Modulation of insulin resistance by renin angiotensin system inhibitors: implications for cardiovascular prevention

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Abstract

Insulin resistance (IR) and the related hyperinsulinemia play a key role in the genesis and progression of the continuum of cardiovascular (CV) disease. Thus, it is reasonable to pursue in primary and secondary CV prevention, the pharmacological strategies that are capable to interfere with the development of IR. The renin-angiotensin-aldosterone system (RAAS) plays an important role in the pathogenesis of IR. In particular, angiotensin II (Ang II) through the generation of reactive oxygen species, induces a low grade of inflammation, which impairs the insulin signal transduction. The angiotensin converting enzyme (ACE) inhibitors are effective not only as blood pressure-lowering agents, but also as modulators of metabolic abnormalities. Indeed, experimental evidence indicates that in animal models of IR, ACE inhibitors are capable to ameliorate the insulin sensitivity. The Ang II receptor blockers (ARBs) modulate the peroxisome proliferator-activated receptor (PPAR)-γ activity. PPAR–γ is a transcription factor that controls the gene expression of several key enzymes of glucose metabolism. A further mechanism that accounts for the favorable metabolic properties of ARBs is the capability to modulate the hypothalamic–pituitary–adrenal (HPA) axis. The available clinical evidence is consistent with the concept that both ACE inhibitors and ARBs are able to interfere with the development of IR and its consequences like type 2 diabetes. In addition, pharmacological inhibition of the RAAS has favourable effects on dyslipidaemias, metabolic syndrome and obesity. Therefore, the pharmacological antagonism of the RAAS, nowadays, represents the first choice in the prevention of cardio-metabolic diseases.

Insulin resistance and cardiovascular risk

Insulin resistance (IR) and the related hyperinsulinemia play a key role in the genesis and progression of the continuum of cardiovascular (CV) disease. In particular, IR is a complex and multifaceted pathogenic mechanism that accounts for the development of CV risk factors, such as type 2 diabetes (T2D), metabolic syndrome (MS), obesity, hypertension, and non-alcoholic fatty liver disease (NAFLD) [1-4]. Furthermore, IR participates to the development and progression of target organ damage (TOD) as left ventricular hypertrophy (LVH), chronic kidney disease (CKD), and atherosclerosis [5-8]; and, is involved in the occurrence of major CV events such as myocardial infarction, ischemic stroke, and heart failure [9-13]. Thus, given the strong relationships between IR and CV risk, it is reasonable to pursue in primary and secondary CV prevention, the pharmacological strategies that are capable to interfere with the development of IR and its complications.

Abnormalities of insulin signaling transduction account for the development of IR. At this regard, it has been documented that dysregulation of the renin-angiotensin-aldosterone system (RAAS) plays a key role in the pathogenesis of IR [14]. In particular, angiotensin II (Ang II), through the generation of reactive oxygen species (ROS), promotes the proteasome-mediated degradation of insulin receptor substrate-1 (IRS-1) [14] resulting in the impairment of insulin action. This effect, at vascular level induces a low grade of inflammation, which accounts for the development of IR and subsequent CV events [15]. Therefore, the pharmacological inhibition of the RAAS, obtained either with angiotensin converting enzyme (ACE) inhibitors or with Ang II receptor blockers (ARBs), nowadays, represents the first choice in primary and secondary CV prevention.
RAAS inhibitors

According to the classic view, the RAAS plays a key role in the regulation of blood pressure (BP) homeostasis. Dysregulation of the RAAS results in the increase of stimulation of type 1 Ang II receptors (AT1R) which is involved in the pathogenesis of hypertension and TOD. In addition, enhanced stimulation of AT1 R has been reported also in T2D, MS, obesity, and NAFLD.

ACE inhibitors

The ACE inhibitors are effective not only as BP-lowering agents, but also as modulators of metabolic abnormalities. Basically, ACE inhibitors have two primary mechanisms that mediate their influences on hemodynamic and metabolic homeostasis. First, ACE inhibitors decrease the conversion of angiotensin I to Ang II; in addition, via the inhibition of the kininase II breakdown [16], they enhance the circulating level of the bradykinin (Figure 1). The higher kinin levels lead to an increased production of prostaglandins (prostaglandin E1 and prostaglandin E2) and nitric oxide (NO) that improve exercise-induced glucose metabolism and muscle sensitivity to insulin [17,18], resulting in enhanced insulin-mediated glucose uptake. Furthermore, the peripheral vasodilatory actions of ACE inhibitors increase the surface area for glucose exchange between the vascular bed and skeletal muscles. Clinical evidence supporting this effect has been provided by Morel et al. [19], who have demonstrated improved insulin sensitivity when enalapril was given for 12 weeks in patients at high CV risk. A similar effect has also been reported with captopril [20]. However, it should be underlined that this can not be considered the only mechanism that account for the increase of insulin sensitivity because this action is not shared by drugs that acts exclusively as vasodilators like hydralazine. Moreover, the protection against the development of IR may be partially due to the regulation of adipocyte cell cycle. In fact, it has been demonstrated that increased levels of Ang II inhibit the differentiation of pre-adipocyte into mature adipocytes, compromising the fat cells’ ability to store fat. This, in turn, results in shunting of fats to the liver, skeletal muscle, and pancreas. This phenomenon compromises the insulin sensitivity. Reducing Ang II levels with an ACE inhibitor or blocking the AT1R may promote the differentiation of pre-adipocytes to mature adipocytes, which serve as a sump for fat. In addition, redistribution of the lipids from the peripheral tissues would improve insulin sensitivity [21]. A further mechanism that accounts for the favourable effect of ACE inhibitors on insulin sensitivity relates to the protective action on the pancreatic beta cell. In particular, the inhibition of the vasoconstrictive effect of Ang II

![Figure 1. Schematic representation of mechanisms of the ACE inhibitors. Angiotensin converting enzyme (ACE) inhibitors, reduce Angiotensin (Ang) II production, and at the same time, inhibit the breakdown of bradykinin, which, in turn interacts with its own receptor. These effects together with the recovery of insulin signaling result in an increased NOS activation and NO production. IRS, insulin receptor substrate; PI3K, phosphatidyl-inositol 3-kinase; NOS, nitric oxide synthase; NO, nitric oxide.](image-url)
in the pancreas increases the islet blood flow [22], resulting in the enhanced release of insulin by beta cells.

There are several experimental and clinical epidemiological data that indicate that ACE inhibitors improve the glucose metabolism in different tissue and organs.

Experimental data

There are experimental studies performed in animal models of hypertension and IR that have demonstrated that acute and/or chronic administration of ACE inhibitors can improve insulin action on whole-body and skeletal muscle glucose disposal. In particular, it has been demonstrated that the acute infusion of captopril in obese Zucker rats, a murine model of IR, enhances insulin sensitivity during a hyperinsulinemic-euglycemic clamp [23]. A similar response to acute infusion of captopril has been observed in an insulin resistant diabetic dog model [24]. In addition, also chronic treatment with ACE inhibitors is able to enhance glucose tolerance. In fact, it has been shown that chronic administration of ACE inhibitors in obese Zucker rats elicits an increase in whole-body insulin action. Chronic oral treatment of obese Zucker rats with the ACE inhibitors captopril [25], trandolapril [26] or imidapril [27] causes substantial improvements in whole-body insulin sensitivity. Interestingly, the ACE inhibitor-mediated improvements in whole-body insulin sensitivity were also associated with decrease in plasma insulin levels and amelioration of lipid profile. Chronic administration of ACE inhibitor in a mouse model of T2D also significantly improves whole-body glucose tolerance and insulin sensitivity [28].

The skeletal muscle is principal target of the metabolic action of ACE inhibitors. In fact, acute administration of the ACE inhibitors captopril [29] or trandolapril [30] significantly enhances insulin-mediated glucose transport activity in skeletal muscle in the obese Zucker rat. ACE inhibitors can beneficially modulate glucose metabolism also in cardiac muscle. Rett et al. [31] have demonstrated in cardiac muscle of the obese Zucker rat using the perfused Langendorff preparation, that the acute administration of bradykinin can significantly increase insulin-stimulated glucose transport activity. The traslocation process of both GLUT1 and GLUT4 mediates this effect.

NAFLD is the hepatic feature of hypercaloric diet-induced IR [32]. At this regard, it has been documented that Inhibition of RAAS obtained either with ACE inhibitors (perindopril) or with ARBs (Ibesartan) is able to prevent the development of IR and liver steatosis in obese Zucker rat, through the reduction of inflammatory mediators like tumor necrosis factor-alpha (TNF-alpha), interleukin-6 (IL-6) and transforming growth factor-beta1 (TGF-beta1) [33].

Experimental evidence indicates that in animal models of IR, ACE inhibitors are capable to ameliorate the insulin sensitivity, and this effect is independent from their antihypertensive action.

Clinical data

The beneficial effects of ACE inhibitors to improve IR come from several observational and interventional studies in human subjects. Since the IR is the principal pathogenic mechanism involved in the development of T2D, it is reasonable to assume that all therapeutic interventions that are able to prevent the incidence of T2D, improve the insulin sensitivity. In the Captopril Prevention Project (CAPPP) [34] and the Heart Outcomes Prevention Evaluation (HOPE) study [35], two large prospective studies involving subjects at risk for developing T2D, there was a lesser incidence of newly-diagnosed T2D in those subjects who received an ACE inhibitor (either captopril or ramipril) compared to the respective placebo control groups. These data were confirmed by the Antihypertensive and Lipid-Lowering Treatment to Prevent Heart Attack Trial (ALLHAT) study [36] which compared in subjects with hypertension the ACE inhibitor lisinopril vs chlorthalidone, and by the Prevention of Events with Angiotensin Converting Enzyme Inhibition (PEACE) Trial [37], which compared in subjects with coronary heart disease the ACE inhibitor Trandolapril vs placebo. The available clinical evidence are consistent with the concept that ACE inhibitors are able to interfere with the development of IR and its consequences.

Angiotensin receptor blockers

The hemodynamic and metabolic effects of Ang II are mediated by two different seven trans-membrane domains, G-protein-coupled receptors: AT1R and Ang II type 2 receptor (AT2R). The AT1Rs are widely expressed in adult organs and tissues and mediate the biological effects of Ang II, like sodium and water retention, increase of vascular peripheral resistances, activation of inflammatory response and pro-thrombotic state, activation of sympathetic nervous system. AT2Rs are expressed during the fetal life and in pathological states. It has been hypothesized that stimulation of AT2R exerts an important role in counterbalancing some of the detrimental effects of Ang II. However, in the last decade, has emerged that the majority of Ang II-mediated effects are counterbalanced by the peptide Ang-(1-7). This peptide is synthesized from Ang II by an ACE homolog: ACE2 and binds to the G-protein-coupled receptor: Mas. It has been demonstrated that the pathway ACE2/Ang-(1-7)/Mas increases the NO production, exerts an anti-proliferative, anti-thrombotic, anti-inflammatory actions [38]. Thus, the block of AT1R by ARBs increases the systemic and local levels of Ang II which are available to be transformed by ACE2 in Ang-(1-7), which, in turn, binds the Mas receptors. Additionally, in the pathological conditions the increased levels of Ang II result in the unopposed stimulation of the AT2R (Figure 2).

Experimental data

ARBs improve the insulin sensitivity not only by blocking the AT1R, but also through additional mechanisms. In particular, its has been demonstrated that Telmisartan, Eprosartan, Ibesartan and Losartan act as a peroxisome proliferator-activated receptor (PPAR)-γ agonists [39,40]. PPAR–γ is a transcription factor that controls the gene expression of several key enzymes of glucose metabolism, and thereby increases insulin sensitivity and preserves pancreatic beta-cell function. The first PPAR identified was PPAR-α, which is the target of fibrates. PPAR-γ is the target of thiazolidinediones, a class of drugs that enhance insulin sensitivity. The pharmacological activation of both PPAR-α, and PPAR-γ provides metabolic benefits [41,42]. A further mechanism that accounts for the favorable metabolic properties of ARBs, is the capability to pharmacologically activate both PPAR-α, and PPAR-γ provides metabolic benefits [41,42]. A further mechanism that accounts for the favorable metabolic properties of ARBs, is the capability to modulate the hypothalamic –pituitary-adrenal (HPA) axis. It has been reported, in murine model of IR, that Ang II mediates the hyperactivity of HPA axis [43]. Of note, the treatment with AT1R antagonist Telmisartan was able to blunt the centrally-mediated effects of Ang II. The capability of ARBs to restore the metabolic homeostasis explains, in part, their effects also to prevent the liver fibrosis in animal models of IR [38].

Clinical data

The revision of 12 randomized controlled clinical trials with ACE inhibitors or ARBs aimed to evaluate the efficacy of these
medications in T2D prevention, showed that ACE inhibitors and ARBs produced a 25% reduction (or a decrease from 17.4 to 14.3 cases per 1000 patient-years) in the incidence of new-onset of T2D [44]. This analysis involved 72,333 non-diabetic patients (approximately 338,000 patient-years of follow-up), with mean duration of follow-up ranged from 1 to 6.1 years. These data were substantially confirmed by a further meta-analysis [45]. Of note, the results of the Trascend Study were not included in both analyses since they were published later [46]. The clinical implications of these meta-analyses are consistent with concept that the inhibition of RAAS interferes with the development of T2D (Figure 3). Therefore, it is possible to speculate that the inhibition of RAAS obtained with either ACE inhibitors or ARBs ameliorates insulin sensitivity.

### Metabolic effects of RAAS inhibition

IR is a complex pathogenic mechanism that can account for different phenotypes, such as essential hypertension, T2D, MS, obesity, NAFLD, and different forms of vascular, cardiac and renal damage. Of note that the combination of different manifestations of IR increases the CV risk [47].

### Dyslipidaemias

IR directly affects the lipidid homeostasis acting mainly through the inflammation and generation of ROS. Of note, these pathogenic mechanisms are, in part, mediated by Ang II. In addition, it has been documented that Ang II exerts several effects that influence atherogenic properties of cholesterol.

### Experimental data

It has been demonstrated that AT1R genetic ablation has a significant effect in reducing hypercholesterolemia-induced atherosclerosis in low density lipoprotein (LDL) receptor-negative mice [48]. In this experimental setting, hypercholesterolemia was associated with increased systemic angiotensinogen and angiotensin peptides, which were reduced in AT1R-deficient mice. Together these data indicate that LDL-cholesterol contributes to development of atherosclerosis through a RAAS-dependent mechanism. Moreover, it has been reported in primary cultures of human monocyte-macrophages, that the pro-atherogenic effects of Ang II are related to upregulate the expression of Acyl-CoA:cholesterol acyltransferase-1 (ACAT1) [49]. This enzyme converts free cholesterol into esters for storage in lipid droplets. This process could promote foam cell formation and increase cholesterol content of atherosclerotic lesions. Finally, Ang II increases the oxidation of LDL in macrophage cell lines.

![Figure 2. Schematic representation of mechanisms of the Ang II receptor blockers. The Angiotensin II receptor blockers (ARBs) block the binding of Angiotensin II (Ang II) with type 1 Ang II receptors (AT1R). This phenomenon increases the systemic and local levels of Ang II which bind to the Ang II type 2 receptor (AT2R) are transformed by Angiotensin converting enzyme (ACE) 2 in the peptide Ang-(1-7), which, in turn, binds the Mas receptors (MAS R).](image-url)
as well as mouse peritoneal macrophages, possibly through activation of NADPH oxidase. Altogether these observations are consistent with the notion that Ang II may influence the atherogenic properties of cholesterol through a redox imbalance without changing its blood concentrations [50]. On the other hand, cholesterol is able to regulate the RAAS activity. In particular, it has been demonstrated that the capability of LDL-cholesterol to increase AT1R gene expression on vascular smooth muscle cells. Similarly, oxidized LDL can also increase AT1R gene expression in human coronary artery endothelial cells [51]. Together, these results clearly demonstrate a cross-talk between hypercholesterolemia and RAAS in the development of atherosclerosis and its clinical consequences. The lack of counteregulatory effect of insulin, in insulin resistant state, has a detrimental effect on this phenomenon.

Clinical data

Dyslipidaemias affects the incidence and the prognosis of CV diseases. Indeed, achievement of low levels of LDL-cholesterol protects against the development of atherosclerosis, and also prevents the long-term complications of myocardial infarction such as, post-infarctal left ventricular remodeling [52]. Interventional studies have demonstrated that the pharmacological interference of RAAS, slightly improves the lipid profile. This beneficial action has been demonstrated for the different ARBs. In particular, Kyvelou et al. demonstrated, in a cohort of 2438 hypertensive patients, followed for 6 months, that ARBs-based monotherapy treatment induces a significant reduction of total and LDL-cholesterol, in addition increases the high density lipoproteins (HDL)-cholesterol [53]. Furthermore, a sub-study of the LIFE trial showed in hypertensive patients that, in comparison to atenolol, losartan-based regimen, induces a less decrease in HDL-cholesterol; and this pharmacological effect is associated with a better prognosis [54]. The authors speculated that less the decrease of HDL-cholesterol may explain around one third of the beneficial effect of losartan-based compared to atenolol-based antihypertensive treatment on composite end-point found in the study. The favorable effects on lipid profile have been documented for ARBs also when these are combined with drugs that worsen the metabolic profile. In particular, the Alpine Study showed that treatment with diuretics, if needed, in combination with a β-blocker was associated with a worsening of metabolic profile; this effect was not detected for patients treated with an ARBs [55]. As above mentioned, some ARBs, have been reported to

| Trial        | CAPPP | HOPE | LIFE | ALLHAT | CHARM | TRASCEND | PEACE | VALUE |
|--------------|-------|------|------|--------|-------|----------|-------|-------|
| Year of publication | 1999  | 2001 | 2002 | 2002  | 2005  | 2008     | 2004  | 2004  |
| Study drug   | Captopril vs β blockers + Diuretics | Conventional therapy + Ramipril vs Conventional therapy + Diuretics | Losartan + Diuretics vs Atenolol + Diuretics | Lisinopril vs Diuretics | Conventional therapy + Candesartan vs Conventional therapy + Placebo | Conventional therapy + Telmisartan vs Conventional therapy + Placebo | Conventional therapy + Trandolapril vs Conventional therapy + Placebo | Valsartan vs Amlopipine |
| Follow-up (years) | 6.1   | 4.5  | 4.8  | 4.9    | 3.1   | 5.3      | 4.8   | 4.2   |
| Number of patients without diabetes at baseline | 10413 | 5720 | 7798 | 21294  | 5436  | 3790     | 6904  | 10419 |

Figure 3. Results of principal intervention trials with renin-angiotensin-aldosterone system (RAAS) inhibitors on new diagnosis of diabetes (T2D). CAPPP, Captopril prevention project; HOPE, Heart outcomes prevention evaluation; LIFE, Losartan intervention for endpoint reduction; ALLHAT, Antihypertensive and lipid lowering treatment to prevent heart attack trial; CHARM, Candesartan in heart failure-assessment of reduction in mortality and morbidity; TRASCEND, Telmisartan Randomized Assessment Study in ACEI Intolerant Subjects with Cardiovascular Disease; PEACE, Prevention of events with angiotensin converting enzyme inhibition; VALUE, Valsartan antihypertensive long-term use evaluation.
stimulate PPARγ [39], resulting in an improvement of insulin sensitivity [56]. This could indirectly influence systemic lipid concentrations.

The vulnerability of atherosclerotic plaque is a direct consequence of the crosstalk between the dysregulation of RAAS and hypercholesterolemia. Indeed, RAAS promotes through the expression of the collagen-degrading proteases, the breakdown of the fibrous cap of the atheroma [57]. In addition, the RAAS stimulates also the activation of coagulation cascade and platelet aggregation. Ang II activates the Tissue Factor in monocytes and vascular endothelial cells [58], which in concert with further mediators such as coagulation factor II receptor, contribute to the pathogenesis coronary heart disease [59]. Notably, the gene encoding for coagulation factor II thrombin receptor, has been proposed as a marker of insulin resistance in MS, obesity, T2D, NAFLD, and atherosclerosis [60].

The beneficial effects of the RAAS inhibition to interfere with the development and progression of atherosclerosis are corroborated by several studies that evaluated the capability of ACE-inhibitors and ARBs to prevent the major cerebrovascular and CV events (i.e., stroke and myocardial infarction) [35,36,46].

Metabolic syndrome and obesity

MS and obesity are two manifestations of IR and are also independent determinants of structural and functional CV diseases [61-63]. In addition, both often are associated with abnormalities of renal function such as CKD and microalbuminuria [64,65] which represents independent risk factors for CV diseases [66,67]. Adipose tissue acts as an endocrine organ, secreting hormones and other substances that create a proinflammatory state and promote formation of atherosclerotic plaques [68,69].

Experimental data

The RAAS plays a key role in the link between obesity and cardio-renal damage. Adipose tissue is an important production site of angiotensinogen, and it has been reported a correlation among plasma level of angiotensinogen, BP, and body mass index. Moreover, in obese Zucker rats it has been documented an increase higher than 50% of gene expression of angiotensinogen, in adipose tissue compared with lean rats [70]. Interestingly, it has been also demonstrated that Ang II is implicated in the regulation of lipid synthesis and storage in the adipocytes, as well as, in the adipocyte growth and differentiation [71]. In addition, it has been documented that the AT1R, and ACE genes were found to be upregulated in the adipose tissue of hypertensive patients with obesity [72]. Altogether these experimental evidence suggest a strong relationship between RAAS and regulation of functional activity of adipose tissue, this phenomenon could be involved in the increase of CV risk.

Clinical data

Many large interventional studies specifically addressed the effects of RAAS inhibition in MS. In particular, the hemodynamic and metabolic effects of two ARBs were evaluated: telmisartan and irbesartan. As pleiotropic effects, these molecules are known to activate PPAR-γ, a well-known target of insulin-sensitizing agents. In particular, the ISLAND study [73] demonstrated that administration of Irbesartan and/or Lipoic acid to patients with the MS improves endothelial function and reduces proinflammatory markers. Furthermore, it has been demonstrated the capability of Telmisartan to activate PPARγ in circulating monocytes of patients with the MS [74] The OLAS study evaluated the effects of different antihypertensive combination therapies on inflammatory and metabolic parameters in non-diabetic hypertensive patients with MS [75]. This study showed that olmesartan-based therapies were effective to reduce insulin resistance index (24%, p<0.01), to increase plasma adiponectin (16%, p<0.05) and to reduce the inflammation markers, with exception except for C-reactive protein. In addition, the risk of new-onset of T2D was significantly reduced by Olmesartan-based treatments.

Experimental and clinical studies indicate that blocking the effects of Ang II (through ACE inhibition or ARBs) increases insulin sensitivity, which may contribute to the reduction of MS/obesity-mediated CV risk. Therefore, ACE inhibitors or ARBs represent the logical first-line anti-hypertensive agent in patients with MS or obesity.

Non-pharmacological modulation of the RAAS and IR

A large body of evidence demonstrates the benefits of physical exercise on CV risk physical exercise has a pleiotropic effect on cardio-metabolic homeostasis. In fact, it improves the vaso tone, enhances the synthesis, the release and the stability of NO, ameliorates the endothelial function, reduces the vascular inflammation, decreases the body weight and adiposity, improves the pancreatic β-cells function, restores the redox balance, increases hepatic fatty acid oxidation (Figure 4). In addition, experimental evidence indicates that the aerobic training modulates the RAAS activity, counterbalancing the detrimental effects of Ang II on insulin action [76]. Altogether these actions act in concert to improve the insulin sensitivity, and contribute to prevent the clinical manifestations of IR, such as metabolic syndrome, T2D, hypertension, and dyslipidemias [77]. From clinical point of view, the most powerful data about the beneficial effects of exercise on the reduction of CV risk, come from epidemiological and interventional studies that evaluated individuals at high risk for the development of T2D. In particular, the Chinese Da Qing Impaired Glucose Tolerance and Diabetes Study [78], the Finnish Diabetes Prevention [79], the Diabetes Prevention Program [80] showed that a prevention program based on lifestyle interventions that includes also a regular physical activity is able to reduce the incidence of the new diagnosis of T2D by 46-58%. Although, the results of the lifestyle interventions in the prevention of T2D and IR are mainly ascribed to weight loss [81], it should be underlined that the exercise plays a key role to reduce and maintain the weight loss.

Several studies and meta-analyses have documented that all types of physical activity, such as the leisure time physical activity, the aerobic and the resistance training, or their combination, and the high intensity interval training are able to reduce the incidence of T2D or improve the insulin sensitivity [82-86]. Thus, nowadays, exercise training is highly recommended by the Scientific Societies for primary and secondary CV prevention. In particular, the ADA and AHA recommend reducing the CV risk to perform at least 150 min of moderate-intensity aerobic physical activity per week or, alternatively, at least 90 min of vigorous aerobic exercise per week [87,88]. Finally, there are few and weak data about the beneficial cardio-metabolic effects of uncommon physical activities like aquatic exercise, Nordic walking, Yoga, Pilates, Tai Chi, and dance [89-92]. However, these data need to be further confirmed by studies with larger cohort of individuals and with longer follow-up [93].
Conclusions

One of the paradigms of cardiology is that T2D accounts for development of atherosclerosis and CV complications. Nowadays, there are several evidence that show that TODs, rather to be the consequence, often precede the development of T2D. Indeed, we have demonstrated that the severity of coronary atherosclerosis is predictive of development of T2D [94], and this phenomenon is mediated by IR [8]. Similarly, uncontrollated hypertension, and LVH precede the new diagnosis of T2D [95,96]. Consistently with this view IR needs to be considered the main target of therapeutic strategies aimed to reduce the cardio-metabiolic risk. This goal can be achieved by the integration of dietary changes, physical exercise [77], and pharmacological inhibition of RAAS.

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Figure 4. Exercise training-induced mechanisms that account for the reduction of cardiovascular risk. Notably, this is a complex and multifactorial process that is mediated by an improvement of insulin sensitivity. ACE, angiotensin converting enzyme; Ang, angiotensin; Ang II, angiotensin II; AT2R, type 2 angiotensin II receptor; CRP, C reactive protein; IL-6, interleukin-6; NO, nitric oxide; ROS, reactive oxygen species; TNF-α, tumor necrosis factor-α.
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