Endurance run increases circulating IL-6 and IL-1ra but downregulates ex vivo TNF-α and IL-1β production

JOOST P. H. DRENTH, STAN H. M. VAN UUM, MARCEL VAN DEUREN, GERARD J. PESMAN, JOHANNA VAN DER VEN-JONGEKRIJG, AND JO W. M. VAN DER MEER

Department of Medicine, Division of General Internal Medicine, and Laboratory of Endocrinology and Reproduction, University Hospital St. Radboud, NL-6500 HB Nijmegen, The Netherlands

Drenth, Joost P. H., Stan H. M. van Uum, Marcel van Deuren, Gerard J. Pesman, Johanna van der Ven-Jongekrijg, and Jos W. M. van der Meer. Endurance run increases circulating IL-6 and IL-1ra but downregulates ex vivo TNF-α and IL-1β production. J. Appl. Physiol. 79(5):1497-1503, 1995.—We investigated whether a 6-h endurance run changes cytokine plasma concentrations and lipopolysaccharides (LPS) stimulated ex vivo production of cytokines in a whole blood culture of 19 well-trained athletes. The average distance covered was 65.1 ± 8.64 (SD) km. At the end of the exercise, the mean plasma concentration of interleukin-1 receptor agonist (IL-1ra), which was 188 pg/ml 24 h before finish, increased to 886 pg/ml (P < 0.0005). The mean plasma interleukin-6 concentration increased from 18.5 ± 4.2 to 71.5 ± 33.3 pg/ml (P < 0.0001). The increase of neutrophils correlated with the increase of IL-1ra concentrations (r = 0.58, P < 0.005). We could not detect an effect of exercise on plasma concentrations of interleukin-1 (IL-1β) (IL-1/β) or tumor necrosis factor-α (TNF-α). The ex vivo LPS-stimulated production of IL-1β in athletes 24 h before the run was significantly higher than in sedentary controls. Exercise induced a decrease of LPS-stimulated production of IL-1β and TNF-α, whereas production of IL-1ra was unchanged. These results show that prolonged exercise elicits a selective downregulation of the proinflammatory cytokine production and upregulation of the cytokines IL-1ra and interleukin-6.

PROINFLAMMATORY CYTOKINES such as tumor necrosis factor-α (TNF-α), interleukin (IL)-1, IL-6, and the anti-inflammatory IL-1 receptor antagonist (IL-1ra) are involved in various immunologic and inflammatory processes (38). In this respect, there are indications that physical exercise modifies plasma cytokine concentration and its production. Early studies indicated that plasma IL-1 bioactivity increases after exercise (6), but this was not confirmed in later studies using immunoaassays (29, 33, 36). For example, a 20-km run did not influence the plasma immunoreactive concentrations of IL-1β, TNF-α, and IL-6 in well-trained runners, although the urinary secretion of these cytokines was temporarily increased just after exercise (33). The effect of physical exercise on ex vivo production of cytokines by blood cells has not been studied extensively, and results are rather conflicting. When using isolated monocytes, Rivier et al. (30) noted a modest increase of spontaneous TNF-α production after exercise, whereas Haahr et al. (20) found no such difference after lipopolysaccharide (LPS) stimulation.

We therefore decided to study the effect of intense prolonged exercise (6-h run) on plasma concentrations of IL-1/β, IL-6, TNF-α, and IL-1ra and ex vivo production (using a whole blood culture system) of IL-1β, TNF-α, and IL-1ra.
tional, UK) and 4 μl choline chloride T (8.9 mmol/l) were added to the tubes and incubated for 10 s. The reaction was terminated by adding 20 μl Na₂S₂O₃ (26.3 mmol/l) in 0.25 M phosphate buffer.

Human recombinant IL-1ra was radiolabeled with ¹²⁵I by the method of Bolton and Hunter (5). In short, 0.28 μg of Bolton-Hunter reagent (0.1 μg/μl) was radioidinated with 37 MBq ¹²⁵I by adding 5 μg NCS (1 μg/μl) as a reductor during 10 min at room temperature. The reaction was stopped after the addition of 5 μg Na₂S₂O₃ as an oxidator. The mixture was evaporated to dryness during ~1 h under a stream of N₂, and subsequently 4 μg IL-1ra (5 μg/μl) in 1.0 M bicarbonate buffer was added to the tubes preincubated at 15 min at 0°C. After the labeling reactions, the reaction mixtures were applied to a Sephadex G-25 column (PD-10; Pharmacia, Uppsala, Sweden) and eluted with phosphate-buffered saline (PBS) (IL-1ß and TNF-α) or 0.25% gelatine in PBS (IL-1ra) to separate labeled proteins from free ¹²⁵I.

Radioimmunoassay (RIA) for cytokines. IL-1ß, TNF-α, and IL-1ra in plasma were measured in duplicate by nonequilibrium RIA. Recombinant human IL-1ß, TNF-α, and IL-1ra were calibrated against standards provided by the National Institute of Biological Standards and Control (Potters Bar, UK). The RIA was performed as follows. One hundred microliters of rabbit polyclonal cytokine antibodies (final dilution of IL-1ß 1:210,000, TNF-α 1:150,000, and IL-1ra 1:60,000, giving a binding with tracer of ~25%), dissolved in RIA buffer per liter containing 13 mM Na₂EDTA, 0.02% sodium azide, 0.25% bovine serum albumin (Behring, Marburg, Germany), 0.1% Triton X-100, 3 mM Na₂HPO₄, and 250,000 kallikrein-inactivating units aprothine, pH 7.4 (Bayer, Leverkusen, Germany), were added to sample and standard. All reagents were prepared with this buffer. For circulating cytokine measurement, 100 μl of sample and standard were added, and for measurement of ex vivo cytokine production, 25 μl (TNF-α) and 10 μl (IL-1ß and IL-1ra) of sample and standard were added. The mixture was incubated for 1 day at room temperature. Subsequently, tracer (10,000 dpm/100 μl) was added, and incubation was continued for another 2 days.

The separate bound and free tracer from the first fraction, 100 μl of a separation agent (10% [vol/vol] sheep anti-rabbit immunoglobulin G and 0.01% [wt/vol] rabbit immunoglobulin G (Sigma, St. Louis, MO)) were added to each tube and incubated for 30 min at room temperature. The antibody complex was completely precipitated by the addition of 1 ml 7.5% polyethylene glycol 6000 (Merck, Darmstadt, Germany). For IL-1ß, TNF-α, and IL-1ra, the range of the standard curve was 20–3,000 pg/ml. The sensitivity of the assay with 100-μl sample was 60 pg/ml (IL-1ra), 40 pg/ml (IL-1ß), and 20 pg/ml (TNF-α). To minimize analytic errors, all samples from the same patient were analyzed in the same run in duplicate.

In our assay for IL-1ß, with complete specific precipitation of the first antibody with the second antibody, chloroform extraction for eliminating interfering factors is not needed (9). Samples treated with chloroform extraction showed a good correlation to those without treatment (r = 0.77). The interference of soluble interleukin-1 receptors (sILr) with the measurement of IL-1ß has not actually been tested in this assay. The recovery, however, of IL-1ß with this assay is 70%. The linearity, as tested by addition of two samples with unknown IL-1ß content to a sample with established IL-1ß concentration, gave a correlation coefficient of 0.99. A fine parallelism has been shown for IL-1ß (r = 0.90) for sample volumes from 3 up to 100 μl. For TNF-α, this RIA measures total TNF-α (both free and complexed to its receptors), as demonstrated by the lack of interference of the addition up to 5 ng/ml recombinant soluble tumor necrosis factor receptors (sTNFR) (p55 and p75) to sera containing known amounts of TNF-α (4). The recovery of TNF-α in our RIA was estimated at 93.3% However, no satisfying parallelism was achieved with TNF-α with this assay. To avoid this problem, sample volumes were adjusted for measurement of circulating TNF-α (100 μl) and ex vivo production (25 μl), and with these quantities accurate intragroup comparison of results was possible.

For IL-1ra, the recovery was estimated at 86.2%. Good parallelism is achieved with native human IL-1ra reagents. With human recombinant IL-1ra, complete parallelism is lacking and only measurements from fixed amounts of sample can be compared. Therefore, the sample volume for measurement of circulating IL-1ra is 100 μl, compared with 10 μl for measurement of ex vivo production. To correct for spontaneous ex vivo cytokine production, we calculated the net LPS-stimulated production according to the following formula: net cytokine production = production with LPS − production without LPS.

The interassay variation of our RIA is estimated at <15%, whereas the intra-assay variation is <10%, which are typical results for these assays.

Control values for cytokine ex vivo production were obtained at a given day from 10 healthy sedentary volunteers (20–45 yr of age). These values were 6,847 ± 2,175 pg/ml (IL-1ß), 3,344 ± 969 pg/ml (TNF-α), and 9,827 ± 2,597 pg/ml (IL-1ra). Very similar concentrations were found in samples drawn from the same volunteers 24 h later.

Enzyme-linked immunosorbent assay (ELISA) for IL-6. IL-6 was measured with an ELISA (Central Laboratory of the Netherlands Red Cross Blood Transfusion Service, Amsterdam, the Netherlands) as follows (21). Flat-bottom microtiter plates were coated for 24 h at room temperature with anti-IL-6 monoclonal antibody (diluted 1:100 in coating buffer). The plates were washed five times with PBS containing 0.005% Tween 20 and were incubated for 1 h with PBS containing 5% bovine serum albumin (Sigma Chemical A-7030) to prevent aspecific binding. Subsequently, the plates were washed five times with washing buffer, and samples (100 μl) were added.

After incubation for 1 h at 37°C, the plate was again washed five times, and biotinylated sheep antibody to human IL-6 in conjugate buffer (100 μl) was added to the wells and incubated for 1 h longer at 37°C. After five more washes, streptavidin horseradish peroxidase conjugate (diluted 1:10,000) was added and the plate was incubated for 30 min at room temperature. After the samples were washed again five times, 100 μl of substrate (2,2-aminobis C3-ethylbenz-thiazoline sulfonic acid, pH 4.0) were added, and after 30-min incubation at room temperature the color reaction was terminated with 100 μl 2% oxalic acid. The optical density was read at 450 nm with a Titertek Multiskan ELISA reader (Effab, Oy, Helsinki, Finland). The sample values were compared with a standard curve; the lower limit of detection with this assay is 14 pg/ml. There is no interference of sIL-6r in the IL-6 ELISA.

Statistical analysis. The paired nonparametric Wilcoxon signed-rank test was used for statistical comparison of values obtained before and after physical exercise. Probability (P) values were calculated on the basis of two-tailed tests. A correlation coefficient was calculated with the Pearson's correlation test. A P < 0.05 was considered to be the lowest level of significance. Data are given in mean ± SD.

RESULTS

Exercise. The average distance covered by the athletes was 65.1 ± 8.6 km (range 51.7–86.2 km). Two
athletes did not complete the 6-h run because of minor injuries. They were excluded from the analysis.

Blood cells. The 6-h endurance run resulted in a significant (P < 0.0005) increase in total leukocytes (2.3-fold), neutrophils (3.4-fold), and monocytes (1.8-fold) (Table 1). The lymphocyte count was reciprocally decreased (P < 0.0005). There was a moderate positive correlation between covered distance and leukocytosis (r = 0.47, P < 0.05).

Circulating cytokines. As shown in Figure 1, A and B, there was no effect of exercise on the plasma concentrations of IL-1β and TNF-α. The plasma IL-1ra concentration increased fivefold during exercise, compared with preexercise values, from 188 ± 72 to 886 ± 395 pg/ml (median 855 pg/ml, range 290–1,450 pg/ml) (P < 0.0005) (Fig. 1C). The mean plasma IL-6 concentration increased from 18.5 ± 4.2 to 71.5 ± 33.3 pg/ml (median 64 pg/ml, range 24–130 pg/ml) immediately after the 6-h run (P < 0.0001) (Fig. 1D). A positive correlation was observed between the postexercise plasma concentrations of IL-1ra and TNF-α (r = 0.57, P < 0.0005), of IL-1ra and IL-6 (r = 0.61, P < 0.005), and of IL-6 and TNF-α (r = 0.48, P < 0.05). A correlation between postexercise values of IL-1β and IL-1ra was absent. The increase of neutrophils did correlate with the increase of IL-1ra concentrations (r = 0.58, P < 0.005).

Ex vivo production of cytokines. Before exercise, ex vivo LPS-stimulated netto production of IL-1β in whole blood culture from athletes was significantly higher than that of sedentary controls (P < 0.0005) (Fig. 2). The preexercise LPS-stimulated production of TNF-α and IL-1ra did not differ between athletes and controls. Before the run, only for TNF-α a moderate positive correlation of age with LPS-stimulated production could be detected (r = 0.045, P = 0.025). This positive correlation disappeared after the end of the run.

After exercise, the LPS-stimulated production of TNF-α and IL-1ß decreased appreciably (P < 0.0005) (Fig. 2). The IL-1ra production did not change significantly. The LPS-stimulated production of TNF-α correlated with that of IL-1ß (r = 0.89, P < 0.0001).
studies using ELISA (27, 35) and, like in our study, radioimmunometric assays, failed to find an effect of exercise on plasma IL-1β concentrations. This discrepancy could be due to the fact that the mouse thymocyte bioassay does not distinguish between IL-1α, IL-1β, and IL-6 (41). Indeed, we and others noted elevated IL-6 concentrations in plasma after exercise, which could explain the above-mentioned results (28, 33, 36).
The LPS-stimulated production of IL-1β ex vivo at baseline from athletes was significantly higher compared with values obtained in our laboratory from healthy but sedentary controls. This finding cannot be attributed to random temporal changes in cytokine production, since no significant differences were detected in sedentary controls in blood drawn at 2 consecutive days. This suggests that regular training results in an enhanced IL-1β response to LPS exposure in vitro. We observed that the 6-h endurance run in these well-trained individuals results in a profound decrease of LPS-stimulated IL-1β and TNF-α production in the whole blood culture system. A similar loss of production capacity of cytokines has been observed in the acute stage of several clinical conditions such as sepsis (27), typhoid fever (24), and after major surgery (25). In studies from our laboratory, this downregulated proinflammatory cytokine response was demonstrated to be associated with a preserved IL-1ra response similar to the one we observed in the current study (24, 25). However, the present results differ from in vitro studies in which isolated mononuclear cells were used (20, 26). In studies of Haahr et al. (20) and Lewicki et al. (26), exercise elicited increased IL-1β concentrations in supernatants from LPS-stimulated monocytes. (20, 25) In another study, spontaneous release of TNF-α from isolated monocytes was slightly increased at the end of an incremental exercise test but decreased significantly at 20 min after the end of exercise (30). The already mentioned results of Haahr et al. (20) did not find that exercise had an effect on TNF-α production by LPS-stimulated monocytes. Again, there are a number of explanations. As indicated before, differences in the degree and duration of exercise and training background of the volunteers may be crucial. In addition, the whole blood culture system used in our study is somewhat different from culture systems using isolated cells. The whole blood culture system reflects the cytokine response of all types of blood cells to a given stimulus, and this is less artificial and less susceptible to unwanted ex vivo stimulation than methods using cells isolated by density centrifugation (39).

It is of interest that the downregulation of LPS-stimulated cytokine production is found despite the elevation of number of monocytes, because these cells are considered the major producers of IL-1β and TNF-α. The downregulation in the whole blood cultures could be due to a plasma factor. In theory, several factors could inhibit cytokine production: cytokines such as transforming growth factor-β (TGF-β), IL-4, and IL-10 have been shown to downregulate TNF-α, IL-1β, and IL-6 production from LPS-stimulated isolated monocytes (12, 13, 34). Furthermore, TGF-β, IL-4, and IL-10 have been shown to upregulate IL-1ra production (23, 40). Epinephrine and endogenous glucocorticoids are released into the circulation in response to exercise, and both compounds inhibit the release of IL-1, IL-6, and TNF-α from isolated monocytes (1, 25, 30). It is of interest that the downregulation of LPS-stimulated cytokine response over a period of ~6 h (3). Exercise-induced suppression of the LPS-stimulated cytokine response may have both detrimental and beneficial consequences. Curtailing the monocyte production of TNF-α and IL-1β may compromise the host defense response against invading pathogens on the one hand; on the other hand, it may protect against cytokine-mediated damage of muscle tissue during and after exercise (7, 10). The finding of decreased response to LPS ex vivo is reminiscent of endotoxin tolerance, i.e., the decreased response to a high dose of LPS after pretreatment with a low dose of LPS. It has been found that intense exercise such as performed in a triathlon is associated with a 3.6-fold increase of plasma LPS concentrations in these athletes, perhaps caused by excessive leakage of LPS from the gastrointestinal tract due to reduced splanchnic flow (31). Consequently, it may be suggested that the downregulation of proinflammatory cytokines after exercise is due to endotoxin (18, 19). Further re-
research is needed to elucidate the mechanism of the downregulation of cytokine production after exercise.

The authors thank the participants in this study for their time and effort. We are indebted to Mariëlle Spruytenburg for the analysis of plasma. The authors thank Pierre N. M. Demacker, Division of General Internal Medicine, University Hospital St. Radboud, for his support in performing the study. Address for reprint requests: J. P. H. Drenth, Department of Medicine, University Hospital St. Radboud, NL-6500 HB Nijmegen, The Netherlands.}

Received 24 March 1995; accepted in final form 14 June 1995.

REFERENCES


36. Ullum, H., P. M. Haahr, M. Diamant, J. Palm, J. Halkjar-Kristensen, and B. K. Pedersen. Bicycle exercise enhances plasma IL-6 but does not change IL-1α, IL-1β, IL-6, or TNF-α pre-mRNA in BMNC. J. Appl. Physiol. 77: 93–97, 1994.


