown GK, Otero LJ, LeGris M, Brown RM. Pyruvate dehydrogenase deficiency. *J Med Genet*, 1995; 31: 875-79.
- [14] Harris RA, Bowker-kinley MM, Huang B, Wu P. Regulation of the activity of the pyruvate dehydrogenase complex. *Adv Enzyme Regul.* 2002; 42:249-59.
- [15] Leung PS, Watanabe Y, Munos S, Teuber SS, Patel MS, et al. Chromosome location and RFLP analysis of PDC-E2: the major autoantigen of primary biliary cirrhosis. *Autoimmunity*, 1993; 14(4):335-40.
- [16] Scherer SW, Otulakowski G, Robinson BH, Tsui LC. Localization of the human dihydrolipoamide dehydrogenase gene (DLD) to 7q31-q32. *Cytogenet Cell Genet*, 1991; 56(3-4):176-177
- [17] Wang YC, Wang ST, Li C, Liu WH, Chen LY, Liu TC. The role of N286 and D320 in the reaction mechanism of human dihydrolipoamide dehydrogenase E3 center domain. *J Biomed Sci*, 2007; 14(2): 203-10.
- [18] Roche TE, Hiromasa Y, Turkan A, et al. Essential role of lipoyl domains in the activated function and control of pyruvate dehydrogenase Kinases and phosphatase isoform 1. *Eur J Biochem.* 2004;270: 1050-56
- [19] Perham RN. Domains, motifs, and linkers in 2-oxo acid dehydrogenase multienzyme complexes: a paradigm in the design of a multifunctional protein. *Biochem* 1991; 30:8501-12.
- [20] Roche TE, Hiromasa Y. Pyruvate dehydrogenase kinase regulatory mechanisms and inhibition in treating diabetes, heart ischemia, and cancer. *Cell Mol Life Sci.* 2007; 64 (7-8):830-49.

- [21] Wieland, OH, Patzelt, C, Loffler GX. Active and inactive forms of pyruvate dehydrogenase in rat liver. Effect of starvation and insulin treatment of pyruvate dehydrogenase interconversion. *Eur J Biochem*, 2007; 26:426-33
- [22] Wieland OH. The mammalian pyruvate dehydrogenase complex: structure and regulation. *Revs Physiol, Biochem Pharmacol*, 1983; 96: 123-1 70.
- [23] Kolobova E, Tuganova A, Boulatnikov I, Popov KM. Regulation of pyruvate dehydrogenase activity through phosphorylation at multiple sites. *Biochem. J*, 2001; 335(Pt1):69-77.
- [24] Korotchikina LG, Patel MS. Mutagenesis study of the phosphorylation sites of recombinant human pyruvate dehydrogenase site specific regulation. *J Biol. Chem*, 1995; 270(24): 14297-304
- [25] Sugden MC, Holness MJ. Recent advances in mechanisms regulating glucose oxidation at the level of pyruvate dehydrogenase complex by PDKs. *Am J Physiol Endocrinol Metab*, 2003; 284(5):E855-62.
- [26] Holness MJ, Kraus A, Harris RA, Sugden MC. Targeted upregulation of pyruvate dehydrogenase kinase (PDK)-4 in slow-twitch skeletal muscle underlies the stable modification of the regulatory characteristics of PDK induced by high-fat feeding. *Diabetes*, 2000; 49:775-81.
- [27] Kwon HS, Huang B, Unterman TG, Harris RA. Protein Kinase B-alpha inhibits human pyruvate dehydrogenase kinase 4-gene induction by dexamethasone through inactivation of FOXO transcription factors. *Diabetes*, 2004; 53:899-10
- [28] Bonnet S, Archer SI, Allalunis, et al. A Mitochondria-K<sup>+</sup>channel axis is suppressed in cancer and its normalization promotes apoptosis and inhibits cancer growth. *Cancer Cell*, 2007; 104:9445-50.
- [29] Cairns RA, Papandreou I, Sutphin PD, Denko NC. Metabolic targeting of hypoxia and HIF1 in solid tumors can enhance cytotoxic chemotherapy. *Proc Natl Acad Sci USA*, 2007; 104: 9445-50
- [30] Pan JG, Mak TW. Metabolic Targeting as an Anticancer Strategy: Dawn of New Era? *Sci STKE*. 2007,e14.
- [31] Sugden MC. PDK Deletion. The way to a man's heart disease. *Am J Physiol Heart Circ Physiol*, 2008; 295:H917-H19.
- [32] Roche TE, Baker JC, Yan X, et al. Distinct regulatory properties of pyruvate dehydrogenase kinase and phosphatase isoforms. *Prog Nucleic Acid Res Mol Bio*, 2001; 70:33-75
- [33] Wu P, Peters JM, Harris RA. Adaptive increase in pyruvate dehydrogenase kinase 4 during starvation is mediated by peroxisome proliferator activated receptor alpha. *Biochem Biophys Res Commun*, 2001; 287:391-96.

- [34] Bajato G, Murakami T, Nagasaki M, Tamura N, Harris RA, et al. Downregulation of the skeletal muscle pyruvate dehydrogenase complex in the Otsuka Long-Evans Tokushima fatty rat both before and after the onset of diabetes mellitus. *Life Sci*, 2004; 75(17):2117-2130.
- [35] Karpova T, Danchuk S, Kolobova E, Popov KM. Characterization of the isoenzymes pyruvate dehydrogenase phosphate implications for the regulations of pyruvate dehydrogenase activity. *Biochem Biophys Acta*, 2003; 1652: 126-135.
- [36] Turkan A, Gong X, Peng T, Roche TE. Structural requirement with in the lipoyl domain for the Ca<sup>2+</sup>-dependent binding and activation of pyruvate dehydrogenase phosphatase isoform 1 or its catalyst subunit. *J. Biol Chem*, 2002; 227:14976-985
- [37] Caruso, M, Maitan MA, Bifulco G, et al. Activation and mitochondrial translocation of protein kinase C are necessary for insulin stimulation of pyruvate dehydrogenase complex activity in muscle and liver cells. *J Biol Chem*, 2001; 276:45088-97.
- [38] Huang HM, Zhang H, Xu H, Gibson GE Inhibition of the dehydrogenase complex alters mitochondrial function cellular calcium regulation. *Biochem Biophys Acta*, 2003; 1637: 119-26.
- [39] Piccinini M, Mostert M, Alberto G, Ramondetti C, Rosa F. Novi, et al. Down-regulation of pyruvate dehydrogenase phosphate in obese subjects is a defect signals insulin resistance. *Obes Res*, 2005; 13: 678-86.
- [40] Robinson BH, MacKay N, Petrova-Benedict R, Ozalp I, Coskun T, et al. Defects in the E2 lipoyl transacetylase and the X-lipoyl containing component of the pyruvate dehydrogenase complex in patients with lactic acidemia. *J Clin Invest*, 1990; 85(6):1821-24
- [41] Braun S, Berg C, Buck S, Gregor M, Kelin R. Catalytic domain of PDC-E2 contain epitopes recognized by antimitochondrial antibodies in primary biliary cirrhosis." *W J Gastro. WJG*, 2010; 16(8): 973-81.
- [42] Mackay IR, Whittingham SF, Fida S et al. The peculiar autoimmunity of primary biliary cirrhosis. *Immunol. Rev*; 2000; 174: 26-37.
- [43] O'Brien C, Joshi S, Feld JJ, Guindi M, Dienes HP, et al. Long-term follow up of anti-mitochondrial antibody-positive autoimmune hepatitis. *Hepatology (Baltimore, Md.)* 2008; 48(2): 550-56.
- [44] De kok A, Hengeveld AF, Martin A, Westphal AH. The pyruvate dehydrogenase multi-enzyme complex from Gram-negative bacteria. *Biochem Biophys Acta*, 1998; 1385(2):353-366
- [45] Chuang DT, Shih VE, Scriver CR, Beaudet AL, Sly WS, Velle D, Childs B, Kinzler KW, Vogelstein B. Maple Syrup urine disease (branched-chain ketoaciduria). In the metabolic and the molecular bases of inherited disease. 2001;(2). New York: McGraw-Hill, 1971-2005.

- [46] Odievre M-H, Chretien D, Munnich A, Robinson BH, Dumoulin R, Masmoudi S, Kadhom N, Rotig A, Rustin P, Bonnefont J-P. A novel mutation in the dihydrolipoamide dehydrogenase E3 subunit gene (DLD) resulting in an atypical form of  $\alpha$ -ketoglutarate dehydrogenase deficiency. *Hum Mut*, 2005.
- [47] B Melegh, G Skuta, L Pajor, G Hegedus, B Sumegi. Autoantibodies against subunits of pyruvate dehydrogenase and citrate synthase in a case of paediatric biliary cirrhosis. *Gut*, 1998; 42:753–56
- [48] Zhou ZH, McCarthy DB, O'Connor CM, Reed LJ, Stoops JK. The remarkable structural and functional organization of the eukaryotic pyruvate dehydrogenase complexes. *Proc Natl Sci USA*, 2001; 98(26):14802-07.
- [49] McCartney RG, Rice JE, Sanderson SJ, Bunik V, Lindsay H, et al. Subunit interactions in the mammalian  $\alpha$ -ketoglutarate dehydrogenase complex. Evidence for direct association of the  $\alpha$ -ketoglutarate dehydrogenase and dihydrolipoamide dehydrogenase components. *J. Biol. Chem*, 1998; 273(37):24158–64.
- [50] Mainul Islam, Wallin R, Wynn R, Myra Conway M, Fujii H, et al. A Novel Branched-chain Amino Acid Metabolon Protein-Protein Interactions In a Supramolecular Complex. *J Biol Chem*, 2007; 282(16): 11893–903
- [51] Parham RN. Swinging arms and swinging domains in multifunctional enzymes: catalytic machines for multistep reactions. *Annu Rev Biochem*, 2000; 69, 961-1004.
- [52] Shi Q, Karuppagounder SS, Xu H, Pechman D, Chen H, et al. Responses of the mitochondrial  $\alpha$ -ketoglutarate dehydrogenase complex to thiamine deficiency may contribute to regional selective vulnerability. *Neurochem Int*, 2007; 50(7-8):921-31.
- [53] Fries M, Jung HI, Parham RN. Reaction mechanism of the heterotetrameric ( $\alpha_2\beta_2$ ) E1 component of 2-oxo acid dehydrogenase multienzyme complex. *Biochemistry*, 2003; 42(23): 6996-02.
- [54] Szabo P, Cai X, Ali G, Blass JP. Localization of the gene (OGDH) coding for the E1 component of the  $\alpha$  ketoglutarate dehydrogenase complex to chromosome 7p13-p11.2. *Genomics*, 1994; 20(2): 324-6.
- [55] Koike K. The gene encoding human 2-oxoglutarate dehydrogenase: structural organization and mapping to chromosome. *Gene*, 1995; 159(2), 261-66.
- [56] Koike K. Cloning, structure, chromosomal localization promoter analysis of human 2-oxoglutarate dehydrogenase gene. *Biochem Biosphy Acta*, 1998; 1385(2): 373-84.
- [57] Scheu KFR, and Blass JP. The  $\alpha$ -ketoglutarate dehydrogenase complex. *Oxidative/energy metabolism in Neurodegenerative Disorders*, 1999; 893:61-78.
- [58] Jun Li, Mischa Machius, Jacinta L. Chuang, R. Max Wynn, and David T. Chuang. The Two Active Sites in Human Branched-chain Keto Acid Dehydrogenase Operate Inde-

- pendently without an Obligatory Alternating-site Mechanism. *J Biol Chem*, 2007; 282(16): 11904–913
- [59] Li J, Wynn, RM, et al. Cross-talk between thiamin diphosphate binding and phosphorylation loop conformation in human branched-chain alpha-keto acid decarboxylase/dehydrogenase. *J Biol Chem*, 2004; 279: 32968-78.
- [60] Nakano K, Takase C, Sakamoto T, Ohta S, Nakagawa S, et al. An unsplitted cDNA for human dehydrolipoamide succinyltransferase: characterization and mapping of the gene to chromosome 14q24.2-q24.3. *Biochem Biophys Res Commun*, 1993; 192(2): 527-33.
- [61] Scherer SW, Otulakowski G, Robinson BH, Tsui LC. Localization of the human dihydrolipoamide dehydrogenase gene (DLD) to 7q31..q32. *Cytogenet Cell Genet*, 1991; 56(3-4):176-177.
- [62] De kok A, Hebgeveld AF, Martin A, Westphal AH. The pyruvate dehydrogenase multi-enzyme complex from Gram-negative bacteria. *Biochem Biophys Acta*, 1998; 1385(2):353-366
- [63] Tretter L, Adam-Vizi V. Alpha ketoglutarate dehydrogenase: a target and generator of oxidative stress. *Philos Trans R Soc Lond B Biol Sci*, 2005; 360: 2335-45.
- [64] Donald Voet, Judith G. Voet, charlotte W. Pratt, 1999. *Fundamentals of Biochemistry*. John Wiley & sons, Inc Voet & voet.
- [65] Strumilo S. Short term regulation of the alpha ketoglutarate dehydrogenase complex by energy-linked and some other effectors. *Biochemistry*, 2005;70: 726-729.
- [66] Gibson GE, Park LCH, Sheu KFR, Blass JP, Calingasan NY. *Neurochem Int*, 2000;36: 97-112.
- [67] Shi Q, Risa O, Sonnewald U, Gibson GE. Mild reaction in the activity of the alpha ketoglutarate dehydrogenase complex elevates GABA shunt and glycolysis. *J Neurochem*, 2009;109: 214-221.
- [68] Shi Q, Karuppagounder SS, Xu H, Pechman D, Chen H, Gibson GE. Responses of the mitochondrial alpha-ketoglutarate dehydrogenase complex to thiamine deficiency may contribute to regional selective vulnerability. *Neurochem Int*, 2007;50(7-8): 921-31.
- [69] Des Jardins, Roger. F. Butterworth. Role of mitochondrial dysfunction and oxidative stress in the pathogenesis of selective neuronal loss in Wernickes encephalopathy. *Mol Neurobiol*, 31: 1-3, 17-25
- [70] Mastrogiacomo, LaMarche J, Do S, Lindsay G, Bettendorff L, et al. Immunoreactive Levels of  $\alpha$ -ketoglutarate Dehydrogenase Subunits in Friedreich's Ataxia and Spinocerebellar Ataxia Type 1. *Neurodegeneration*, 1996;5(1): 27-33.
- [71] Kumar MJ, Nicholls DG, Andersen JK. Oxidative alpha ketoglutarate dehydrogenase inhibition via subtle elevations in monoamine oxidase B levels results in loss of spare

- respiratory capacity: implications for parkinson's disease. *J Boil Chem*, 2003;278: 46432-439.
- [72] Huang HM, Zhang H, Xu H, Gibson GE "Inhibition of the dehydrogenase complex alters mitochondrial function cellular calcium regulation." *Biochem Biophys Acta*, 2003;1637: 119-126.
- [73] Habelhah H, Laine A, Erdjument Bromage H, Tempst P, Gershwin ME, et al. Regulation of 2-oxoglutarate (alpha ketoglutarate) dehydrogenase stability by the RING finger ubiquitin ligase siah. *J Biol Chem*, 2004;279: 53782-788
- [74] Abboud M, Alexander D., Najjar S. Diabetes mellitus, thiamine-dependentmegaloblastic anemia, and sensorineural deafness associated with deficient  $\alpha$ -ketoglutarate dehydrogenase activity,*J Paeds*; 107(4): 1A-28A.
- [75] Zubay G.*Biochemistry*.1983.Addison-Wesley Publishing Company,Inc.
- [76] Christopher K, Mathews KE, Holde V, Kevin GA: *The Pentose Phosphate Pathway Biochemistry* 3rd edition, 511-20.
- [77] Antje Krüger and Markus Ralser. The pentose phosphate pathway is a metabolic redox sensor and regulates transcription during the anti-oxidant response. *Sci Signaling*, 2011;4(167):pe17
- [78] Seckl JR, Walker BR. Minireview: 11beta-hydroxysteroid dehydrogenase type 1-a tissue-specific amplifier of glucocorticoid action. *Endocrinology*,2001;142 (4): 1371-76.
- [79] ImmunologyatMCG1/cytotox <http://lib.mcg.edu/esimmuno/ch/cytotox.htm>
- [80] Cappadoro M, Giribaldi G, O'Brien E, et al. Early phagocytosis of glucose-6-phosphate dehydrogenase (G6PD)-deficiency erythrocytes parasitized by plasmodium falciparum may explain malaria protection in G6PD deficiency. *Blood*,1998 ;92(7): 2527-34.
- [81] Schafer ZT, Grassian AR, Song L, Jiang Z, Gerhart-Hines Z, Irie HY, Gao S, Puigservier P, Brugge JS: Antioxidant and oncogene rescue of metabolic defects caused by loss of matrix attachment. *Nat*, 2009;461:109-113
- [82] Wang J, Yi J. Cancer cell killing via ROS: to increase or decrease,that is the question. *Cancer Biol Ther*, 2008;1875-84.
- [83] Vafa O, Wade M, Kern S, Beeche M, Pandita TK, Hampton GM, Wahl GM: c-Myc can induce DNA damage, increase reactive oxygen species, and mitigate p53 function: a mechanism for oncogene-induced genetic instability. *Mol Cell*, 2002, 9:1031-44.
- [84] Trachootham D, Alexandre J, Huang P: Targeting cancer cells by ROS-mediated mechanisms: a radical therapeutic approach? *Nat Rev Drug Discov*,2009, 8:579-591.

- [85] Ishikawa K, Takenaga K, Akimoto M, Koshikawa N, Yamaguchi A, Imanishi H, Nakada K, Honma Y, Hayashi J: ROS-generating mitochondrial DNA mutations can regulate tumor cell metastasis. *Science*, 2008; 320:661-64.
- [86] DeBerardinis RJ, Mancuso A, Daikhin E, Nissim I, Yudkoff M, Wehrli S, Thompson CB: Beyond aerobic glycolysis: transformed cells can engage in glutamine metabolism that exceeds the requirement for protein and nucleotide synthesis. *Proc Natl Acad Sci USA*, 2007; 104:19345-350
- [87] Kochetov, Sevpstyanova IA: Binding of the coenzyme and formation of the transketolase active center. *JUBMB Life*, 2005; 57 (7): 491-97
- [88] Lindquist, G Schneider, U Ermler and M Sundstrom. Three dimensional structure of transketolase, a thiamine diphosphate dependent enzyme, at 2.5 Å resolution. *EMBO J*, 1992; 11(7): 2373-79.
- [89] McCool BA, Plonk SG, Martin PR Singleton CK. Cloning of human transketolase cDNAs and comparison of the nucleotide sequence of the codon region in wernicke-Korsakoff and non-wernicke-Korsakoff individuals. *J Biol Chem*, 1993; 268 (2): 1397-04.
- [90] Abedinia M, Lapsys NM, Layfield R, Jones SM, Nixon PF, Mattick JS. Nucleotide and predicted amino acid sequence of a cDNA clone encoding part of human transketolase. *Biochem Biophys Res Commun*, 1992; 183 (3): 1159-66.
- [91] Lapsys NM, Layfield R, Baker E, Callen DF, Sutherland GR. Chromosomal location of the human transketolase gene. *Cytogenet Cell Genet*, 1992; 61(4): 274-75
- [92] Coy JF, Dressler D, Wilde J, Schubert P: Mutations in the transketolase-like gene TKTL1: clinical implications for neurodegenerative disease, diabetes and cancer. *Clin Lab*, 2005; 51(5-6): 257-73.
- [93] Coy JF, Dubel S, Kioschis P, Thomas K, Micklem G. "Molecular cloning of tissue-specific transcripts of a transketolase-related gene: implications for the evolution of new vertebrate genes." *Genomics*, 1996; 32(3): 309-16. : 8838793
- [94] Weimann S, weil B, wellenreuther R, Gassenhuber J, Glassl S. Toward a catalog of human genes and Proteins: sequencing and analyzing of 500 novel complete protein coding human cDNAs. *Genome Res*, 2001; 11(3): 422-35.
- [95] Booth, C. K., & Nixon, P. F. Reconstitution of holotransketolase is by a thiamin-diphosphate-magnesium complex. *Eur J Biochem*, 1993; 218: 261-65.
- [96] Cristian Obiol-Pardo and Jaime Rublo-Martines. Homology modeling of human transketolase: description of critical sites useful for drug design and study of the co-factor binding mode. *J Mol Graph Model*, 2009; 27: 723-34.

- [97] Nikkola, M., Lindqvist, Y., and Schneider, G. Lindqvist, Y., and Schneider, G. Refined Structure of Transketolase from *Saccharomyces cerevisiae* at 2.0 Å resolution (1994) *J Biol Chem.*, 238, 387-04.
- [98] M. Reynen, H. Sahm, Comparison of the structural genes for pyruvate decarboxylase in different *Zymomonas* strains, *J. Bacteriol*, 1988; 170: 3310-3313
- [99] Hawkins, C. F., Borges, A., and Perham, R. N. A common structural motif in thiamin pyrophosphate-binding enzyme. *FEBS Lett*, 1989; 255: 77-82
- [100] Kochetov GA, Sevostyanova IA. Functional non equivalence of transketolase active centers. *IUBMB Life*. 2010 Nov;62(11):797-802
- [101] James J.WangL. Aspartate 155 of human transketolase is essential for thiamine diphosphate-magnesium binding, and cofactor binding is required for dimer information. *Biochimica et Biophys Acta*, 1997;1341:165-72.
- [102] Martin, P.R., Pekovich, S.R., McCool, B.A., and Singleton C.K. Molecular Genetics of transketolase and its role in the pathogenesis of the Wernicke-Korsakoff syndrome *Metab Br Dis*, 1995;10: 189-94
- [103] Traviesa, D. C. Magnesium deficiency: a possible cause of thiamine refractoriness in Wernicke-Korsakoff encephalopathy. *Journal Neurol Neurosurg Psych*, 1974;37, 959-962.
- [104] Coy JF, Dressler D, Wilde J, Schubert P. Mutations in the transketolase-like gene TKTL1: clinical implications for neurodegenerative disease, diabetes and cancer. *Clin Lab*, 2005;51(5-6):257-73.
- [105] Hu LH, Yang JH, Zhang DT, Zahng S, Wang L, Cai PC, Zheng JF, Huang JS: The TKTL1 gene influences total transketolase activity and cell proliferation in human colon cancer LoVo cells. *Anticancer Drugs*, 2008: 18: 427-33.
- [106] Zerilli M, Amato MC, Martorana A. Increased expression of transketolase-like-1 in papillary thyroid carcinomas smaller than 1.5 cm in diameter is associated with lymph-node metastases. *Cancer*, 2008;113:936-44.
- [107] Kohrenhagen N, Voelker HU, Suchmidt M, Kapp M, Lrockenberger M, et al. Expression of transketolase-like 1 (TKTL1) and p-Akt correlates with the progression of cervical neoplasia. *Mol cell Proteomics*, 2008;7: 2337-2349.
- [108] Krockenberger, Honig A, Rieger L. Transketolase-like 1 expression correlates with subtypes of ovarian cancer and the presence of distant metastases. *Int J Gynecol Cancer*, (2007);17: 101-106.
- [109] Foeldi M, Stickeler E, Bau L, Kretz O, Watermann D, et al. Transketolase protein TKTL1 overexpression: A potential biomarker and the therapeutic target in breast cancer. *Oncol Rep*, 2007;17: 841-45.

- [110] Zhang W L, Zhou YH, L. Xiao et al., "Biomarkers of nasopharyngeal carcinoma," *Progress in Biochemistry and Biophysics*, 2008;35(1) : 7–13.
- [111] Voelker H U, Hagemann C, Coy J. (2008) Expression of transketolase-like 1 and activation of Akt in grade IV glioblastoma as compared with grades II and III astrocytic gliomas. *Am J Clin Pathol*, 130:50-57.
- [112] Lovato L, Cianti R, Gini B, Marconi S, Bianchi L, et al. : Transketolase and 2',3'-cyclic-nucleotide 3' -phosphodiesterase type I isoforms are specially recognized by IgG autoantibodies in multiple sclerosis patients. *Mol cell proteomics* 2008; 7(12):2337-49
- [113] Thomas AA, Le Huerou Y, De Meese J, Gunawardana I, Kaplan T, et al. Synthesis in Vitro and in Vivo activity of thiamine antagonist transketolase inhibitors. *Bioorg Med Chem Lett*, 2008;18: 2206-10.
- [114] Hammes HP, Du X, Edelstein D: Benfotiamine blocks three major pathways of hyperglycemic damage and prevents experimental diabetic retinopathy. *Nat Med*, 2003; 9:294-99.
- [115] Goodman Gillman. *Insulin, Oral Hypoglycaemic agents and the endocrine pancreas. The Pharmacological Basis of Therapeutics Tenth Edition*, 2006;61:1686-10.
- [116] Katzung B.G. *Basic and clinical pharmacology Eighth edition. Pancreatic Hormones and Anti Diabetic Drugs*. 2004;711-34.
- [117] Schwartz, Theodore B. Meinert, Curtis L. The UGDP Controversy: thirty-four years of contentious ambiguity laid to rest. *Perspectives in Biology and Medicine*, 2004; 47(4) : 564-74
- [118] Starlix package insert. East Hanover, NJ, Novartis Pharmaceuticals Corporation, Dec. 2000.
- [119] Holstein A, Plaschke A, Egberts EH. Lower incidence of severe hypoglycemia in type 2 diabetic patients treated with glimepiride versus glibenclamide. *Diabetologia* 43: A40.
- [120] Volk A, Maerker E, Rett K, Haring HY, Overkamp D1, et al. : Effects on peripheral insulin sensitivity. *Diabetologia*, 2000;43:A39
- [121] Campbell RK. Glimperipride role of a new sulfonylurea in the treatment of type 2 diabetes mellitus. *Ann Pharmacother*, 1998;32:1044-52
- [122] Hollander PA, Schwartz SL, Gatli MR, Haas S, Zheng H, et al. Natenglinide but not glyburide, selectively enhances early insulin release and more effectively controls post meal glucose excursions with less total insulin exposure. *Diabetes*, 2000;49:447
- [123] Katzung B.G. *Basic and Clinical pharmacology Eighth edition. Pancreatic Hormones and Anti Diabetic Drugs*, 2009;727-47.

- [124] Goodman Gillman. Insulin, Oral Hypoglycaemic agents and the the pharmacology of endocrine pancreas. The Pharmacological Basis of Therapeutics Eleventh Edition, 2006;60:1686-10.
- [125] Brown&Bennet. Diabetes mellitus, insulin,oral anti diabetes agents,obesity.Clinical Pharmacology Ninth Edition. 2004;8:679-695
- [126] Lebovtiz HE. Alpha glucosidase inhibitors as agents in the treatment of diabetes. Diabetes Rev, 1998;6: 132.
- [127] Chiasson JL, et al. Acarbose for prevention of type 2 diabetes mellitus: the STOP-NIDDM randomized trial. Lancet, 2002;359: 2072.
- [128] Holst JJ, Gromada J. Role of incretin hormones in the regulation of insulin secretion in diabetic and nondiabetic humans. Am. J. Physiol Endocrinol Metab, 2004;287:E1953-59.
- [129] Deacon CF. Circulation and degradation of GIP and GLP-1. Horm Metab Res, 2004;36:761-65
- [130] Ehses JA, Pelech SL, Pederson RA, and McIntosh CH. Glucose-dependent insulinotropic polypeptide activates the Raf-Mek1/2-ERK1/2 module via a cyclic AMP/cAMP-dependent protein kinase/Rap1-mediated pathway. J Biol Chem,2002;277: 37088-097.
- [131] Trümper A, Trümper K, and Hörsch D. Mechanisms of mitogenic and antiapoptotic signaling by glucose-dependent insulinotropic polypeptide in beta(INS-1)-cells. J Endocrinol, 2002;174: 233-46
- [132] Eckel RH, Fujimoto WY, Brunzell JD: Gastric inhibitory polypeptide enhanced lipoprotein lipase activity in cultured preadipocytes. Diabetes, 1979;28 :1141-42.
- [133] Beck B, Max JP. Gastric inhibitory polypeptide enhancement of the insulin effect on fatty acid incorporation into adipose tissue in the rat. Regul Pept, 1983;7:3-8.
- [134] Oben J, Morgan L, Fletcher J, et al Effect of the entero-pancreatic hormones, gastric inhibitory polypeptide and glucagon-like polypeptide-1 (7-36) amide, on fatty acid synthesis in explants of rat adipose tissue. J Endocrinol 1991;130:267-72.
- [135] Gault VA, Irwin N, Green BD, McCluskey JT, Greer B, Bailey CJ, Harriott P, O'Harte FP, Flatt PR: Chemical ablation of gastric inhibitory polypeptide receptor action by daily (Pro3)GIP administration improves glucose tolerance and ameliorates insulin resistance and abnormalities of islet structure in obesity-related diabetes. Diabetes, 2005;54 :2436 -46.
- [136] Bailey CJ, Gross JL, Pieters A, Bastien A, List JF. Effect of dapagliflozin in patients with type 2 diabetes who have inadequate glycaemic control with metformin: a randomized, double-blind, placebo-controlled trial. Lancet,2010;375(9733):2223-33.

- [137] Traish AM, Saad F, Guay A. The dark side of the testosterone deficiency: II. Type 2 diabetes and insulin resistance. *J Androl*, 2009;30(1):23-32.
- [138] Zitzmann M. Testosterone deficiency, insulin resistance and the metabolic syndrome. *Nature Reviews Endocrinology*, 2009;5(12): 673-81.
- [139] Makoto Hiromura et al. Glucose lowering activity by oral administration of bis (allixin) oxidovanadium (IV) complex in streptozotocin-induced diabetic mice and gene expression profiling in their skeletal muscles. *Metallomics*, 2009.
- [140] Yuriko Sanches-Zamora, Luis I Terrazas, Alonso Vilches-Flores, Emmanuel Leal, Imelda Juarez, et al. Macrophage migration inhibitory factor is a therapeutic target in treatment of non-insulin dependent diabetes mellitus. *The FESEB Journal*, 2010.
- [141] Frangioudakis G, Garrard J, Raddatz K, Nadler J.L, Mitchell T.W, C. Schmitz-Peiffer. Saturated and n-6 polyunsaturated-fat diets each induce ceramide accumulation in mouse skeletal muscle: Reversal and improvement of glucose tolerance by lipid metabolism inhibitors. *Endocrinology*, 2010;151(9): 4187.
- [142] Zandong Yang, University of Virginia Health System. Drug Shows Promise in Preventing Type 1 Diabetes. *ScienceDaily*, 2003.
- [143] Takeshi Ogihara, Jen-Chieh Chuang. Liver X Receptor Agonists Augment Human Islet Function through Activation of Anaplerotic Pathways and Glycerolipid/Free Fatty Acid Cycling. *J Biol Chem*, 2010;285(8): 5392-04.
- [144] Aiello LP, Cahill MT, Cavallerano JD. Growth factors and protein kinase C inhibitors as novel therapies for the medical management diabetic retinopathy. *EyeSci J Roy Coll Ophthalmol*, 2004;18:117-125.
- [145] Adams TD, Gress RE, Smith SC, et al. Long-term mortality after gastric bypass surgery. *N E J M*, 2007;357(8):753-61.
- [146] Cohen RV, Schiavon CA, Pinheiro JS, Correa JL, Rubino F. Duodenal-jejunal bypass for the treatment of type 2 diabetes in patients with body mass index of 22-34Kg/m<sup>2</sup>: a report of 2 cases: *Sur Obes& Related Dis*, 2007;3(2): 195-97
- [147] Vasonconcelos, Alberto. "Could type 2 diabetes be reversed using surgery?" *New scientist*, 2007;2619: 11-13.
- [148] Cuningham JJ. The glucose/insulin system and vitamin C: implications in insulin dependent diabetes mellitus. *J. Am Coll Nutr*, 1998;17:105-8.
- [149] Chaudhry PS, Cabrera J, Juliani HR, Varma SD. Inhibition of human lens aldose reductase by flavonoides, sulindac and indomethacin. *Biochem Pharmacol*, 1983;32:1995-98.
- [150] Kunisaki M, Bursell SE, Clermont AC. Vitamin E prevents Diabetes induced abnormal retinal blood flow via the diacylglycerol protein kinase c pathway. *Am J Physiol*, 1995;269: E239-E46.

- [151] Keegan A, Walbank H, Cotter MA, Cameron NE. Chronic vitamin E treatment prevents defective endothelium-dependent relaxation in diabetic rat aorta. *Diabetologia*, 1995; 38:1475-78.
- [152] Bursell SE, Clermont AC, Aiello LP, Aiello LM, Schlossman DK, et al. High dose vitamin E supplementation normalizes retinal blood flow and creatinine clearance in patients with type 1 diabetes. *Diabetes Care*, 1999; 22:1245-51.
- [153] Tosiello L, (1996) Hypo magnesemia and diabetes mellitus: A review of clinical implications, *arch Intern Med*;156:1143-48.
- [154] Mooradian AD, Failla M, Hoogwerf B. Selected vitamins and minerals in diabetes (technical review). *Diabetes Care*, 1994; 17:464-79.
- [155] Nair AR, Biju Mp, Paulose CS. Effect of pyridoxine and insulin administration on brain glutamate dehydrogenation activity and blood glucose control in streptozotocin-induced diabetic rats. *Biochem biophys Acta*, 1998;1381:351-54.
- [156] Ho E, Chen G, Bray TM. Supplementation of N-acetylcysteine inhibits NF $\kappa$ B activation and protects against alloxan-induced diabetes in CD-1 mice. *FASEB*, 1999;13:1845-54.
- [157] Poucheret P, Verma S, Grinpas MD. Vanadium and Diabetes. *Mol Cell Biochem*, 1998;188:73-80.
- [158] Cam MC, Rodrigues B, McNeill JH. Distinct Glucose lowering and Beta cell protective effects of vanadium and food restriction in streptozotocin diabetes. *Eur J Endocrinol*, 1999;141: 546-54.
- [159] Rudich A, Tirosh A, Potashnik R, Khamaisi M, Bashan N. Lipoic acid protects against oxidative stress induced impairment in insulin stimulation of protein kinase B and glucose transport in 3T3-L1 adipocytes. *Diabetologia*, 1999;42:949-57.
- [160] Mukherjee B, Anbazhagan S, Roy A, Ghosh R, Chatterjee M. Novel. Implications of the potential role of selenium on antioxidant status in streptozotocin-induced diabetic mice. *Biomed Pharmacother*, 1998;52: 89-95.
- [161] Han DH, Hasen PA, Chen MM, Holloszy JO. DHEA treatment reduces fat accumulation and protects against insulin resistance in male rats. *J Gerontol A Biol Sci Med Sci*, 1998;53:B19-24.
- [162] Provisional report by UK Expert Group on Vitamins and Minerals. August 2002. (<http://www.food.gov.uk/foodindustry/Consultations/ukwideconsults/evmconsulteg>). Safe Upper Levels of Vitamins and Minerals, Expert Group on Vitamins and Minerals, 2003.
- [163] Combs, G.F. Jr. *The vitamins: fundamental aspects in nutrition and health*. 3<sup>rd</sup> edition. Ithaca, NY: Elsevier academic Press (2008).

- [164] Mahan LK, Escott-Stump S, Krause's food, nutrition, and diet therapy. 10<sup>th</sup> ed. Philadelphia: W.B. Saunders Company, 2000.
- [165] Dutta B, Huang W, Molero M, Kekuda R, Leibach FH, et al. Cloning of the human thiamine transporter, a member of the float transporter family. *J Biol Chem*, 1999;274: 31925-29.
- [166] Matherly LH. Molecular and the cellular biology of the human reduced folate carrier. *Progr Nucleic Acid Res Mol Biol*, 2001;67:131-62.
- [167] Zhao RB, Gao F, Wang YH, Diaz GA, Gelb BD, et al. Impact of the reduced folate carrier on the accumulation of active thiamine metabolites in murine leukemia cells. *J Biol Chem*, 2001; 276:1114-18.
- [168] Zhao RB, Gao F and Goldman ID. Reduced folate carrier transports thiamine monophosphate: an alternative route for thiamine delivery into mammalian cells. *Am J Physiol Cell Physiol*, 2002; 282:C1512-C17
- [169] Said HM, Balamurugan K, Subramanian VS, and Marchant JS. Expression and functional contribution of hTHTR-2 in thiamine absorption in human intestine. *Am J Physiol. Gastrointest. Liver Physiol*, 2004;286: G491-G98.
- [170] Reidling JC, Said HM. In vitro and in vivo characterization of the minimal promoter region of the human thiamin transporter SLC 19A2. *Am J Physiol Cell Physiol*, 2003;285:C633-C41.
- [171] Balamurugan K, and Said HM. Functional role of specific amino acid reduces in human thiamine transporter SLC19A2: mutational analysis. *Am. J. Physiol-Gastrointest. Liver Physiol*, 2002;283: G37-G43.
- [172] Fleming JC, Tertaglini E, Steinkamp MP, Schordret DF, Chon N. The gene mutated in thiamine-responsive anaemia with diabetes and deafness (TRMA) encodes a functional thiamine transporter. *Nat Gen*, 1999;22:305-12.
- [173] Eudy JD, Spiegelstein O, Barber RC, Wlodarczyk BJ, Talbot J. Identification and characterization of the human and mouse SLC19A3 gene: A novel member of the reduced folate family of micronutrient transporter gene. *Molec. Gene Metab*, 2000;71: 581-590.
- [174] Trippet TM, Garcia S, Manova K, Mody R, Cohen-Gould L. Localization of a human reduced folate carrier protein in the mitochondrial as well as the cell membrane of the leukemia cells. *Cancer. Res*, 2001;61:1941-47.
- [175] Babaei-Jadidi R, Karachalias N, Ahmed N, Battah S, Thornalley PJ. Prevention of incipient diabetic nephropathy by high-dose thiamine and benfotiamine. *Diabetes*, 2003;52:2110-20.
- [176] Chin E, Zhou J and Bondy C. Anatomical and development patterns of facilitative glucose transporter gene-expression in the rat kidney. *J.Clin. Invest*, 1993;91: 1810-15.

- [177] Tallaksen C. M., Bohmer T., Karlsen J. and Bell H. Determination of thiamin and its phosphate esters in human blood, plasma, and urine. *Meth. Enzymol*, 1997;279, 67–74.
- [178] Gastaldi G, Coya E, Verri A, Laforenza U, Faellin A and Rindi G. Transport of thiamine in rat renal brush border membrane vesicles. *Kidney Int.* 2002;57: 2043-54.
- [179] Morshed KM, Ross DM, and McMartin KE. Folate transport proteins mediate the bi-directional transport of 5-methyltetrahydrofolate in cultured human proximal tubule cells. *J Nutr*, 1997;127: 1137-47.
- [180] Rindi G and Laforenza U. Thiamine intestinal transport and related issues: recent aspects. *PSEBM*, 2000;224:246-255.
- [181] Smeets, E.S.J., Muller, H., and Wael, J.D. X. A NADH-transketolase dependent assay in erythrocyte hemolysate. *Clin. Chim. Acta.* 2000;33: 379-86.
- [182] Brady JA, Rock CL, And Horneffer MR. Thiamine status diuretic medications and the management of congestive heart failure. *J. Am. Diet. Assoc*, 1995;95: 541-44.
- [183] Thornalley PJ, Babaei-Jadidi R, Al Ali H et al. High prevalence of low plasma thiamine concentration in diabetes linked to marker of vascular disease. *Diabetologia*, 2007;50:2164-70.
- [184] Pekovich SR, Martin PR, Singleton CK. Thiamine deficiency decreases steady-state transketolase and pyruvate dehydrogenase but not  $\alpha$ -ketoglutarate dehydrogenase mRNA levels in three human cell types. *J Nutr*, 1998;128: 683-87.
- [185] Bettendorff L, Peters M, Jouan C, Wins P., Schoffeniels E. Determination of thiamine and its phosphate esters in cultured neurons and astrocytes using an ion-pair reversed-phase high-performance liquid chromatographic method. *Annal. Biochem*, 1991;198(1): 52-59.
- [186] Losa R, Sierra MI, Fernandez A, Blanco D, Buesa JM. Determination of thiamine and its phosphorylated forms in human plasma, erythrocytes and urine by HPLC. *JPBA*, 2005;37(5):1025-29.
- [187] Lu J, Frank EL. Rapid HPLC measurement of thiamine and its phosphate esters in whole blood. *Clin Chem*, 2008;5495:901-06.
- [188] Shabangi M, Sutton JA. Separation of thiamine and its phosphate esters by capillary zone electrophoresis and its application to the analysis of water soluble vitamins. *Journal of Pharma Biomed analysis*, 2005; 38(1): 66-71.
- [189] Barile M, Valenti D, Brizio C, Quagliariello E and Passarella S. Rat liver mitochondria can hydrolyse thiamine pyrophosphate to thiamine monophosphate which can cross the mitochondrial membrane in carrier-mediated process. *FEBS Lett*, 1998;435:6-10.

- [190] Babaei-Jadidi R, Karachalias N, Kupich C, Ahmed N, Thornalley PJ. High dose thiamine therapy counters dyslipidaemia in streptozotocin-included diabetic rats. *Diabetologia*, 2004;47:2235-46.
- [191] Wakabayashi Y. Purification properties of porcine thiamine pyrophosphokinase. *Vitamins*, 1978;52: 223-36.
- [192] Makarchikov AF, Lakaye B, Gulyai IE, Czerniecki J, Coumnas B. Thiamine triphosphate and thiamine triphosphatase activities: from bacteria to mammals. *Cell Molec Life sci*, 2003;60 :1477-88.
- [193] Weber W, Kewitz H. Determination of thiamine in human plasma and its pharmacokinetics. *Eur J Clin Pharmacol*, 1985;28:213-19.
- [194] Ariaey-Nejad MR, Balaghi M, Baker EM, Sauberlich HE. Thiamin metabolism in man. *Am J Clin Nutr*, 1970;23:764-778.
- [195] Tanphaichitr V, Shills ME, Olsen JA, Shike M et al. Thiamin In: Modern nutrition in health and disease. Lippincott Williams & Wilkins, 9<sup>th</sup> ed. 1999. Baltimore.
- [196] University of California Santa Cruz Genome Browser(UCSC) <http://genome.ucsc.edu>.
- [197] Schneider, G., and Lindqvist, Y. Crystallography and mutagenesis of transketolases: Mechanistic implications for enzymatic thiamine catalysis. *Biochem Biosphy Acta*, 1998;1385: 387-98.
- [198] Schellenberger, A. Sixty years of thiamine diphosphate biochemistry. *Biochem Biosphy Acta*, 1998;1385:177-86.
- [199] Cizak EM, Korotchkina LG, Dominiak PM, Sidhu S, and Patel MS. Structural basis for flip-flop action of thiamine pyrophosphate-dependent enzyme relevelated by human pyruvate dehydrogenase. *JBiolChem*, 2003;278:21240-246.
- [200] Sheu KFR, Blass JP. The alpha ketoglutarate complex. *Ann NY Acad Sci*, 1999; 893: 61-78.

