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Combined methotrexate and coenzyme Q\textsubscript{10} therapy in adjuvant-induced arthritis evaluated using parameters of inflammation and oxidative stress*

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**Abstract**

Rheumatoid arthritis (RA) is a common severe joint disease that affects all age groups, and thus is of great importance to develop new strategies for its treatment. The aim of the present study was to examine the combined effect of coenzyme Q\textsubscript{9} (CoQ\textsubscript{9}) and methotrexate (MTX) on the progression of adjuvant-induced arthritis in rats. Adjuvant arthritis (AA) was induced by a single intradermal injection of heat-inactivated Mycobacterium butyricum in incomplete Freund's adjuvant. The experiments included healthy animals, arthritic animals not treated, arthritic animals treated with CoQ\textsubscript{10}, with methotrexate, and with a combination of CoQ\textsubscript{10} and methotrexate. The two latter groups received a daily oral dose of 20 mg/kg b.w. of CoQ\textsubscript{10}, either alone or with methotrexate in an oral dose of 0.3 mg/kg b.w. twice a week. We found that CoQ\textsubscript{10} potentiated both the antiarthritic (decrease of hind paw volume) and the antioxidant effect of methotrexate on the level of oxidation of proteins (suppression of protein carbonyl level in plasma) as well as lipoperoxidation (suppression of levels of HNE-adducts and MDA-adducts to plasma proteins). The same effect was observed for plasmatic levels of CoQ\textsubscript{9} and IL-1\textalpha, and partially also γ-glutamyltransferase activity assessed in joints and spleen. Moreover, the combination therapy improved the functionality of peripheral blood neutrophils in AA, with a balancing effect on the immunosuppression caused by MTX monotherapy. In summary, combined administration of CoQ\textsubscript{10} and methotrexate suppressed arthritic progression in rats more effectively than did MTX alone. This finding may help improve treatment of rheumatoid arthritis.

Keywords: combined therapy, methotrexate, coenzyme Q, arthritis, inflammation, oxidative stress

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**INTRODUCTION**

Rheumatoid arthritis (RA) is a common severe joint disease affecting all age groups. It is thus of great importance to develop new strategies for its treatment. As a number of disease-modifying anti-rheumatic drugs (DMARDs) often have side effects at high doses and/or during long-term administration, increased efficacy without increased toxicity are expected for combination therapy of RA. Methotrexate (MTX), a folic acid antagonist, has become the predominant immunosuppressive agent used in the treatment of patients with RA (Williams et al., 1985). MTX acts mainly on actively proliferating cells during the S-phase of proliferation, suppresses macrophage function, modulates interleukin-1 (IL-1) and superoxide anion production, and inhibits neutrophil chemotaxis (Moreland et al., 1997). Furthermore, MTX treatment was shown to decrease synovial collagenase gene expression in patients with RA (Genestier et al., 2000). The use of MTX has been limited by some of its toxic manifestations, such as abdominal discomfort, alopecia, oral ulcerations, and cytopenia (Alarcon et al., 1989). In clinical studies, infliximab or etanercept have been used in combination with methotrexate to produce greater efficacy of the treatment of RA (Maini et al., 1998; Weinblatt et al., 1999). TNF\textalpha blockers may be used alternatively with other candidates for RA combination therapy. The lack of thorough understanding of the pathogenesis of RA is a major problem in the introduction of new therapies. Several clinical studies as well as preclinical animal models of RA have documented an imbalance in the body redox homeostasis to a more pro-oxidative environment, suggesting that therapies that restore the redox balance may have beneficial effects (Kunsch et al., 2005). Bauerova and Bezek (1999) and Jaswal et al. (2003) described oxidative stress as a primary factor in the pathogenesis of RA. However, the use of antioxidants to treat RA has yielded conflicting results (Bauerova et al., 2005). Mammalian cells, undergoing cell stress and proliferation, require antioxidant defense mechanisms to protect cellular components from the damaging effects of reactive oxygen species (ROS), such as superoxide radicals (O\textsuperscript{2-}), hydroxyl radicals (OH\textsuperscript{-}), and hydrogen peroxide (H\textsubscript{2}O\textsubscript{2}). The most unique antioxidant defense molecule is coenzyme Q (CoQ), a mitochondrial membrane-bound molecule that functions as a redox mediator between ROS and the mitochondrial electron transport chain.

**Keywords**

CoQ\textsubscript{10}, RA, inflammation, oxidative stress

**Abbreviations**

AA, adjuvant arthritis; AA-CoQ\textsubscript{10}, arthritic animals treated with coenzyme Q\textsubscript{10}; AA-MTX, arthritic animals treated with methotrexate; AA-MTX+CoQ\textsubscript{10}, arthritic animals treated with combination of CoQ\textsubscript{10} and methotrexate; ACK, ammonium-chloride-potasium chloride; b.w., body weight; BSA, bovine serum albumin; CoQ\textsubscript{9}, coenzyme Q\textsubscript{9}; CoQ\textsubscript{10}, coenzyme Q\textsubscript{10}; DNP, dinotrophenylhydrazine; ELISA, enzyme linked immunosorbent assay; FITC, fluorescein isothiocyanate; GGT, gammaglutamyl transferase; GSH, glutathione; HC, healthy animals; HNE, 4-hydroxy-2-nonenal; HPLC, high-performance liquid chromatography; HPV, hind paw volume; HRP, horse radish peroxidase; IgG, immunoglobulin; IL-1, interleukin-1; IL-1\textalpha, interleukin-1 alpha; MB, Mycobacterium butyricum; MDA, malondialdehyde; MTX, methotrexate; PMNs, polymorphonuclear leukocytes; RA, rheumatoid arthritis; SEM, standard error of the mean; sol. inj., solution for injection; SPA-FITC, fluorescein-labeled opsonized S. aureus; TBARS, thiobarbituric acid reacting substances; TNF\textalpha, tumor necrosis factor-alpha; γ-GPN, gamma-glutamyl-para-nitroanilide
involved in the pathogenetic changes during rheumatoid arthritis. In our studies, synthetic and natural substances with antioxidant activity were evaluated by using adjuvant arthritis (AA) — an animal model of RA which allows monitoring the disease processes in the acute (days 14–21) and subchronic phase (after day 28). The advantage of this model is its great similarity to RA, such as symmetrical joint involvement, persistent joint inflammation, synovial hyperplasia, and a good response to most therapies effective in RA (Bina & Wilder, 1999). Many of the substances with antioxidant properties tested in monotherapy proved to be effective in suppressing the progression of AA (Bauerova et al., 2005a; 2005b; 2008a; 2008b; 2009; Drabikova et al., 2009; Gvozdjakova et al., 2004; Jancinova et al., 2009; Kogan et al., 2005; Nasal et al., 2007; Rovensky et al., 2008; 2009a; Sotnikova et al., 2008; 2009).

Based on our results with mitochondrial energetics and the observed anti-inflammatory and antioxidant effects (Gvozdjakova et al., 2004; Bauerova et al., 2005a; 2008a; Ponist et al., 2007), we chose CoQ10 as a candidate for combinatory therapy of RA. Patients with RA often suffer muscle weakness and atrophy. It is assumed that progressive muscle atrophy in RA patients is caused by damaged myofibrils and impaired mitochondria (De Palma et al., 2000). Disruption of mitochondrial bioenergetics caused by free radicals is involved in development of myopathies. Oxidative stress– caused alteration of mitochondrial functions can manifest in different manners (Cardoso et al., 1999). Leakage of free radicals from the respiratory chain leads to damaged mitochondrial membrane, proteins, DNA and inhibits oxidative phosphorylation (Luft, 1995; Miesel, 2010). It is assumed that mitochondrial damaged membrane, proteins, DNA and inhibits oxidative phosphorylation (Luft, 1995; Miesel, 2010). Based on our results with mitochondrial energetics and the observed anti-inflammatory and antioxidant effects (Gvozdjakova et al., 2004; Bauerova et al., 2005a; 2008a; Ponist et al., 2007), we chose CoQ10 as a candidate for combinatory therapy of RA. Patients with RA often suffer muscle weakness and atrophy. It is assumed that progressive muscle atrophy in RA patients is caused by damaged myofibrils and impaired mitochondria (De Palma et al., 2000). Disruption of mitochondrial bioenergetics caused by free radicals is involved in development of myopathies. Oxidative stress– caused alteration of mitochondrial functions can manifest in different manners (Cardoso et al., 1999). Leakage of free radicals from the respiratory chain leads to damaged mitochondrial membrane, proteins, DNA and inhibits oxidative phosphorylation (Luft, 1995; Miesel, 2010). It is assumed that mitochondrial damaged membrane, proteins, DNA and inhibits oxidative phosphorylation (Luft, 1995; Miesel, 2010).

MATERIAL AND METHODS

Animals, experimental design and treatments. Male Lewis rats weighing 160–180 g were obtained from the Breeding Farm Dobra Voda (Slovakia). The rats had free access to standard pelleted diet and tap water. The animal facilities comply with the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Purposes. The experimental protocol was approved by the Ethics Committee of the Institute of Experimental Pharmacology and Toxicology and by the Slovak State Veterinary Committee of Animal Experimentation. Adjuvant arthritis (AA) was induced by a single intradermal injection of heat-inactivated Mycobacterium butyricum (MB) in incomplete Freund’s adjuvant (Difco Laboratories, Detroit, MI, USA). The injection was performed near the tail base. The experiments included healthy animals (HC), arthritic animals not treated (AA), arthritic animals treated with coenzyme Q10 (AA-CoQ10), arthritic animals treated with methotrexate (AA-MTX), and arthritic animals treated with the combination of CoQ10 and methotrexate (AA-MTX+CoQ10). The two latter groups received a daily oral dose of 20 mg/kg b.w. of CoQ10 either alone (AA-MTX) or with methotrexate in the oral dose of 0.3 mg/kg b.w. twice a week (AA-MTX+CoQ10). AA-MTX was performed as a reference treatment. Methotrexate® Lachema 50 sol. inj. was used. CoQ10 in the form of Li-Q-Sorb® was purchased from Tischcon Corp. (USA). In each experimental group, 8–10 animals were used. The duration of the experiment was 28 days. Blood was collected under light ketamin/xylasine anesthesia from the retro-orbital plexus on day 7 and immediately flow cytometric measurements were performed. After the animals had been sacrificed under deep ketamin/xylasine anesthesia, blood for plasma preparation and tissues for spleen and for hind paw joint homogenate preparation were taken on day 28. Plasma was stored at –70°C until biochemical and immunological analysis.

Clinical parameter evaluated: hind paw volume. We monitored one basic clinical parameter: the hind paw volume (HPV). The HPV increase was calculated as the percentage increase in the HPV on a given experimental day relative to the HPV at the beginning of the experiment. Hind paw volume was recorded on days 1, 14, 21, and 28 with the use of an electronic water plethysmometer (UGO BASILE, Comerio-Varese, Italy).

Biochemical and immunological analysis. Protein carbonyl assay. Enzyme linked immunosorbent assay (ELISA) was used for quantitative determination of protein carbonyls in plasma (Buss et al., 1997). Protein samples were derivatized with dinitrophenylhydrazine (DNPH) and adsorbed in multwell plates (Nunc Immunosorp plates, Roskilde, Denmark). A biotin-conjugated anti-dinitrophenyl rabbit IgG (Sigma, USA) was used as the primary antibody and a peroxidase conjugated monoclonal anti-rabbit-IgG antibody (Sigma, USA) as the secondary antibody. The development was performed with ortho-phenylenediamine. Absorbance was determined at 492 nm. The method was calibrated using oxidized bovine serum albumin (BSA). Oxidized and reduced BSA was prepared according to the method of Buss et al. (1997).
Determination of lipid peroxidation. The presence of oxidative damage was assessed in plasma by determining the fluorescent adducts formed between peroxidation-derived aldehydes and plasma proteins. In particular, two types of protein-aldehyde adducts were determined: HNE-protein adducts (355 nm excitation; 460 nm emission) and MDA-protein adducts (390 nm excitation; 460 nm emission). Preparation of samples and fluorimetric measurements were performed according to Tsuchida et al. (1985) and Biasi et al. (1995). Briefly, 150 μl of plasma was suspended in 6 ml ethanol/ether (3:1, v/v); after 10 min incubation in ice, the samples were centrifuged at 1500 g, the supernatant discarded and the pellets washed twice with ethanol/ether (3:1, v:v). After the last centrifugation the pellets were dissolved in 3 ml of 0.1 % sodium dodecyl sulfate (SDS) and immediately used for spectrofluorimetry (Kontron SFM 25). In parallel, standard curves were prepared with decreasing amounts of HNE or MDA dissolved in BSA (1 mg/ml): the adducts aldehydes with BSA were allowed to form by incubating the solutions at 37°C for 40 min, after which the samples were immediately read for fluorescence. Data were expressed as arbitrary units/mg protein. Protein detection was done with the Peterson method (Peterson et al., 1977).

Coenzyme Q₉ determination. Concentration of oxidized coenzyme Q₉ was determined by isocratic high performance liquid chromatography (HPLC, LKB, Sweden) according to Lang et al. (1986) with some modifications (Kucharska et al., 1998). Plasma samples (500 μl) were vortexed twice for 5 min with 2 ml of a mixture of hexane/ethanol (5:2, v/v; Merck, Germany). Collected organic layers were evaporated under nitrogen; the residue was taken up in ethanol and injected into a Separon SGX C18 7 μm 3 mm ×150 mm column (Tessek, Czech Republic). Elution was performed with methanol/acetone/ethanol (6:2:2, by vol; Merck, Germany). The concentration of coenzyme Q₉ was determined spectrophotometrically at 275 nm, using external standards (Sigma, Germany). Data were collected and processed using a CSW 32 chromatographic station (DataApex Ltd, Czech Republic). Concentrations of compounds in the plasma were calculated in μmol·l⁻¹.

For determination of IL-1z in plasma an ELISA kit from Bender MedSystems was used as described in the product manual Rat IL-1z ELISA BMS627 and BMS627TEN. The rat IL-1 ELISA is an assay for quantitative detection of rat IL-1. Rat IL-1 present in the samples binds to anti-rat IL-1 antibodies adsorbed to the microwells. The reaction of a secondary biotin-conjugated anti-rat IL-1 antibody is evaluated by Streptavidin-HRP. Tetramethylbenzidine oxidation with HRP bound to the immune complex was measured at 490 nm against reference wavelength of 620 nm. The results were calculated from a standard curve obtained for internal standards.

Tissue activity of cellular γ-glutamyltransferase. The activity of cellular γ-glutamyltransferase (GGT) in hind paw joint tissue and in spleen tissue homogenates was measured by the method of Orlowski and Meister (1970) as modified by Ondrejčaková et al. (1993). Samples were homogenized in a buffer at 1:9 (w/v) (buffer composition: 2.6 mM NaH₂PO₄, 50 mM Na₂HPO₄, 15 mM EDTA, 68 mM NaCl; pH 8.1) by Ultra Turrax TP 18/10 (Janke & Kunkel, Germany) for 1 min at 0°C. Substrates (8.7 mM γ-glutamyl-p-nitroanilide (γ-GPN); 44 mM methionine) were added in 65 % isopropanol to final concentrations of 2.5 mM and 12.6 mM, respectively. After incubation for 60 min at 37°C, the reaction was stopped with 2.3 ml cold methanol and the tubes were centrifuged for 20 min at 5000 rpm. Absorbance of supernatant was measured in a Hewlett Packard Vectra 286/12 spectrophotometer in 0.5 cm cuvette at 406 nm. Reaction mixtures in the absence of either the substrate or acceptor were used as reference samples.

Simultaneous phagocytosis and oxidative burst. Throughout phagocytosis accompanied by respiratory burst of rat granulocytes, the double fluorescence of fluorescein isothiocyanate (FITC)-labeled ingested *Staphylococcus aureus* cells and that of hydroxyethidine (HE) oxidized to ethidium bromide were evaluated by flow cytometry (Beckman-Coulter FC 500 flow cytometer running under CXP software). The previously reported method (Kronek et al., 2010) was modified for whole rat blood. For each blood sample, a fluorescence histogram of 5000 cells was generated and analyzed. Gates were set around granulocytes to exclude debris. Measurement of phagocytosis, i.e. the ingestion of bacteria, took place under controlled conditions, using fluorescein-labeled opsonized *Staphylococcus aureus* (SPA-FITC) (Invitrogen Molecular Probes, USA). Metabolic activity was determined as the oxidative burst causing transformation of the originally non-fluorescent hydroxyethidine (Invitrogen Molecular Probes, USA) into ethidium following SPA-FITC ingestion. Aliquots of rat peripheral blood in lithium-heparin were incubated with HE (15.75 mg in 5 ml of dimethylformamide) for 15 min at 37°C. Following treatment with SPA-FITC for the next 15 min at 37°C, the reaction was stopped by placing the samples on ice. The subsequent ethidroxyrythrosine lysis was performed for 15 min with an ice-cold ammonium-chloride-potassium chloride (ACK) lysis buffer (200 ml deionized water, 1.658 g NH₄Cl; 0.2 g KHCO₃; 7.4 mg Na₂EDTA, pH 7.2–7.4) (Lachema, Czech Republic). Blood specimens were obtained by retroorbital sinus puncture under light anesthesia (ketamine/xylazine) of animals. Whole blood samples were collected into lithium heparin (Sarstedt Multivette) blood sample collectors.

Statistics. The data were expressed as arithmetic mean ± S.E.M. Arthritis group untreated was compared with healthy control animals (*), treated arthritis groups were compared with untreated arthritis animals (#), and arthritis groups with combination therapy were compared with the reference treatment (#). For significance calculations unpaired Student’s t-test (two sample, unequal variance) was used with the following significance designations: extremely significant (P<0.001); highly significant (P<0.01); significant (P<0.05); not significant (P>0.05).

RESULTS AND DISCUSSION

Clinical manifestation of adjuvant arthritis and effects of therapy

We monitored the hind paw volume change after clinical development of arthritis on experimental days 14, 21 and 28. In our previous experiments, we confirmed that clinical parameters, such as hind paw volume and body weight, became significantly modified starting around day 14 (Bauerova et al., 2007). As illustrated in Fig. 1, the HPV is significantly increased for the arthritis group in comparison with healthy control already on day 14 and this increase is maintained until the end of the experiment. CoQ₁₀ supplementation to arthritis animals slightly decreased the HPV on all experimental days. In the
treatment of RA, methotrexate (MTX) is the most commonly prescribed disease-modifying anti-rheumatic drug. It has suppressive effects on inflammation in AA, first described by Welles et al. (1985). In the present study, the decreasing effect of MTX monotherapy on hind paw swelling was evident on all monitored days (Fig. 1). The significance of this effect was a confirmation of its well-known antiarthritic effect, which we proved also previously on the adjuvant arthritis model (Nosal et al., 2007; Jurcovicova et al., 2009; Rovensky et al., 2009a). Due to the adverse effects of MTX accompanying its administration to arthritic patients, which are factors often limiting the acceptable dose, duration and safety of the therapy with MTX (Visser & van der Heijde, 2009), a combinatorial therapy of MTX is recommended with the aim to eliminate or minimalize these limitations. Besides the classical antirheumatics given in the combination schedule with a low dose of MTX, new candidates with antioxidative properties are being studied (Rovensky et al., 2002, 2008; 2009a; 2009b; Cuzzocrea et al., 2005; Dadhania et al., 2010; Kogure et al., 2010). As the pathogenesis of arthritis is associated predominantly with the formation of free radicals at the site of inflammation, we chose CoQ10 as an appropriate candidate. Antirheumatic treatment affecting the level of CoQ10 was found to slow down the progression of the disease in arthritic patients (Comstock et al., 1997; Knekt et al., 2000). Mitochondrial function in the heart and skeletal muscle and efficacy of supplementation with CoQ10 depended on the severity of the induced adjuvant arthritis (AA) in rats. The results with solubilized CoQ10 (water-soluble form) indicated its therapeutic effect in the experimental model of AA (Gvozdzikova et al., 2004; Bauerova et al., 2005a; 2005b; Ponist et al., 2007). These findings are of potential significance in the treatment of patients with rheumatoid arthritis. On the basis of the results achieved with CoQ10 monotherapy, we selected this endogenous antioxidant with the aim to establish its suitability for the combination with MTX. The selected oral doses (for MTX 0.3 mg/kg of b.w. twice a week and for CoQ10 20 mg/kg of b.w. daily over one month) were established previously (Bauerova et al., 2005a; Jurcovicova et al., 2009). As shown in Fig. 1, the combination therapy was the most effective in decreasing the HPV of arthritic animals on all experimental days selected. Moreover, for day 14, we found a statistically significant difference between MTX monotherapy and its combination with CoQ10.

**Different parameters of oxidative stress monitored in adjuvant arthritis and effect of treatment**

These promising clinical results were further completed by measurements of HNE- and MDA-protein adducts and protein carbonyls in plasma (Fig. 2). We obtained a good agreement of HPV with the parameters of oxidative stress: the effect was increasing in the order CoQ10 alone, MTX alone, combination of CoQ10 and MTX. The most pronounced effect found for the combination of MTX and CoQ10 was significant for all oxidative stress parameters compared with non-treated arthritic animals. Moreover, the combination decreased all parameters close to the control group values, being more effective than the individual substances (Fig. 2). On using measurements of plasmatic protein carbonyls, we found damage of proteins caused by oxidative stress accompanying arthritis in past experiments (Bauerova et al., 2005b; Kogan et al., 2005; Strosova et al., 2009). Progression of lipid peroxidation in AA was previously described by analysis of TBARS plasmatic levels (Bauerova et al., 2005a; 2008b; 2009; Bauerova & Bezek, 2009; Strosova et al., 2008; 2009). Although the percentage increase was not so high for adducts as for protein carbonyls and TBARS levels in plasma, advanced measurements of HNE- and MDA-protein adducts showed for non-treated arthritis damaged animals the same level of significance as found for protein carbonyls (Fig. 2). Significant changes in the levels of CoQ9 and/or CoQ10 have been noted in a wide variety of diseases in both animal and human studies. These changes may be caused by impairment in CoQ biosynthesis or excessive utilization of CoQ by the body, or any combination of these processes (Littarru et al., 1991; Bauerova et al., 2008a). In this experiment, we focused on evaluating the CoQ9 plasmatic levels as the dominant form of CoQ in rats. Its concentration is about 10 times higher than the concentration of CoQ10 (Dallner & Sindelar, 2000).
of synoviocytes, chondrocytes and osteoblasts. Moreover, IL-1 is a key mediator of synovial inflammation and pannus formation (Dinarello & Moldawer, 2002). In the AA model used in our experiments, IL-1α was significantly increased in plasma on day 14 and also on day 28.

**Figure 3. Levels of CoQ9 in plasma determined in the model of adjuvant arthritis on day 28.**

Effects of CoQ9 and methotrexate in monotherapy and combined therapy on plasma concentration of CoQ9. The data were expressed as arithmetic mean ± S.E.M. Each group contained 8–10 animals. Statistical significance was evaluated applying Student’s t-test for independent variables: *P < 0.01 with respect to control healthy animals; P < 0.05 with respect to untreated arthritic animals.

As shown in Fig. 3, the arthritis process increases significantly the level of CoQ9 in comparison with HC. The effect of therapy on this phenomenon reveals a picture comparable to that found for other oxidative stress parameters (Fig. 2). The combination therapy was again the most effective and significant in comparison to the untreated arthritic group (Fig. 3). The improvement is on the level of HC. Evidently, the arthritic processes stimulate the synthesis of CoQ and its transport to plasma. These results are, in good agreement with the results obtained on rat experimental diabetes models, in which increased concentrations of CoQ9 in plasma may indicate adaptive changes in diseases associated with oxidative stress (Kucharska et al., 2000; Kuzelova et al., 2008).

Supplementation with CoQ9 is not sufficient to inhibit these processes, while the combination of CoQ9 with MTX proved successful in returning the increased plasma levels of CoQ9 to control levels (Fig. 3).

**Changes in plasma pro-inflammatory cytokine IL-1 levels**

For further evaluation of the efficacy of the administration of CoQ9+MTX, and with the aim to support the obtained clinical and biochemical data with immunological measurements, we performed an analysis of IL-1α in plasma, which is one of the most important pro-inflammatory cytokines. IL-1α is secreted by monocytes/macrophages activated via TNFα and/or bacterial endotoxin. Furthermore, IL-1α markedly potentiates the toxic effect of TNFα in animal experiments (Waage et al., 1991). Rheumatoid arthritis is associated with elevated levels of IL-1 in the synovium. IL-1α is closely related to inflammation and articular damage in several arthritis models and it is therefore generally accepted that IL-1α has a pivotal role in the pathophysiology of rheumatoid arthritis. In particular, IL-1α is a potent stimulator of synoviocytes, chondrocytes and osteoblasts. Moreover, IL-1α is a key mediator of synovial inflammation and pannus formation (Dinarello & Moldawer, 2002). In the AA model used in our experiments, IL-1α was significantly increased in plasma on day 14 and also on day 28 (Bauerova et al., 2007; 2009). Figure 4 shows that the effects of the given treatments on the AA-increased IL-1α levels are very close to the effects illustrated in Figs. 1 and 2. The improving effect on the increased cytokine plasmatic levels is rising in the order CoQ9+MTX and CoQ9+MTX. Furthermore, a statistically significant difference was found between MTX monotherapy and its combination with CoQ9.

**Activity of GGT in selected tissues**

As the only enzyme of the γ-glutamyl cycle located on the outer surface of the plasma membrane, γ-glutamyltransferase (GGT) plays a key role in glutathione (GSH) homeostasis by breaking down extracellular GSH and providing cysteine, the rate limiting substrate for intracellular de novo synthesis of GSH (Zhang et al., 2005). Moreover, GGT is a multifunctional protein. There is evidence that cellular GGT plays an important role in the antioxidant defense system (Kugelman et al., 1994; Lieberman et al., 1996). Ectoplasmic GGT favors the cellular supply of GSH, the most important non-protein antioxidant of the cell. Some epidemiological studies have suggested that serum GGT within its normal range might be an early marker of oxidative stress (Lee & Jacobs, 2005) as well as of the activation of systemic inflammation (Yamada et al., 2006). GGT activity in organs such as spleen and joint could be a simple and inexpensive marker of AA and RA develop-

**Figure 5. GGT activities in spleen homogenates of rats 28 days after arthritis induction.**

Effects of CoQ9 and methotrexate in monotherapy and combined therapy on plasma concentration of IL-1α. The data were expressed as arithmetic mean ± S.E.M. Each group contained 8–10 animals. Statistical significance was evaluated applying Student’s t-test for independent variables: **P < 0.001 with respect to control healthy animals; ***P < 0.001 with respect to untreated arthritic animals.”
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activity. The processes of phagocytosis and the subsequent production of reactive oxygen intermediates during oxidative burst are crucial components of the host defense system. Apparently, neutrophils exhibit many of the properties of phagocytotic cells of the monocyte/macrophage lineage. Neutrophils are present in a number of chronic inflammatory diseases, such as arthritis, and this is indicative of their important role in chronic inflammation. Their rapid secretion of different factors, released also by macrophages, lymphocytes and fibroblasts, indicates that neutrophils can play similar roles in chronic inflammation. Many of these factors are pivotal in causing tissue destruction, either directly or indirectly (Edwards & Hallett, 1997; Haynes, 2007). Recent data have revealed that RA-derived peripheral and synovial fluid neutrophils develop an intense respiratory burst (Cascao et al., 2010). In the model of AA, we observed already on experimental day 7 that AA was accompanied by an increased number of neutrophils in blood and by a more pronounced spontaneous as well as phorbol myristate acetate-stimulated chemiluminescence (Nosal et al., 2007). Interestingly, increased production of ROS by neutrophils emerged already in an early phase of disease, therefore we decided to investigate this finding more precisely using flow cytometry. Another reason was that the changes in neutrophils occur before the clinical parameter HPV starts to be increased. The functionality of peripheral blood neutrophils in AA was evaluated by phagocytosis, oxidative burst and metabolic activity (Fig. 7). Both phagocytosis and oxidative burst were increased due to arthritis. Metabolic activity of neutrophils is the percentage of double positive cells — simultaneously phagocytotic and positive for oxidative burst. Decreased metabolic activity could be explained with increased number of “arthritic” neutrophils, which are positive only for oxidative burst and therefore are not counted as double positive cells. The immunosuppressive effect of MTX was demonstrated in lowering all parameters, not only in comparison with arthritis but also with HC. The addition of CoQ10 to MTX modulated all processes back to the level of HC. The observed immunomodulating activity of CoQ10 may prove beneficial in MTX routine treatment. In this experiment, flow cytometric determination of the functionality of neutrophils was first applied for an adjuvant arthritis experimental model on rats.

In summary, we found that CoQ10 could potentiate both the antiarthritic (decrease of hind paw volume) and the antioxidant effect of methotrexate on the level of oxidation of proteins (suppression of levels of protein carbonyls in plasma) as well as lipoperoxidation (suppression of levels of HNE adducts and MDA adducts to plasma proteins). Further, the same effect was observed for plasmatic levels of CoQ9 and IL-1α, partially also for γ-glutamyltransferase activity assessed in joints and spleen. Moreover, the combination therapy improved the functionality of peripheral blood neutrophils in AA, with a balancing effect on the immunosuppression caused by MTX monotherapy.

In conclusion, combined administration of CoQ10 and methotrexate suppressed arthritic progression in rats more effectively than did MTX alone. This finding may become a beneficial contribution to the treatment of rheumatoid arthritis. Restoration of redox imbalance in chronic inflammatory diseases may be of significant importance in new therapeutic strategies.