An investigation into the mechanism ofInverse relationship between S.Creatinine and HDL-C In CKD

Abstract

An inverse relationship between the raised Serum creatinine (Cr) and High-density lipoprotein cholesterol (HDL-C) is well known. A raised S.Creatinine / low estimated glomerular filtration rate (eGFR) is a marker of chronic kidney disease (CKD). Besides, e GFR indicates the rate of progression of (CKD) and helps in the staging of CKD. Any relationship involving the raised creatinine or reduced eGFR necessitates the presence of the CKD in the background. While the CKD itself can cause both, the mechanism of an inverse relationship between the two is not clear. Each of the raised creatinine and low HDL-C, have independent risk factors ofeach, but the only common risk factor for both is the sedentary lifestyle. The role of the sedentary lifestyle in the inverse relationship between the raised Cr and low HDL-C is examined. A possible molecular mechanism is being suggested,connecting the four variables- the raised Cr, low HDL-C, the CKD, and the sedentary lifestyle. To this extent, the relevant metabolism of both S creatine and HDL-C are briefly reviewed, as knowledge of the same is intricate to a better understanding of the molecular mechanism proposed.

Keywords

Creatine phosphate, creatine kinase, ABC 1 transporter , , Ubiquitous mitochondria creatine shuttle , High density cholesterol, creatinine , Reverse cholesterol transport .

Introduction

A perusal of the literature reveals that the relationship between the low HDL-C and CKD has been studied from several points of view.

Low HDL-C is reported as an independent predictor of increased renal dysfunction as evidenced by the MDRD study[1]. and the Atherosclerosis Risk in Communities (ARIC) cohort study [2]. Bowe et al., in a retrospective cohort study using the U.S. Veterans Administration (VA) databases, found that low HDL-C was significantly associated with the risk of incident kidney disease and its progression [3]. Low HDL-C levels are associated with the risk of progression of CKD [4]. Individuals with HDL-C concentrations <30 mg/dl had a 10%–20% higher risk for CKD and/or progression of CKD compared with individuals with concentrations≥40 mg/dl [5]. Association between low HDL-C or a high triglyceride to HDL-C ratio and poor kidney function or progression of CKD, Is noted[6,7,8,9].Low levels of high-density lipoprotein cholesterol increase the risk of incident kidney disease and its progression [9]. studies showed that the level of oxidized low-density lipoprotein (LDL) cholesterol increases and high-density lipoprotein (HDL) cholesterol d[ysfunction occurs as kidney function declines and inflammation becomes more pronounced [10]. Low HDL in particular was significantly associated with an increased risk of developing renal dysfunction in men with an initial creatinine level of less than 1.5 mg/dl [11]. CKD is associated with increased plasma triglycerides and very-low-density lipoprotein (VLDL) cholesterol as well as

decreased HDL cholesterol[12,13]. The proteome and lipidome of HDL particles are heavily disturbed not only in the uremic state but also in the very early stages of kidney impairment [14].

A brief review of creatine synthesis, transport into the cell, resynthesis, and degradation to creatinine :

Creatine (Cr) in the form of Creatine phosphate (Cr P),is a quickly replenishable source of energy (ATP), needed for muscle contraction. 95% of the body's creatine stores are found in the skeletal muscle and the remaining 5% is distributed in the brain, liver, kidney, and testes [15]. 95% of total creatine and phosphocreatine stores are found in skeletal muscle, while the remaining is distributed in the blood, brain, testes, and other tissues.[16][17] .The average amount of total creatine stored in the body is approximately 120 mmol/kg of dry muscle mass[18].An average70 kg young male has a creatine pool of around 120-140 g which varies between individuals [19,20].The creatine excreted /day is 1.7 mg [21].The actual reaction catalyzed by adenine guainine amido transferase (AGAT) is the synthesis of guanidinoacetate from arginine and glycine,

This is the rate-limiting step.
AGAT activity in tissues is regulated by

1. Induction by growth hormone[22]. and thyroxine[23].
2. Inhibition of the enzyme by ornithine.
3. Repression of synthesis of the enzyme by creatine [24,25].

2. The guanidinoacetate produced is then combined with *S*-Adenosyl-L-methionine, a reaction catalyzed by (Guanine alanine methyl transferase (GAMT,) to produce creatine and *S*-Adenosyl-L-homocysteine. in exchange for a proton to become guanidinoacetate and renew the catalyst.

S-adenosyl-L-methionine + guanidinoacetate → S-adenosyl-L-homocysteine + creatine.

The creatine, thussynthesized,is transported to the cell through blood. In the cell, the creatine is compartmentalizedinto 3 compartments,- the mitochondria, the cytosol, and the blood. There are two types of mitochondria,the ubiquitous (uMtCK) and the M line of the sarcomere. (sMtck) Creatine Kinase (CK),the enzyme that catalyzes the reverse reaction of creatine to creatine phosphate, is present in both types of mitochondria but plays different roles. In the ubiquitous mitochondria, it is phosphorylated to form creatine phosphate,which is an endergonic reaction and hence depends on the supply of ATP energy.It is transported through the cytosol, into M line mitochondria of the sarcomere, where the reverse reaction occurs ie phosphorylation leading to the breakdown of CrP into Cr, creatine, and Pi. The high-energy pi bong is added to ADP, resulting in ATP formation. The ATP, thus formed is used by the myosin and contractile actin resulting in muscle contraction. reversible conversion between creatine and phosphocreatine, which is coupled to the equilibrium between ATP and ADP, CK helpsmaintain energy homeostasis in tissues. The ATP from the CrP is the immediate source of energy for sustaining the Intermittent exercise like walking, aiming, etc.

The ATP is replenished during the resting phase of the exercise, by a mechanism called " the creatine shuttle".

While the ATP is used up by the contracting muscle, the creatin released above in the M line mitochondria is recycled to creatine phosphate, in the uMtc , which is readily made available in the M line MTC for furnishing ATP, for the next contraction Thus a continuous and uninterrupted supply of energy for carrying out light, Intermittent type of muscular exercise has ensued. During moderately severe and sustained exercise, the energy supplied by the hydrolysis of CrP is not sufficient and hence the energy dependence is on the substrate and oxidative phosphorylation(OX Phos) reaction generating ATP.

The creatine transporters :

The creatine that is synthesized, is transported through the bloodstream and taken up through sodium-dependent creatine transporters by cells that require creatine[26].

Two types of transporters (CrT) are known.

1. Mitochondrial CrT
2. Plasma membraneCrT.

Intracellular compartmentalization of creatine :

This is a crucial factor for the formulation of the proposed mechanism ,as could be seen during the discussion of the same . The three compartments in which the creatine is sequestered are – the blood , the cytosol , and mitochondria .

A huge gradient of Cr, between the blood and cytosol exists. Against this gradient and with the help of Na cl transporter, cr enters the cytosol. About 2/3 of Cr thus entered is converted into phosphocreatine. Pm CrT allows Cr but not Cr P and hence CrP is trapped inside the cell. Since it is not in equilibrium with creatine in the blood, the quantities of creatine and CrP/Cr ratios differ. The mitochondrial CrT allows creatine to be transported into the mitochondria. Since the biological membranes of the cell and its organelles are impervious to both Cr and CrP, the Compartmentation of the 3 pools is complex.

Regulation of the CrT :

intracellular Cr regulates either the number or intrinsic activity of the CrT (Loike et a. [27], the data from both the cell-culture studies [28].and in vivo human experiments [29].Support the regulation of CRT by intracellular creatine.Based on urinary Cr excretion, showed, that the short-term exposure to high extracellular Cr levels, inhibited cellular Cr uptake.High extracellular Cr causes an initial increase in Cr uptake as well as an elevation in intracellular Cr concentration, which in turn, subsequently inhibits Cr uptake by the feeds back inhibition of CrT. Wanget al[30]. showed that this feedback inhibition occurs by reducing the activity of a nonreceptor protein tyrosine kinase, known as a c-Src kinase.

A brief review of HDL-C metabolism :

The HDL is synthesized in the liver as a lipoprotein and phospholipid complex. The cholesterol in excess of the need by cells and the macrophages limning the blood vessels is collected and returned to the liver to be degraded and excreted in the bile. The efflux of the cholesterol from the cells is assisted by two transporter proteins, ABC 1 and ABG 1, the

former transporting, to Apo lipoprotein A1)(apo A1)[31, 32].and the later to HDL[33, 34]. respectively. ABCA1 and ABCG1 both, thus have anti-atherogenic activity, as the [35 36] free cholesterol in HDL is esterified by an enzyme, lecithin acetyltransferase (LACT) to cholesteryl ester and is sequestered into the hydrophobic core of the HDL particles. The enzyme cholesterol esters transferase enzyme exchanges, the cholesteryl ester of HDL, with the triglycerides of the Apo B containing lipoproteins (VLDL,iDL, and LDL). The HDL particles are either transported by a direct pathway to steroidogenic tissues like Testis, ovarian adrenals, etc. and are removed by the Scavenger cell receptors of HDL (SR-B1), which mediate the selective uptake of cholesterol from HDL, or by indirect pathway to the liver where it is degraded by the hepatic lipase enzyme and excreted into the bile.

Discussion

Some of the mechanisms suggested in the literature causing low levels of HDL-C are summed below.

- Gene deletion of Apo a1/APOA1 results in extremely low levels ofHDL-C in mice [37]. and in humans [38].
- Gene deletion of Apoa2 in mice markedly reduces HDL-C levels [39]. suggesting that apoA-II is also required for normal HDL.
- LCAT deficiency in humans [40]. and in mice [41] causes markedly reduced levels of HDL-C and rapid catabolism of apoA-I and apoA-II[42].
- Endothelial lipase (EL) in mice causes a reduction in HDL-C levels [44]. and also reduces apoA-I levels because of increased catabolism primarily via the kidneys [45]
- The activity of lipoprotein lipase is inversely associated with HDL-C levels [46].
- Mice lacking PLTP have a significant reduction in HDL-C levels [47].
- Hepatic overexpression of SR-BI in mice markedly increases hepatic HDL cholesterol uptake and reduces plasma HDL-C levels [48].
- Rodents naturally lack CETP, and when engineered to express it, they experience a substantial reduction in HDL-C levels [49].
- The proof that CETP is important for human HDL metabolism came from the discovery of humans genetically deficient in CETP [50,51].
- enhanced activity of cholesteryl ester transfer protein (CETP)[52].
- LCAT deficiency and the lack of LCAT-mediated cholesterol esterification results in accelerated ApoA-I catabolism [53].
- Mice that lack ABCA1 specifically in the liver have HDL-C levels that are reduced by 80% [54]. and mice that lack ABCA1 in the intestine have a 30% reduction in HDL-C [55].
- The level of oxidized low-density lipoprotein (LDL) cholesterol increases and high-density lipoprotein (HDL) cholesterol dysfunction occurs as kidney function declines and inflammation becomes more pronounced [56,57].

Role of sedentary lifestyle:

- Several previous studies have reported the associations of sedentary behavior and physical activity with renal function[58- 61]. Insufficient moderate- to vigorous-

intensity physical activity (MVPA) is known to be associated with the onset of renal dysfunction [62].

- evidence suggests that sedentary behavior is defined as any waking behavior characterized by an energy expenditure ≤1.5 metabolic equivalents, such as television viewing time[63]. maybe another risk factor for renal dysfunction [64,65].
- patients with CKD should undertake moderate physical activity for at least 30 min five times per week, in line with recommendations for the general population[66].
- sedentary behavior (detrimentally) and physical activity (beneficially) may affect renal function and replacing sedentary behavior with MVPA may benefit renal health in older adults [67].

The proposed mechanism :

- The proposed mechanism of an inverse relationship between raised Cr and low HDL-C envisages a competition for ATP, between the ABC 1/ABG 1 transporters involved in the efflux of cholesterol into the HDL and synthesis of CrP by Creatine kinase enzyme both of which are ATP dependent and ATP driven.
- There is no competition for ATP when CrP in the sarcolemmal mitochondria is hydrolyzed, as the reaction does not need ATP, because the reaction itself is (exergonic).
- In the resting physiological state of the skeletal muscles, the source of energy is the stored ATP in the cells of myofibrils.When Intermittent light exercise is indulged in, the stored energy(ATP), supplemented by the ATP produced by the hydrolysis of Cr P, is the immediate source of energy for the muscles to work. The combined source of energy is called the " phosphagen system". which lasts for less than ten seconds, but it is quickly replenished by means of the "creatine shuttle", which creates a buffer stock of CrP.
- The hydrolysis of CrP occurs when the muscle at work needs supplemented energy as in Intermittent exercise with periods of rest. During moderate to severe sustained exercise The supplementation of ATP from glycolysis takes a bit longer time and along with energy released by OX Phos , is utilized.
- Accordingly, the stored ATP is freely available for the ABC transporter's use, when CrP is not synthesized,(ie. During the rest period of the Intermittent exercise) , which helps maintain the normal blood level of HDL-C.
- This is expected when Cr metabolism occurs under physiological conditions. But suppose, the mechanism of the CrP synthesis from Cr , in the mitochondria, is deranged pathologically, the continued synthesis of CrP would curtail the availability and supply of ATP for the ABC 1/ ABG 1 transporters to perform their function. Obviously, the HDL-C level then is bound to fall, as the efficiency of the enzyme, which in turn depends on the supply of ATP, diminishes.
- This situation is possible when the sedentary lifestyle with little exercise carried out, co-exists, as explained hereunder:
  Of the two steps involved in the synthesis of the creatine in the liver and other organs, that are transported to the uMtck, the rate-limiting step catalyzing the first step in the creatine synthesis, involving the AGAT enzyme, controls the amount of creatin present in the cell (uMtck) .(see above) Conversely, absence of creatine in

uMtc (due to disturbed re synthesis of creatine by the creatine shuttle, stimulates the resynthesis of creatine by AGAT.

- There is evidence indicating that the Cr in the mitochondria exerts a repressive effect on the step catalyzed by AGAT. (see ref.24 & 25 above).
- Likewise, the CrTs are also under feedback inhibition from the concentration level of the Cr in the cll (both intracellular and extracellular) (see ref 27 to 30 above). This reciprocal arrangement between the intracellular creatine concentration and its synthesis as well as its transporters, helps to regulate the creatine concentration commensurate with the capacity of the enzyme, CK in the U Mtckwhich phosphorylate Cr to CrP. Subsequent renewal of creatin for resynthesis of CrP is supplied through the “creativeshuttle".
- It follows that the creatine from the resynthesisby the creatine shuttle in u Mtck inhibits the AGAT, as long as the creatine shuttle is operating. In other words, if the creatine from the creatine shuttle is not available, the absence of creatine repressive effect in the uMtc is no longer operating, and accordingly, the AGAT starts synthesizing creatine, which is transported into the UMtck , by the Cr T.
- How the disturbed creatine shuttle occurs needs to be explained. Here comes the role played by the lack of exercise due to the sedentary life style, with little physical exercise, precludes the hydrolysis of the CrP, as the same is coupled to .the muscle contraction process.
- This has two effects. Firstly the creatine is not available to be shuttled back to the UMtck unlike what happens normally and the absence of creatine in UMtc removes the repressor effect on the synthesis of creatine by AGAT, as already seen above. Secondly the CrP is not hydrolyzed by the CK enzyme in the sarcolemmel mitochondria, and alternatively, the spontaneous dissociation of the CrP results . (for reasons explained below)
- The spontaneous dissociation of CrP iinturn has rwo consequences,
  1.the disturbed ratio between the CrP and creatininein the muscle cell.
  2.The increased total creatine content of the cytosol of the cell.
  This results, consequently ,in the increased degradation of creatine into creatinine , with subsequent increase in the S. Creatinine .
  The mechanism of spontaneous dissociation of CrP and its aftermath need to be explained .

Spontaneous dissociation of CrP and its after math :

This requires a bit of recapitulation of the laws of thermodynamics, and the concept of Gibbs Free energy and how it is related to the changes in enthalpy and entropy, and for better understanding of which , readers might consult a standard text book of Chemistry.

- Under the sedentary life style conditions,with little scope for exercise, the hydrolysis of CrP, in the sarcollemal M line mitochondria (smMtc) does not take place, as the release of the product of the hydrolysis , the ATP, is coupled to the contraction of myofibrils.

- The high energy phosphate in the compound CrP, is responsible for the spontaneous dissociation of CrP, as its entropy is high.The high energy compounds (like CrP) spontaneously dissociate into low energy molecules, which are thermodynamically, more stable.
- The best indicator of spontaneity in a reaction is the change in Entropy (S orΔS)
- The Second Law of Thermodynamics states that for a reaction to be spontaneous, there must be an increase in entropy .
- It is known fact that, the free energy of the reactants is greater than that of the products, the entropy will increase and hence , the reaction takes place in the forward direction, as is the case of dissociation of CrP .
- While entropy decides the spontaneity of the reaction, the Gibbs free energy decides the direction of the reversible chemical reaction subject to the fulfillment of the following criteria.
    A. ΔG< 0 The reaction will occur spontaneously to the right.
    B. ΔG>0: The reaction will occur spontaneously to the left.
    C. ΔG=0: The reaction is at equilibrium and will not proceed in either direction
- The Gibbs free energy, (ΔG°) of hydrolysis of creatine phosphate reaction is –43.1 KJ/mol. The negative sign indicates, that the reaction is exergonic, (gives out energy) and that it spontaneously decomposes and proceeds in the forward direction only.
- The negative sign of Gibbs free energy is because the change in entropy is greater than the changes in enthalpy as Per the following reaction(1)

$\Delta G = \Delta H - T\Delta S$, ---------- (1)

where ΔG indicates change in free energy. Is change in the enthalpy and TΔS , indicates the product of absolute temperature and the change in the entropy .

Hence the decomposition reaction (2) of CrP might be written as follows

CrP ~~CK~~→ Cr + pi [free energy]……..(2)

- The spontaneous decomposition of the (as against the enzymatic hydrolysis of CrP by CK.) has two effects.

A. The crreleased is not available to be recycled in the creatine shuttle , due to the Compartmentation of creatine, between the cytosol, Mitochondria and blood, as already seen above . As a result, thee creatine released by spontaneous decomposition of CrP is not available for creatin shuttle for resynthesis of CrP in u Mtck, as against what happens during the enzymatic hydrolysis of CrP .
B. The creatine, thus formed, increases the creatine present in the
C. un phosphorylated form in the cytosol.

- Consequently, the total creatine content of the cytosol is increased . The normal average amount of total creatine (creatine and phosphocreatine) stored in the body is approximately 120 mmol/kg of dry muscle mass.[18]
- With increased creatine In the cytosol, the normal ratio of CrP to Cr is disturbed.

- As a result,the Cr degradation rate, also is increased, the normal being in humans being about 1.6% (2 g) per day [5] to keep the Cr :CrP ratio in the cell.
- This increases the percentage of creatine degraded Per day, the normal rbeing 1 % of creatine present in the Cell.
- Thus the total creatinine, the degradation product of creatin, is increased in the blood .
- Thus the proposed mechanism offers an answer to the observed inverse relationship between the Low HDL and S. Creatinine.

Concusion

A possible molecular mechanism, underlying the inverse relationship between the raised Creatinine and Low HDL-C , in the backdrop of CKD and the sedentary lifestyle, has been proposed.This foresees,a competition between ABC1/ ABG1 transporters, that facilitate the efflux of excess/ unused cholesterol from the cells into the HDL-C and the synthesis by CK, of CrP in the uMtck, respectively .and the role of the sedentary lifestylebehind the mechanism, is established. Thatexercise increases the HDL-C levels and reduces the raised S creatinine levels, supporting the contentions expressed in the proposed mechanism. The suggested mechanism has therapeutic implications also, as it shows the way to reduce the risk from the two individual risk factors(the low JDL-C and raised S. Creatinine), for the cardiovascular and renal morbidly and mortality

References

1 .Caggiula A, England BK, Greene T, Kusek JW, et al. Predictors of the progression of renal disease in. the Modification of Diet in Renal Disease Study. Kidney Int. (1997) 51:1908–19.

2 . Muntner P, Coresh J, Smith JC, Eckfeldt J, Klag MJ. Plasma lipids and risk of developing renal dysfunction: the atherosclerosis risk in communities study. Kidney Int. (2000) 58:293–301.

3 . Bowe B, Xie Y, Xian H, Balasubramanian S, Al-Aly Z. Low levels of high-density lipoprotein cholesterol increase the risk of incident kidney disease and its progression. Kidney Int. (2016)

4 . Kawachi K, Kataoka H, Manabe S, Mochizuki T, Nitta K. Low HDL cholesterol as a predictor of chronic kidney disease progression: a cross-classification approach and matched cohort analysis. Heart Vessels. 2019 Sep;34(9):1440-1

5 . Bowe B, Xie Y, Xian H, Balasubramanian S, Al-Aly Z: Low levels of high-density lipoprotein cholesterol increase the risk of incident kidney disease and its progression. Kidney Int 89: 886–896, 2016.

6 .Moradi H, Vaziri ND, Kashyap ML, Said HM, Kalantar-Zadeh K: Role of HDL dysfunction in end-stage renal disease: a double-edged sword. J Ren Nutr 2013; 23: 203–206.

7 . Schaeffner ES, Kurth T, Curhan GC, et al. Cholesterol and the risk of renal dysfunction in apparently healthy men. J Am SocNephrol. 2003;14(8):2084–2091. [PubMed] [Google Scholar] .

8 . Vaziri ND. Lipotoxicity and impaired high density lipoprotein-mediated reverse cholesterol transport in chronic kidney disease. J Ren Nutr. 2010;20(Suppl):S35–S43.

9 . AM KH, Chang TI, Joo YS, Kim J, Lee S, Lee C, et al.. Association between serum high-density lipoprotein cholesterol levels and progression of chronic kidney disease: results from the KNOW-CKD. J Am Heart Assoc. (2019)

10 . Lamprea-Montealegre JA, Sharrett AR, Matsushita K, Selvin E, Szklo M, Astor BC: Chronic kidney disease, lipids and Apo lipoproteins, and coronary heart disease: The ARIC study. Atherosclerosis 234: 42–46, 2014

11. Cases A, Coll E: Dyslipidemia and the progression of renal disease in chronic renal failure patients. Kidney IntSuppl 99: S87–S93, 2005

12 . Bae JC, Han JM, Kwon S, Jee JH, Yu TY, Lee MK, et al.: LDL-C/apoB and HDL-C/apoA-1 ratios predict incident chronic kidney disease in a large apparently healthy cohort. Atherosclerosis 251: 170–176, 201

13 . Holzer M, Birner-Gruenberger R, Stojakovic T, El-Gamal D, Binder V, Wadsack Cy, et al.: Uremia alters HDL composition and function. J Am SocNephrol 22: 1631–1641,2011

14 .Schaeffner ES, Kurth T, Curhan GC, Glynn RJ, Rexrode KM, Baigent C, Buring JE, Gaziano JM. Cholesterol and the risk of renal dysfunction in apparently healthy men. J Am SocNephrol. 2003 Aug;14(8):2084-2091. Moradi H, Vaziri ND, Kashyap ML, Said HM, Kalantar-Zadeh K: Role of HDL dysfunction in end-stage renal disease: a double-edged sword. J Ren Nutr 2013; 23: 203–206.

15 . Humm A, Fritsche E, Steinbacher S, Huber R (June 1997). "Crystal structure and mechanism of human L-arginine:glycineamidinotransferase: a mitochondrial enzyme involved in creatine biosynthesis". EMBO J. 16 (12): 3373–85.

16 . Cooper R, Naclerio F, Allgrove J, Jimenez A (July 2012). "Creatine supplementation with specific view to exercise/sports performance: an update". Journal of the International Society of Sports Nutrition. 9 (1): 33.

17 . Brosnan ME, Brosnan JT (August 2016). "The role of dietary creatine". Amino Acids. 48 (8): 1785–91.

18 .Hultman E, Söderlund K, Timmons JA, Cederblad G, Greenhaff PL (July 1996). "Muscle creatine loading in men". Journal of Applied Physiology. 81 (1): 232–7. .

19 .Bemben M, Lamont H. Creatine supplementation and exercise performance: recent findings. Sports Med. 2005;35:107–125. doi: 10.2165/00007256-200535020-00002. [PubMed] [CrossRef] [Google Scholar]

20 .Brosnan JT, da Silva RP, Brosnan ME. The metabolic burden of creatine synthesis. Amino Acids. 2011;40:1325–1331.

21. Wyss M, Kaddurah-Daouk R. Creatine and creatinine metabolism. Physiol Rev 2000;80:1107–213.

22. McGuire DM, Tormanen CD, Segal IS, Van Pilsum JF (February 1980). "The effect of growth hormone and thyroxine on the amount of L-arginine:glycineamidinotransferase in kidneys of hypophysectomized rats. Purification and some properties of rat kidney transamidinase". J. Biol. Chem. 255 (3): 1152–9.

23 .Sipilä I (1980). "Inhibition of arginine-glycine amidinotransferase by ornithine. A possible mechanism for the muscular and chorioretinal atrophies in gyrate atrophy of the choroid and retina with hyperornithinemia". Biochim. Biophys. Acta. 613 (1): 79–84. 1.

24 . McGuire DM, Gross MD, Van Pilsum JF, Towle HC (October 1984). "Repression of rat kidney L-arginine:glycineamidinotransferase synthesis by creatine at a pretranslational level". J. Biol. Chem. 259 (19): 12034–8.

25 . Guthmiller P, Van Pilsum JF, Boen JR, McGuire DM (July 1994). "Cloning and sequencing of rat kidney L-arginine:glycineamidinotransferase. Studies on the mechanism of regulation by growth hormone and creatine". J. Biol. Chem. 269 (26): 17556–60.

26 .Humm A, Fritsche E, Mann K, Göhl M, Huber R (March 1997). "Recombinant expression and isolation of human L-arginine:glycineamidinotransferase and identification of its active-site cysteine residue". Biochem. J. 322 (3): 771–6.

27 .Zange, J., C. Kornblum, K. Muller, S. Kurtscheild, H. Heck, R. Schroder, T. Grehl, and M. Vorgerd. Creatine supplementation results in

elevated phosphocreatine/adenosine triphosphate (ATP) ratios in the

calf muscle of athletes but not in patients with myopathies. Ann. Neur.

28 .Loike, J. D., D. L. Zalutsky, E. Kaback, A. F. Miranda, and S. C.

Silverstein. Extracellular creatine regulates creatine transport in rat and

human muscle cells. Proc. Nat. Acad. Sci. USA. 85:807–811, 1988.

29 .Harris, R. C., K. Soderlund, and E. Hultman. Elevation of creatine in

resting and exercised muscle of normal subjects by creatine supplemen-

tation. Clin. Sci. 83:367–374, 1992.

30 . Snow RJ, Murphy RM: Creatine and the creatine transporter: A review. Mol Cell Biochem. 2001, 224: 169–181. 10.1023/A:10119086068

31. F. Oram, R. M. Lawn, M. R. Garvin, D. P. Wade, ABCA1 is the cAMP-inducible apolipoprotein receptor that mediates cholesterol secretion from macrophages. J. Biol. Chem. 275, 34508–34511 (2000).

32 . N. Wang, D. L. Silver, P. Costet, A. R. Tall, Specific binding of ApoA-I, enhanced cholesterol efflux, and altered plasma membrane morphology in cells expressing ABC1. J. Biol. Chem. 275, 33053–33058 (2000).

33 . M. A. Kennedy et al., ABCG1 has a critical role in mediating cholesterol efflux to HDL and preventing cellular lipid accumulation. Cell Metab. 1, 121–131 (2005).

34 . N. Wang, D. Lan, W. Chen, F. Matsuura, A. R. Tall, ATP-binding cassette transporters G1 and G4 mediate cellular cholesterol efflux to high-density lipoproteins. Proc. Natl. Acad. Sci. U.S.A. 101, 9774–9779 (2004).

35.M. Westerterp et al., Deficiency of ATP-binding cassette transporters A1 and G1 in macrophages increases inflammation and accelerates atherosclerosis in mice. Circ. Res. 112, 1456–1465 (2013).

36 . M. Westerterp et al., Cholesterol efflux pathways suppress inflammasome activation, NETosis, and atherogenesis. Circulation 138, 898–912 (2018).

37 . Williamson R., Lee D., Hagaman J., Maeda N. Marked reduction of high density lipoprotein cholesterol in mice genetically modified to lack apolipoprotein A-I. Proc. Natl. Acad. Sci. U. S. A. 1992;89:7134–7138. [

38 . Schaefer E.J., Heaton W.H., Wetzel M.G., Brewer H.B. Plasma apolipoprotein A-1 absence associated with a marked reduction of high density lipoproteins and premature coronary artery disease. Arteriosclerosis. 1982;2:16–26. [PubMed] [Google Scholar

39 .Weng W., Breslow J.L. Dramatically decreased high density lipoprotein cholesterol, increased remnant clearance, and insulin hypersensitivity in apolipoprotein A-II knockout mice suggest a complex role for apolipoprotein A-II in atherosclerosis susceptibility. Proc. Natl. Acad. Sci. U. S. A. 1996;93:14788–14794. [

40 .Kuivenhoven J.A., et al. The molecular pathology of lecithin:cholesterol acyltransferase (LCAT) deficiency syndromes. J. Lipid Res. 1997;38:191–205. [PubMed] [Google Scholar]

41 .Ng D.S. Insight into the role of LCAT from mouse models. Rev. Endocr. Metab. Disord. 2004;5:311–318. [PubMed] [Google Scholar]

42 . Rader D.J., et al. Markedly accelerated catabolism of apolipoprotein A-II (ApoA-II) and high density lipoproteins containing ApoA-II in classic lecithin: cholesterol acyltransferase deficiency and fish-eye disease. J. Clin. Invest. 1994;93:321–330.

43 .Jaye M., et al. A novel endothelial-derived lipase that modulates HDL metabolism. Nat. Genet. 1999;21:424–428.

44 . Hirata K., et al. Cloning of a unique lipase from endothelial cells extends the lipase gene family. J. Biol. Chem. 1999;274:14170–14175. [PubMed] [Google Scholar]

45 .Maugeais C., et al. Dose-dependent acceleration of high-density lipoprotein catabolism by endothelial lipase. Circulation. 2003;108:2121–2126. [PubMed] [Google Scholar

46 . Rader D.J. New insights into the regulation of HDL metabolism and reverse cholesterol tr 27. Timmins J.M., et al. Targeted inactivation of hepatic Abca1 causes profound hypoalphalipoproteinemia and kidney hypercatabolism of apoA-I. J. Clin. Invest. 2005;115:1333–1342.

47 .Jiang X.C.., et al. Targeted mutation of plasma phospholipid transfer protein gene markedly reduces high-density lipoprotein levels. J. Clin. Invest. 1999;103:907–914.

48 . Agellon L.B., et al. Reduced high density lipoprotein cholesterol in human cholesteryl ester transfer protein transgenic mice. J. Biol. Chem. 1991

49 . M.L., et al. Molecular basis of lipid transfer protein deficiency in a family with increased high-density lipoproteins. Nature. 1989;342:448–451.

50 . Inazu A., et al. Increased high-density lipoprotein levels caused by a common cholesteryl-ester transfer protein gene mutation. N. Engl. J. Med. 1990;323:1234–1238.

51 .Timmins J.M., et al. Targeted inactivation of hepatic Abca1 causes profound hypoalphalipoproteinemia and kidney hypercatabolism of apoA-I. J. Clin. Invest. 2005;115:1333–1342.

52 . Brunham L.R., et al. Intestinal ABCA1 directly contributes to HDL biogenesis in vivo. J. Clin. Invest. 2006;116:1052–1062.

53 . Rader D.J., et al. Markedly accelerated catabolism of apolipoprotein A-II (ApoA-II) and high density lipoproteins containing ApoA-II in classic lecithin: cholesterol acyltransferase deficiency and fish-eye disease. J. Clin. Invest. 1994;93:321–330. [PMC free article] [PubMed] [Google Scholar]

54 .Timmins J.M., et al. Targeted inactivation of hepatic Abca1 causes profound hypoalphalipoproteinemia and kidney hypercatabolism of apoA-I. J. Clin. Invest. 2005;115:1333–1342. Scholar55Brunham L.R., et al. Intestinal ABCA1 directly contributes to HDL biogenesis in vivo. J. Clin. Invest. 2006;116:1052–1062. doi: 10.1172/JCI27352. [PMC free article] [PubMed]

56 .Moradi H, Vaziri ND, Kashyap ML, Said HM, Kalantar-Zadeh K: Role of HDL dysfunction in end-stage renal disease: a double-edged sword. J Ren Nutr 2013; 23: 203–206.

57. Vaziri ND: Role of dyslipidemia in impairment of energy metabolism, oxidative stress, inflammation and cardiovascular disease in chronic kidney disease. ClinExpNephrol 2014; 18: 265–268.

[58] Bharakhada N, Yates T, Davies MJ, Wilmot EG, Edwardson C, Henson J, Webb D, Khunti K. Association of sitting time and physical activity with CKD: a cross-sectional study in family practices. Am J Kidney Dis. 2012;60(4):583–90.

59. Hawkins MS, Sevick MA, Richardson CR, Fried LF, Arena VC, Kriska AM. Association between physical activity and kidney function: National Health and nutrition examination survey. Med Sci Sports Exerc. 2011;43(8):1457–64.

60 . Robinson-Cohen C, Katz R, Mozaffarian D, Dalrymple LS, de Boer I, Sarnak M, Shlipak M, Siscovick D, Kestenbaum B. Physical activity and rapid decline in kidney function among older adults. Arch Intern Med. 2009;169(22):2116–23.

61. Finkelstein J, Joshi A, Hise MK. Association of physical activity and renal function in subjects with and without metabolic syndrome: a review of the third National Health and nutrition examination survey (NHANES III). Am J Kidney Dis. 2006;48(3):372–82.

62. Hallan S, de Mutsert R, Carlsen S, Dekker FW, Aasarod K, Holmen J. Obesity, smoking, and physical inactivity as risk factors for CKD: are men more vulnerable? Am J Kidney Dis. 2006;47(3):396–405.

63. Tremblay MS, Aubert S, Barnes JD, Saunders TJ, Carson V, Latimer-Cheung AE, Chastin SFM, Altenburg TM, Chinapaw MJM, Participants STCP. Sedentary behaviour research network (SBRN) - terminology consensus project process and outcome. Int J BehavNutrPhys Act. 2017;14(1):75.

64. Hawkins M, Newman AB, Madero M, Patel KV, Shlipak MG, Cooper J, Johansen KL, Navaneethan SD, Shorr RI, Simonsick EM, et al. TV watching, but not physical activity, is associated with change in kidney function in older adults. J Phys Act Health. 2015;12(4):561–8.

65 . Lynch BM, White SL, Owen N, Healy GN, Chadban SJ, Atkins RC, Dunstan DW. Television viewing time and risk of chronic kidney disease in adults: the AusDiab study. Ann Behav Med. 2010;40(3):265–74.

66 . Levin A, Stevens PE. Summary of KDIGO 2012 CKD guideline: behind the scenes, need for guidance, and a framework for moving forward. Kidney Int. 2014;85(1):49–61.

67 .Kosaki, K., Tanahashi, K., Matsui, M. *et al.* Sedentary behaviour, physical activity, and renal function in older adults: isotemporal substitution modelling. *BMC Nephrol* **21,** 211 (2020).

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