Interleukin-6 (IL-6) as an Anti-inflammatory Cytokine: Induction of Circulating IL-1 Receptor Antagonist and Soluble Tumor Necrosis Factor Receptor p55

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The aim of this study was to investigate whether interleukin (IL)-6 induces the production of IL-1 and tumor necrosis factor (TNF) antagonists. Serial plasma samples were obtained from cancer patients participating in phase I and II trials of recombinant IL-6 administered as a 120-hour continuous intravenous (IV) infusion. Plasma IL-1 receptor antagonist (IL-1Ra) and soluble TNF receptor p55 (TNFsRp55) levels were measured by specific radioimmunoassays (RIAs). IL-1Ra levels increased rapidly, reaching peak values (9.6 ± 1.7 ng/mL) within 2 to 4 hours of beginning treatment. Thereafter, levels promptly declined, reaching a near baseline within 24 hours despite continuation of IL-6. TNFsRp55 plasma levels increased within 4 to 8 hours after initiating treatment and increased progressively throughout the duration of therapy. IL-1β and TNF-α plasma levels were below the detection limit in all samples tested. Peripheral blood mononuclear cells (PBMC) exposed to IL-6 produced only small amounts (1.56 ± 0.3 ng/mL) of IL-1Ra, even in the presence of exogenous soluble IL-6 receptor (gp80). TNFsRp55 levels measured in the supernatants of IL-6–stimulated PBMC were below the detection limit of the assay. Macrophages generated by culturing monocytes in granulocyte-macrophage colony-stimulating factor (GM-CSF) were much more responsive to IL-6 than freshly isolated unfractionated or adherent PBMC and synthesized almost as much IL-1Ra when stimulated with IL-6 as with endotoxin. These results suggest that the antiinflammatory properties of IL-6 may be due, in part, to the induction of IL-1Ra synthesis and the release of soluble TNF receptors. Our findings also suggest that tissue macrophages may be an important source of IL-6–induced IL-1Ra.

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MATERIALS AND METHODS

Clinical materials. Patients who participated in this study were enrolled in phase I and II trials performed by the Cytokine Working Group. These clinical trials were approved by the Human Investigation Review Committee at the New England Medical Center, and all study participants gave written, informed consent. Patients received 30 μg/kg/24 hours of IL-6 (Sandoz, East Hanover, NJ) intravenously (IV) for 5 consecutive days as a 120-hour continuous infusion. Blood samples for cytokine assays were collected in EDTA-containing tubes immediately before and 1, 2, 4, 8, 24, 48, 72, 96, and 120 hours after therapy start. Samples were centrifuged within 20 minutes of venipuncture at 2,000g for 10 minutes and the plasma stored at −70°C.

Reagents. The IL-6 used in both in vivo and in vitro studies was recombinant, derived from Escherichia coli, and provided by the Cytokine Development Unit, Sandoz Inc. Soluble IL-6 receptor (sIL-6R) was obtained from R & D Systems (Minneapolis, MN) and as a gift from D. Novick, Weizmann Institute of Science, Rehovot.

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were quantitated with specific radioimmunoassays (RIAs) as previously described. The RIA for IL-1Ra is unaffected by the presence of IL-1β and the IL-1β assay is not influenced by IL-1Ra. Likewise, the RIA for TNF-α is not affected by TNFSrR55 and the RIA for TNFSrR55 is unaffected by TNF-α. A glycosylated form of TNFSrR55 expressed in Chinese hamster ovary cells was used to immunize New Zealand white rabbits in the generation of the anti-TNFSrR55 antibody used in the RIA. This glycosylated form of TNFSrR55 was also used to generate the standard curve for the RIA. The limit of detection was 80 to 160 pg/mL for all RIAs used.

**Statistics.** All results are shown as the mean ± SEM. Student’s *t*-test was used to determine statistical significance.

### RESULTS

**Plasma IL-1Ra and TNFSrR55 levels during IL-6 immunotherapy.** Six patients with advanced malignancy were studied. Before therapy, plasma IL-1Ra levels in the patients were slightly, but not significantly, elevated compared with those of healthy controls (3.2 ± 0.07 vs. 0.29 ± 0.08 ng/mL, *n* = 10). Levels increased rapidly, reaching a peak of 9.6 ± 1.7 ng/mL within 2 to 4 hours of initiating the IL-6 infusion (Fig 1). Thereafter, levels gradually declined to nearly baseline values within 24 hours (0.67 ± 0.14 ng/mL). Levels remained slightly elevated compared with pretreatment values until the end of therapy.

Pretreatment TNFSrR55 levels were significantly higher in patients than in healthy controls (3.2 ± 0.4 vs. 1.4 ± 0.2 ng/mL, *n* = 10; *P* < 0.05). Levels increased within 4 hours of beginning treatment and thereafter increased continuously until the end of the 120-hour infusion. Peak levels (12.2 ± 1.5 ng/mL) were observed on day 5 (Fig 2). IL-1β and TNF-α levels were assayed at the same time points as the IL-1Ra and TNFSrR55 measurements and were consistently below the detection limit of the assays (data not shown).

**IL-6-induced IL-1Ra synthesis and TNFSrR55 release by PBMC.** PBMC were incubated for 24 hours with increasing concentrations of IL-6. TNFSrR55 levels measured

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**Fig 1.** In vivo production of IL-1Ra in patients treated with a 120-hour continuous infusion of IL-6. Data represent the mean ± SEM from six patients. EDTA-containing specimens were obtained before, and 1, 2, 4, 8, 24, 48, 72, 96, and 120 hours after therapy start. *P* < 0.05 compared with time = 0; **P** < 0.005 compared with time = 0.

**Fig 2.** Circulating TNFSrR55 levels in patients treated with a continuous IL-6 infusion. Plasma samples used in these measurements were identical to those in Fig 1. *P* < 0.05 compared with time = 0; **P** < 0.005 compared with time = 0.
IL-6–INDUCED CYTOKINE ANTAGONISTS

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IL-6 (ng/ml)

1

1

2

Fig 3. (A) Production of IL-1Ra by human PBMC stimulated with increasing concentrations of IL-6. Data are shown as the mean ± SEM and are derived from experiments with eight different donors. \*P < .05 compared with baseline (no IL-6). (B) Production of IL-1Ra by PBMC stimulated with LPS (II) or with LPS + IL-6 (10 ng/mL) (II). Data are expressed as the mean ± SEM (n = 3). \*P < .05 compared with baseline (no LPS or IL-6); \**P < .005 compared with baseline (no LPS or IL-6).

in the supernatants were below the detection limit of the assay (data not shown). IL-6 was a weak inducer of IL-1Ra synthesis, yielding levels rarely in excess of 1.5 ng/mL, even with high IL-6 concentrations (100 ng/mL) (Fig 3A). In the same experiments, LPS (10 ng/mL) induced 8.3 ± 1.3 ng/mL of IL-1Ra. IL-6 (10 ng/mL) did not enhance the response to LPS at LPS concentrations of 0.1 ng/mL or greater (Fig 3B). Even the modest enhancement apparent with low LPS concentrations was not statistically significant. On the other hand, neither did IL-6 suppress LPS-induced IL-1Ra production as previously demonstrated for LPS-induced IL-1 and TNF synthesis.4,5

The weak response of PBMC to IL-6 could have been due to a lack of IL-6 receptors (gp80). In circumstances in which a low level of gp80 expression limits IL-6 signaling, exogenous sIL-6R has been shown to enhance the response to this cytokine. For example, sIL-6R augments IL-6–induced acute-phase protein synthesis by hepatocytes.25 However, this truncated receptor had no effect on IL-6–induced IL-1Ra synthesis by PBMC at sIL-6R concentrations of up to 500 ng/mL (data not shown), suggesting that gp80 expression was not a limiting factor in IL-6–induced IL-1Ra synthesis. The poor response to IL-6 was also not due to a dependency on glucocorticoids. Whereas IL-6–induced acute-phase protein synthesis by hepatocytes is steroid-dependent,26 glucocorticoids (10−7 mol/L dexamethasone) actually suppress IL-6–induced IL-1Ra production by PBMC (data not shown).

PBMC from four of six patients treated with a 5-day continuous IL-6 infusion were isolated before therapy and on day 3. Unstimulated PBMC obtained before treatment from these patients produced significantly more IL-1Ra (2.95 ± 0.97 ng/mL) than did PBMC from healthy controls (0.5 ± 0.1 ng/mL, n = 8; \( P < .01 \)). Despite increased constitutive production, PBMC from the cancer patients were refractory to stimulation with IL-6 alone or in combination with sIL-6R (Fig 4). The response to LPS was comparable to that of PBMC from healthy donors. Constitutive production of IL-1Ra in vitro by PBMC obtained 48 hours into the treatment

Fig 4. Production of IL-1Ra by PBMC isolated from four patients treated with IL-6. PBMC were isolated before therapy start (II) and on day 3 (48 hours) (II). IL-6 was used at a concentration of 10 ng/mL, sIL-6R at 100 ng/mL, and LPS at 100 ng/mL. Data are presented as the mean ± SEM. \*P < .05 compared with baselines (no IL-6).
Measurements of IL-1Ra levels during an IL-6 infusion showed an unexpected pattern. Levels promptly increased and then rapidly declined to nearly baseline levels, despite continuing the IL-6 infusion. In contrast, plasma IL-1Ra levels in patients receiving repeated bolus injections of IL-2 remain persistently elevated throughout the treatment course. The reason for the rapid decline in IL-1Ra levels despite continuous IL-6 administration is not clear. The administration of IL-6 results in the release of glucocorticoids. The release of endogenous hydrocortisone has been shown to limit the levels of circulating TNF and IL-1Ra resulting from an injection of LPS, and it is likely that a similar process is responsible for the kinetics of IL-1Ra release induced by IL-6. The contention that endogenous steroids may be involved in this short-lived increase in IL-1Ra levels is further supported by our finding that IL-6-induced IL-1Ra synthesis in PBMC is completely abolished by dexamethasone. An alternative explanation for the rapid decline in IL-1Ra levels could be the downregulation of the IL-6-binding subunit (gp80) of IL-6R, which has been demonstrated to occur in hepatoma cells in response to IL-6. However, low levels of membrane gp80 may not appreciably compromise IL-6 responses in vivo, as sIL-6R present in plasma may be able to substitute for the membrane-bound receptor in cells in which gp80 expression is limited. This is in fact the case with hepatocytes in which exogenous sIL-6R has been shown to augment IL-6-induced acute-phase protein synthesis.

The constitutive production of IL-1Ra by PBMC isolated on day 3 of treatment was much greater than that of pretreatment PBMC. As with the pretreatment cells, those obtained on day 3 were unresponsive to stimulation with IL-6 alone or in conjunction with sIL-6R (Fig 4).

**IL-6-induced IL-1Ra synthesis by GM-CSF-primed macrophages.** We studied the possibility that macrophages, rather than monocytes, could synthesize IL-1Ra in response to IL-6. Macrophages (5 × 10⁶ cells) were obtained by culturing monocytes from healthy donors in GM-CSF-containing medium for 6 days. After three washes, cells were incubated for 24 hours in medium alone or medium containing IL-6, sIL-6R, IL-6 plus sIL-6R, or LPS. As shown in Fig 5, macrophages synthesized more IL-1Ra than did equal numbers of freshly isolated adherent PBMC from the same donors (P < .001). Furthermore, these cells were highly responsive to IL-6, generating as much IL-1Ra in response to this cytokine (46.2 ± 4.3 ng/mL) as they did to LPS (50.3 ± 3.8 ng/mL). As with PBMC, the addition of sIL-6R to the cultures did not further enhance IL-6–induced IL-1Ra production.

**DISCUSSION**

Cytokines such as IL-4, IL-10, and tumor growth factor-β (TGF-β) exert their antiinflammatory effects, in part, by suppressing IL-1 and TNF synthesis. IL-4 and TGF-β are also potent inducers of IL-1Ra, which may contribute to their antiinflammatory actions by neutralizing the biological effects of IL-1. Our results indicate that IL-6 belongs to this category of antiinflammatory cytokines, which both suppress IL-1 and TNF synthesis and induce the production or release of IL-1 and TNF antagonists.

![Fig 5. Production of IL-1Ra by GM-CSF–primed macrophages (●) and freshly isolated adherent PBMC (□). Macrophages from three donors were prepared as described in Materials and Methods. IL-1Ra RIA was performed with cell lysates as described in Materials and Methods.](image-url)
an important source of this cytokine antagonist. In our studies, macrophages produced five to 10 times more IL-1Ra than did fresh monocytes, and were highly sensitive to IL-6, indicating that IL-1Ra production changes during macrophage differentiation both with respect to the quantities synthesized and to the range of inducing agents to which the cells are responsive.

IL-6 is known to enhance the expression of TNF receptors on hepatoma cells and hepatocytes.\(^{29}\) We now show that IL-6 immunotherapy is associated with the shedding of TNF-Rp55 into the circulation. However, IL-6 failed to induce the release of TNF-Rp55 from PBMC in vitro. This lack of in vitro activity has been observed with both PBMC and neutrophils exposed to LPS, IL-1, TNF, and other cytokines that induce high levels of TNF-Rp55 when administered in vivo.\(^{22,23,40}\) The basis for this discrepancy is so far unexplained.

IL-6 has been shown to suppress inflammation in several animal models.\(^{22}\) These effects have been attributed to the inhibition of IL-1 and TNF production. Our results suggest that the induction of IL-1Ra synthesis by IL-6, as well as the release of soluble TNF receptors into the circulation, may be equally important factors in the modulation of inflammatory responses.

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