

Anti-atherosclerotic Drugs from Natural Products

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Abstract

Atherosclerosis is the cause of more than 50% mortality in industrial countries. Atherosclerosis develops over many years, so the anti-atherosclerotic therapy should be long-term or even lifelong. Tachyphylaxis, long-term toxicity and cost amongst other issues may present problems for the use of conventional medications in the long-term. Drugs based on natural products can be a good alternative.

We have developed a series of natural compounds that are specifically designed to act at the vessel wall and modulate the atherosclerotic lesion. Clinical efficacy was determined in atherosclerosis regression studies with ultrasound examination of carotid arteries. The AMAR study (Atherosclerosis Monitoring and Atherogenicity Reduction) was designed to estimate the effect of two-year treatment with time-released garlic-based drug Allicor on the progression of carotid atherosclerosis in asymptomatic men in double-blinded placebo-controlled randomized clinical trial. The primary outcome was the rate of atherosclerosis progression, measured by high-resolution B-mode ultrasonography as the increase in carotid intima-media thickness (IMT) of the far wall of common carotid arteries. The mean rate of IMT changes in Allicor-treated group was significantly different from the placebo group in which there was moderate progression. The results of AMAR study demonstrate that long-term treatment with Allicor has a direct anti-atherosclerotic effect on carotid atherosclerosis. These results encouraged clinical trials of two other drugs based on natural products, including: Inflaminat (calendula, elder and violet), possessing anti-cytokine activity and the phytoestrogen-rich drug Karinat (garlic powder, extract of grape seeds, green tea leaves, hop cones, β -carotene, α -tocopherol and ascorbic acid), designed for postmenopausal women. As in the AMAR trial Inflaminat caused regression of carotid atherosclerosis while Karinat prevented its development.

It should be noted that the anti-atherosclerotic effects of drugs based on natural products are not inferior to the effects of such drugs as statins and calcium antagonists. Thus, natural products can be considered as promising drugs for anti-atherosclerotic therapy.

Keywords: Allicor; Anti-Atherosclerotic therapy; Atherosclerosis; Cell culture; Drugs; Imaging; Intracellular cholesterol retention; Natural products

Abbreviations: AMAR: Atherosclerosis Monitoring and Atherogenicity Reduction; CIMT: Carotid Intima-media Thickness; HDL: High-density Lipoprotein; LDL: Low Density Lipoprotein

Introduction

Development of anti-atherosclerotic drugs is based on our current knowledge and hypotheses on the mechanisms of atherogenesis. The only hypothesis that has received confirmation in the clinic is the cholesterol hypothesis. This hypothesis was proposed more than 100 years ago by Nikolai Anitschkow. The Anitschkow's hypothesis linked atherosclerosis with high levels of total cholesterol in the blood. The modern paradigm only explains some aspects of this hypothesis, in particular as atherosclerosis is not associated with the total level of cholesterol but with atherogenic low-density lipoprotein (LDL) cholesterol and anti-atherogenic high-density lipoprotein (HDL) cholesterol [1-3].

Retention of intracellular lipids or lipidosis that is the accumulation of cholesterol and other lipids in the arterial cells is the most prominent manifestation of atherosclerosis at the arterial cell level. Williams and Tabas [4,5] proposed so-called the Response-to-Retention model of atherogenesis. Although atherosclerosis is a complex and multifactorial process, the key initiating process in atherogenesis is the sub endothelial cholesterol retention that is both necessary and sufficient to provoke lesion initiation. Retention of cholesterol transported by low density lipoprotein (LDL) in sub endothelial space of arterial wall is an absolute requirement for lesion development. According to Tabas et al. [6] the molecular basis of lipoprotein retention is associated with interaction of lipoprotein and extracellular matrix molecules. Local responses to these

retained lipoproteins include inflammatory response with subsequent lesion development [7]. Specific focus is placed on the potential of these innate immune targets for therapeutic interventions to retard the progression of atherosclerosis or to induce its regression [8]. The response-to-retention model considers only the retention of cholesterol on extracellular matrix, while completely ignoring the retention of intracellular cholesterol.

Intracellular cholesterol retention is accompanied by increased proliferative activity of vascular cells and increased synthesis of extracellular matrix [9,10]. Along with the retention of intracellular cholesterol, both proliferation and fibrosis are characteristic features of atherosclerosis at the arterial cell level, too. Thus, intracellular cholesterol retention may be initial event of all major manifestations of atherosclerosis on cellular level. Intracellular cholesterol retention may be regarded as a novel target for anti-atherosclerotic therapy. This allows us to consider cellular retention of cholesterol as a novel target for anti-atherosclerotic therapy. In this case the target is not the level of blood cholesterol but the level of cholesterol in vascular cells.

This review summarizes the results of basic studies shedding

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light on the mechanisms of intracellular retention of cholesterol. We describe our cellular models to search for anti-atherosclerotic agents and demonstrate the use of these models for the development of anti-atherosclerotic drugs.

Atherosclerosis develops over many years, so the anti-atherosclerotic therapy should be long-term or even lifelong. Tachyphylaxis, long-term toxicity and cost amongst other issues may present problems for the use of conventional medications in the long-term. Drugs based on natural products can be a good alternative. We reported successful translation of innovative attempts and novel drugs from natural products into clinical practice.

Basic Studies

Intracellular retention of cholesterol is induced by LDL. It is well known that native lipoprotein usually does not increase the cholesterol content of the cell; however the incubation of cultured cells with chemically modified LDL results in a massive accumulation of cholesterol in the cells [11]. Thus, modified, but not native, LDL is the source of cholesterol retention in arterial cells. Cells populating atherosclerotic lesions are often overloaded with lipids, and their cytoplasm is almost completely filled with lipid inclusions [12]. These cells are referred to as foam cells because of foamy appearance of their cytoplasm.

In the blood of patients with coronary and extra coronary atherosclerosis we have discovered modified (desialylated) LDL [13-16]. This naturally occurring modified LDL induces cholesterol retention in cultured arterial cells [13-16]. Circulating modified LDL is multiple modified lipoprotein characterizing by lower sialic acid, triglyceride and cholesterol contents; smaller particle size; greater density and negative charge; higher aggregative activity; and some other specific features [17]. We have discovered an enzyme, trans-sialidase, which is responsible for the desialylation of LDL particles in the blood [18].

In addition to desialylated LDL, more electronegative LDL and small dense LDL have been found in human blood [19,20]. In cooperation with researchers who found more electronegative LDL and small dense LDL we carries out comparative studies and showed that the more electronegative LDL is desialylated LDL [21] as well as desialylated LDL isolated from patient blood [13-16] is more electronegative. Desialylated LDL particle is smaller and denser than that of native LDL [22] as well as small dense LDL isolated from patients has a low content of sialic acid, i.e., it is desialylated [23].

Modified (desialylated) LDL stimulates anti-LDL auto-antibodies production [24-28]. Anti-LDL auto-antibodies and modified LDL form LDL-containing circulating immune complexes [29]. We have demonstrated LDL-containing circulating immune complexes and anti-LDL auto-antibodies in the blood of atherosclerotic patients [29-31]. We have also found a positive correlation between the levels of LDL-containing immune complexes and the severity of atherosclerosis [29-33]. LDL is able to form complexes with collagen, elastin, and proteoglycans isolated from human aortic intima [34-39]. These LDL-containing complexes induce intracellular cholesterol retention as a result of increased uptake and decreased intracellular degradation of lipoproteins in complexes [38]. Naturally occurring multiple modified LDL has tendency to associate and forms self-associates, while native LDL does not associate [37]. We found a positive correlation between intracellular cholesterol retention caused by modified LDL and the degree of LDL self-association [37,38]. LDL-associates isolated by gel filtration were shown to induce dramatic intracellular cholesterol retention. Thus, the formation of large LDL containing complexes

(self-associates, immune complexes, and complexes with connective tissue matrix) is a necessary and sufficient condition for intracellular cholesterol retention.

Our knowledge of mechanisms of intracellular cholesterol retention allowed us to consider the prevention of intracellular cholesterol retention as a target for anti-atherosclerotic therapy. As a model of intracellular cholesterol retention we use primary culture of sub endothelial aortic cells and modified LDL or blood serum containing modified LDL. We use this model for the development of anti-atherosclerotic drugs.

Cellular Models

Cells are isolated from the subendothelial part of the human aortic intima between the endothelial lining and the media [39]. Using collagenase and elastase, viable cells are isolated from the subendothelial layer of the intima [40-42]. Isolated cells can be classified as the mixture of smooth muscle cells, pericyte-like cells, and macrophages [39-43]. The culture on which our experiments are performed is represented by this mixed population [39].

Cells isolated from atherosclerotic lesions retain all major characteristics of atherosclerotic cells when cultured. They are capable of synthesizing collagen, proteoglycans and other components of the extracellular matrix [9]. Cell cultured from fatty lesions have an enhanced proliferative activity [41], higher than that of cells cultured from unaffected intima [44,45]. Considerable part of cells cultured from atherosclerotic lesions is foam cells, which contain numerous inclusions, likely lipid droplets, which fill the entirety of the cytoplasm [41]. Excess lipids in foam cells are mainly free cholesterol and cholesteryl esters [41]. It is important that the content and composition of lipids in cultured cells within the first 10-12 days in culture remain unchanged and correspond to the respective indices of freshly isolated cells [41,45]. Thus, our investigations are carried out directly on exactly those cells that require a therapeutic action *in vivo*.

To induce intracellular cholesterol retention we used blood sera obtained from coronary heart disease patients [46]. These sera contain modified LDL [11-14]. As a result serum is atherogenic, i.e., it is able to cause retention of intracellular cholesterol and stimulate other atherogenic manifestations in cultured cells [10,46-48]. Atherogenic serum was added to primary culture of subendothelial cells derived from an unaffected intima. Drug efficacy is judged by the ability to prevent the deposition of intracellular cholesterol in cultured cells. The prevention of intracellular cholesterol retention may be regarded as anti-atherosclerotic effect. In terms of arterial cells, any drug effect that does not directly prevent intracellular cholesterol retention is regarded as an indirect anti-atherosclerotic action. Only a drug that exhibits its preventive activity at the arterial level is a direct anti-atherosclerotic drug. Using this model, we have examined the effects of different drugs and chemicals.

Using our cellular model we have tested three classes of cardiovascular drugs, calcium antagonists, beta-blockers and nitrates. These drugs are widely used in clinics in the therapy of various disorders that resulted from atherosclerosis of different arteries. The effect of several calcium antagonists on intracellular cholesterol retention was tested. Verapamil and nifedipine completely inhibited the accumulation of intracellular cholesterol induced by the sera, while other calcium antagonists, such as diltiazem, nicardipine, isradipine, and darodipine, substantially reduced cholesterol accumulation [49]. The examined calcium antagonists demonstrated anti-atherogenic action *in vivo* by inhibiting the development of experimental atherosclerosis in animals

[50,51]. Thus, our *in vitro* data obtained using the cellular model corresponds to the *in vivo* observations.

Nitrates and beta-blockers have been tested to examine their effect on atherosclerotic cellular indices. Nitrates only minimally affected cholesterol levels [52]. In contrast, all the examined beta-blockers, i.e., propranolol, alprenolol, metoprolol, pindolol, and timolol, increased intracellular cholesterol retention, i.e., all of these drugs exhibited pro-atherogenic activity in culture [49,52]. If beta-blockers have a similar effect *in vivo*, one may assume that these drugs are atherogenic and induce their atherogenic effects at the arterial cell level. Apparently, nitrates do not follow a similar trend.

Thus, three classes of cardiovascular drugs exert a different influence on intracellular cholesterol retention. Calcium antagonists exhibit anti-atherosclerotic actions. In contrast, beta-blockers are pro-atherogenic. Nitrates do not have an effect on intracellular cholesterol retention. Our data are consistent with the results of a clinical study reported by Loaldi et al. [53] who demonstrated that long-term oral administration of propranolol aggravates coronary atherosclerosis in patients with angina of effort compared with the calcium antagonists' nifedipine and isorbide dinitrate. Nifedipine showed the best effect on coronary atherosclerosis by suppressing the development of existing atherosclerotic lesions and preventing the appearance of new lesions. Isosorbide dinitrate was less effective. These clinical observations confirming our *in vitro* results encourage us to develop an anti-atherosclerotic therapy using our cellular model.

Naturally, the question arises whether the anti-atherosclerotic effects revealed in *in vitro* cellular model can be manifested *in vivo*. To answer this question, an *ex vivo* model was developed. In the *ex vivo* model, instead of agents, blood sera taken from patients after oral drug administration is added to cultured cells.

Two calcium antagonists, verapamil and nifedipin, and two beta-blockers, propranolol and pindolol, were examined using the *ex vivo* model [52,54]. Within 2-4 hours after nifedipine or verapamil oral administration, the patients' sera were less atherogenic; i.e., induced less intracellular cholesterol retention. In contrast, the sera of patients who received propranolol or pindolol were pro-atherogenic. Its pro-atherogenic properties manifested themselves at the arterial cell level via the rise of intracellular cholesterol accumulation. This finding allows us to assume that not only *in vitro*, but also *in vivo*, calcium antagonists and beta-blockers are anti-atherosclerotic and pro-atherogenic drugs, respectively.

The effect of nifedipine on serum properties during a course has been assessed [49]. A patient received 20-mg doses of nifedipine three times a day at an 8-hour interval for 7 days. Twenty-eight days after regular nifedipine therapy, the atherogenicity of the patient's serum was considerably lower than at the beginning of the therapy. Directly after new dose of nifedipine, the intracellular cholesterol retention was not revealed. In contrast, after a course treatment with the beta-blocker propranolol, the patient's serum acquired stable atherogenic properties. At the beginning of the course, the serum of this patient did not induce intracellular cholesterol retention; however, 28 days of regular propranolol therapy led to the emergence of atherogenicity, revealed even before the drug administration.

Natural Products

Ex vivo cellular model can be used to test natural products. We have investigated prevention of intracellular cholesterol retention caused by certain mushroom species and sea products. Extracts from 20 Korean mushroom species exhibit intracellular cholesterol retention revealed by

cell culture test [55]. Among sea products, mollusk and krill meat were investigated. Two hours after a single dietary load with canned meat of a mollusk belonging to the genus *Buccinum*, the patient's blood serum acquired marked anti-atherosclerotic properties [56]. Incubation of this serum with cultured atherosclerotic cells led to a fall in intracellular cholesterol retention. Patients of another group received a single dietary dose of Antarctic krill meat. Two hours later, the retention of cellular cholesterol induced by blood sera decreased, and four hours later, it was practically absent [56].

To develop a dietary therapy based on the krill meat, the effective dose and proper regimen have been established. The anti-atherosclerotic activity of krill meat was evaluated by the ability to reduce intracellular cholesterol retention. The dose-effect dependence was revealed by comparing the efficacy of the two doses, and we found that krill meat possesses anti-atherosclerotic effects at a dose of 10-20 g, half-maximum effect was reached at a dose of 30 g, and the maximum effect was achieved at a dose of 50 g. We believe that this approach will be useful in the development and optimization of anti-atherosclerotic dietary therapies.

We have tested numerous extracts of natural products to reveal their effects on their capacity to prevent intracellular cholesterol retention caused by atherogenic blood sera from atherosclerotic patients. Naturally, the tested agents included anti-atherosclerotic, pro-atherogenic, and neutral products. Among the anti-atherosclerotic natural products, the most effective was garlic.

We investigated the *in vitro* effect of garlic extract on intracellular cholesterol retention. Garlic prevented the serum-induced accumulation of free cholesterol and reduced the accumulation of cholesteryl esters [57]. The effect of garlic on cholesteryl esters may be explained by the action on enzymes responsible for cholesteryl ester metabolism. We have shown that garlic inhibits acyl-CoA: cholesterol acyltransferase, which participates in cholesteryl ester formation, and stimulates cholesteryl ester hydrolase, which degrades cholesteryl esters [57].

Further investigations *ex vivo* confirmed the *in vitro* effects of garlic [58]. In *ex vivo* experiments we applied dry garlic powder. Using *ex vivo* model we optimized the effective dose of oral garlic powder administration. The anti-atherosclerotic activity of garlic powder was evaluated by the ability to reduce intracellular cholesterol retention. The dose-effect dependence was revealed by comparing the efficacy of the two doses, and we found that garlic powder possesses anti-atherosclerotic effects at a dose of 50-300 mg. The minimum dose causing maximum effect was 150 mg.

Using the optimal dose of 150 mg garlic powder we have showed that long-term treatment for months and years leads to a significant reduction of intracellular cholesterol retention or its extinction [58,59]. These data stimulated us to develop a drug based on garlic powder and carried out a clinical study of the effects of this drug on atherosclerosis regression.

Translation into Clinics

We have developed the time-released garlic powder tablets referred to as Allicor that have been registered and are now being manufactured by INAT-Farma, Ltd. (Russia). The AMAR study (Atherosclerosis Monitoring and Atherogenicity Reduction) was carried out to estimate the effect of two-year treatment with Allicor on the progression of carotid atherosclerosis in asymptomatic men in a double-blinded, placebo-controlled randomized clinical trial (ClinicalTrials.gov Identifier, NCT01734707). The primary outcome was the rate of atherosclerosis

progression, measured by high-resolution B-mode ultrasonography as the increase in carotid intima-media thickness (CIMT) of the far wall of common carotid arteries [59].

At the baseline, blood serum taken from patients induced 1.56-fold increase in intracellular cholesterol retention in cell culture test. In the placebo group, the mean value of serum induced intracellular cholesterol retention did not change significantly during two years. On the opposite, in Allicor-treated patients the mean level of intracellular cholesterol retention was significantly lowered already after first 3 months of treatment, and this effect was maintained during the study. We found statistically significant difference in the dynamic of changes in intracellular cholesterol retention between Allicor-treated and placebo groups. Allicor significantly reduced CIMT compared to baseline and the placebo group, while spontaneous atherosclerosis progression prevailed in the placebo group.

Our data are generally consistent with the results of a double-blinded, placebo-controlled randomized study by Koscielny et al. [60]. That study has been demonstrated that 4-year treatment with the garlic-based drug Kwai inhibited the increase in volume of atherosclerotic plaques in carotid and femoral arteries by 5-18%.

Atherosclerosis regression effect of Allicor revealed in the AMAR study is comparable with the results of most successful trials with other compounds [61-68]. Those studies employed potent lipid-lowering agents or calcium antagonists, whose beneficial effects of treatment were attributed to reduction in LDL cholesterol, the major risk factor for atherosclerosis development, or arterial wall stress.

Effects of Allicor promoted new clinical trials of two other drugs based on natural products, Inflaminat, which possesses anti-cytokine activity, and the phytoestrogen-rich drug Karinat, which is designed for postmenopausal women.

Inflammatory cytokines play significant role at every stage of atherogenesis [69-71]. So, anti-cytokine drugs may be effective for the prevention of atherosclerosis. We have developed drug Inflaminat, which is based on calendula, elder and violet. Our laboratory investigations demonstrated that Inflaminat suppresses secretion of pro-inflammatory cytokines and reduces intracellular cholesterol retention. We have carried out a pilot study (Clinical Trials.gov Identifier, NCT01743404) with Inflaminat using a protocol similar to that of the AMAR study. New study demonstrated atherosclerosis regression effects of Inflaminat and a statistically significant difference from the baseline as well as from placebo group in asymptomatic men [59].

The effective approaches to atherosclerosis prevention in postmenopausal women do not exist. Hormone replacement therapy is not acceptable due to the negative results of clinical studies, including WHI, PEPI, and HERS [72-77]. Phytoestrogens may be an alternative to hormone replacement therapy, but practically nothing is known about their effects on atherosclerosis.

We selected phytoestrogen-rich botanicals on the basis of their ability to prevent intracellular cholesterol retention in *ex vivo* test system. The following combination was chosen: garlic powder, extract of grape seeds, green tea leaves, and hop cones, all of them produced significant anti-atherogenic effects. This combination was used for development of novel isoflavonoid-rich dietary supplement Karinat. Karinat prevents intracellular cholesterol retention and is characterized by good phytoestrogen profile, providing additional amounts of biologically active polyphenols, including resveratrol, genisteine, and daidzeine. Moreover Karinat contains additional amounts of

β -carotene, α -tocopherol and ascorbic acid to provide the necessary daily intake of antioxidants.

We have carried out a randomized, double-blinded, placebo-controlled pilot clinical trial to reveal possible atherosclerosis-related effects of Karinat in healthy postmenopausal women ([http://clinicaltrials.gov/Identifiers, NCT01741974](http://clinicaltrials.gov/Identifiers/NCT01741974) and [NCT01742000](http://clinicaltrials.gov/Identifiers/NCT01742000)). The annual rate of changes in CIMT was monitored. In the Karinat group the average CIMT was not changed (statistically insignificant increase of 6 μ m per year, less than 1%). The progression of existing plaques was slower by 32% per year. Thus, the use of Karinat in postmenopausal women almost completely suppresses the formation of new atherosclerotic lesions, and it slows the progression of existing lesions [59].

Conclusion

Our basic studies have demonstrated that intracellular cholesterol retention is the key initiating process in atherogenesis. On the basis of our data we have developed cellular models and an approach to prevent intracellular cholesterol retention. We have demonstrated that prevention of intracellular cholesterol retention leads to the prevention of atherosclerosis progression and/or its regression in patients. We can conclude that our basic findings were successfully translated into clinics.

Unfortunately, natural products with anti-atherosclerotic therapeutic potential are not prescribed by medical practitioners as anti-atherosclerotic agents. However, our data allows us to consider botanicals as anti-atherosclerotic prescriptions [78].

Conflict of Interest

The author confirms that this article presents no conflicts of interest.

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