Evidence for Cytokine-inducible Nitric Oxide Synthesis from L-Arginine in Patients Receiving Interleukin-2 Therapy

John B. Hibbs, Jr.,* Christof Westenfelder,† Read Taintor,* Zdenek Vavrin,* Carl Kablitz,‡ Robert L. Baranowski,§ John H. Ward,‖ Ronald L. Menlove,‖ Martha P. McMurry,‖ James P. Kushner,‖ and Wolfram E. Samloewski∥

Medical Service, Veterans Affairs Medical Center, and Divisions of Infectious Diseases, *Hematology-Oncology, † and Nephrology, ‡ Department of Internal Medicine, Clinical Research Center, ‖ and Division of Epidemiology and Biostatistics,∥ University of Utah School of Medicine, Salt Lake City, Utah 84132

Abstract

An interferon-γ, tumor necrosis factor, and interleukin-1-inducible, high-output pathway synthesizing nitric oxide (NO) from L-arginine was recently identified in rodents. High-dose interleukin-2 (IL-2) therapy is known to induce the same cytokines in patients with advanced cancer. Therefore, we examined renal cell carcinoma (RCC; n = 5) and malignant melanoma (MM; n = 7) patients for evidence of cytokine-inducible NO synthesis. Activity of this pathway was evaluated by measuring serum and urine nitrate (the stable degradation product of NO) during IL-2 therapy. IL-2 administration caused a striking increase in NO generation as reflected by serum nitrate levels (10- and 8-fold increase [P < 0.001, P < 0.003] for RCC and MM patients, respectively) and 24-h urinary nitrate excretion (6.5- and 9-fold increase [both P < 0.001] for RCC and MM patients, respectively). IL-2-induced renal dysfunction made only a minor contribution to increased serum nitrate levels. Metabolic tracer studies using L-[guanidino-15N]arginine demonstrated that the increased nitrate production was derived from a terminal guanidino nitrogen atom of L-arginine. Our results showing increased endogenous nitrate synthesis in patients receiving IL-2 demonstrate for the first time that a cytokine-inducible, high-output L-arginine/NO pathway exists in humans. (J. Clin. Invest. 1992. 89:867-877.) Key words: acute renal failure • malignant melanoma • nitrate • nitrite • renal cell carcinoma

Introduction

Many host responses to microbial agents and neoplastic cells are mediated by cytokines. Interleukin 2 (IL-2), which is primarily synthesized by activated T lymphocytes, has a central role in the development of cell-mediated immunity (1) and is a key factor in the induction of a complex network of cytokines that include tumor necrosis factor/cachetin (TNF), interferon-γ (IFNγ), interleukin 1 (IL-1), and interleukin 6 (2–7). It was observed, in both mice and humans, that normal resting lymphocytes treated with high concentrations of IL-2 developed the ability to kill a wide range of syngeneic and allogeneic tumor cells (8). IL-2-activated cells were functionally defined as lymphokine-activated killer (LAK) cells and administration of IL-2 plus LAK cells to mice caused regression of established syngeneic tumors (9). Clinical trials of IL-2 plus LAK cells or of IL-2 alone demonstrated objective regressions in ~25–33% of patients including 5–10% complete remissions in patients with advanced melanoma or renal cell carcinoma (10). Clinical use of IL-2 therapy, with or without LAK cells, has been limited by the low rate of complete remissions and by severe toxicity that requires intensive care monitoring. Patients receiving IL-2 therapy often develop potentially life-threatening side effects that include fever, chills, hypotension, capillary leak syndrome, as well as evidence of multiple organ system dysfunction, specifically including acute renal insufficiency and cholestatic jaundice (10).

Studies of rodent cytotoxic activated macrophages as an effector component of cell-mediated immunity resulted in the identification of a cytokine (IFNγ and TNF)-inducible pathway that was capable of producing high levels of nitric oxide (NO) and L-citrulline synthesis from L-arginine (11–18) (for reviews, see references 19 and 20). NO is a short-lived paramagnetic lipid-soluble gas which, when present in high concentration in the cellular environment, causes widespread iron-sulfur nitrosyl complex formation that inhibits certain iron-dependent enzymes (21, 22) (Fig. 1). NO has been shown to be a biochemical effector of L-arginine-dependent cell-mediated immune responses to neoplastic cells (11–13, 16, 17, 19) as well as to certain helminths and intracellular pathogens (20, 23–29) in rodent cells in vitro.

A constitutive low-output pathway synthesizing small amounts of NO and L-citrulline from L-arginine was also recently identified (30–33). NO synthesized from L-arginine by the constitutive NO synthase functions as an intercellular and/or intracellular signal. For example, NO synthesized by the constitutive isoenzyme of endothelial cells targets a heme moiety associated with soluble guanylate cyclase of vascular smooth muscle cells and mediates functional linkage between these two cell types (34). Examples of constitutive NO synthase activity include modulation of vascular tone (30) and neurotransmission (31–33).

NO synthesized by either isoenzyme undergoes oxidative degradation to the stable inorganic nitrogen oxides nitrite (NO2-) and nitrate (NO3-). NO2- entering the vascular system reacts rapidly with oxyhemoglobin (35). This results in stoichiometric formation of methemoglobin and NO3- from oxyhemoglobin and NO2- (see Fig. 1). Therefore, NO synthesized...

Address reprint requests to Dr. Hibbs, Division of Infectious Diseases, School of Medicine, University of Utah, Room 48322, 50 North Medical Drive, Salt Lake City, UT 84132.

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1. Abbreviations used in this paper: BUN, blood urea nitrogen; FE, fractional excretion; GC/MS, gas chromatography-mass spectrometry; LAK, lymphokine-activated killer; MM, malignant melanoma; RCC, renal cell carcinoma; TNF, tumor necrosis factor; TPN, total parenteral nutrition.

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from a terminal guanidino nitrogen atom of l-arginine is detected in serum or urine as NO\textsubscript{3}. The study reported here was undertaken to examine (a) whether IL-2 administration to patients with cancer caused a rise in NO synthesis from l-arginine; (b) whether urine and serum NO\textsubscript{3} levels could serve as markers of IL-2-stimulated NO generation; and (c) the extent that IL-2-induced renal dysfunction (36, 37) contributed to elevations in serum NO\textsubscript{3} levels.

**Methods**

**Subjects.** The study protocol was reviewed and approved by the University of Utah School of Medicine Institutional Review Board and written informed consent was obtained from all patients. The patients (n = 12) were admitted to the University Hospital's Clinical Research Center for study and treatment (Table I). The patients had metastatic malignant melanoma (MM [n = 7; mean age 44 yr, range 24-63]) or metastatic renal cell carcinoma (RCC [n = 5; mean age 53 yr, range 39-63]) that was unresponsive to conventional treatment. All the patients with RCC had fully recovered from a unilateral nephrectomy before IL-2 therapy. There were three female MM patients and one female RCC patient enrolled in this study.

**High-dose bolus IL-2 treatment with or without LAK cells.** Patient eligibility included the following criteria: pathologic confirmation of tumor histology, measurable disease, Karnofsky performance status > 70%, normal stress multiple-uptake gated acquisition or thallium scan, normal pulmonary function (forced expiratory volume in [FEV\textsubscript{1}] > 75% of predicted), normal bone marrow, and liver and renal function. The creatinine clearance of MM patients was normal (mean = 122 ml/min). The creatinine clearance of RCC patients with unilateral nephrectomies was ~ 50% of normal (mean = 59 ml/min). Exclusion criteria included pregnancy, active infection (including HIV), steroid therapy, organ allografts, brain metastases, or prior malignancy. All patients were treated for anticipated IL-2 toxicity with acetaminophen 650 mg p.o. every 4 h, indomethacin 25 mg p.o. every 6 h, and ranitidine 150 mg i.v. every 12 h. Patients also received meperidine 25-50 mg every 4 h i.v. as needed for chills due to IL-2 or LAK cell administration, as well as symptomatic treatment for pruritus, vomiting, or diarrhea as required. Each patient received highly purified recombinant human IL-2 from *Escherichia coli* (sp act 18 x 10\textsuperscript{6} IU/mg) generously provided by Cetus Corp., Emeryville, CA, at 600,000 IU/kg i.v. every 8 h on days 1-5 (induction course). The IL-2 used in these experiments contained < 0.012 ng/ml LPS by *Limulus* amebocyte lysate assay (18 x 10\textsuperscript{6} IU of IL-2 in 1 ml of PBS). Patients received either IL-2 alone, or IL-2 in conjunction with LAK cells during days 11-15 (consolidation course). Table I. All five patients with RCC received induction IL-2 therapy. Patient 1 was not given a consolidation course of IL-2 because of a severe decrease in renal function.

Patients who randomized to IL-2 with LAK cells were leukapheresed for 5 h/d on days 7-10. The cells from each pheresis were cultured for 3-4 d in vitro in serum-free Ex Vivo-10 medium (M. A. Bioproducts, Walkersville, MD) containing 2 mM L-glutamine and 1,500 U of IL-2/ml, and readministered to the patient in a single i.v. daily infusion, (250 ml of saline containing 5% albumin and 30,000 U of IL-2) during the second (consolidation) IL-2 treatment course on days 11, 12, and 14. Doses of IL-2 were held for National Cancer Institute common toxicity grade III or IV toxicity, usually oliguria, hypotension.
Table I. Characteristics of Patients Treated with IL-2

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<tr>
<th>Patient</th>
<th>Diagnosis*</th>
<th>Age/Sex</th>
<th>Date of treatment</th>
<th>IL-2 doses</th>
<th>Total IU IL-2 ×10⁶</th>
<th>Total LAK cells ×10⁶</th>
<th>Clinical response (duration)</th>
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<td>9/5/89</td>
<td>Consolidation</td>
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<td>PD</td>
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<td>627</td>
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<td>702</td>
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<td>6</td>
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* RCC, renal cell carcinoma; and MM, malignant melanoma.

1 Patient 5 was administered two complete courses of IL-2.

requiring > 4 μg/kg min dopamine, severe hypoxia, or neurologic toxicity. Central venous pressure and systemic blood pressure were measured every 4 h, during hospitalization. Our patients were monitored closely for evidence of infection (urine, blood, and intravascular device cultures for oral temperatures > 38°C). Three episodes of line infection were documented in two patients (coagulase-negative Staphylococcus [patient 4] and coagulase-negative Staphylococcus follow by Proteus mirabilis [patient 6]).

Nutrition regimen. All patients received parenteral nutrition (TPN) infused via a central line. The TPN solution (a mixture of equal parts of 8.5% Aminosyn [Abbott Laboratories, North Chicago, IL] and 50% dextrose plus standard vitamin and mineral solutions, and infused at a rate of ~100 ml/h [standard TPN regimen]) consistently tested negative for NO- and NO3-. Lipids (Liposyn, Abbott Laboratories) were given two times per week. The standard TPN regimen provided 10.2 g of l-arginine daily.

Low NO3-/NO2- foods were also provided in small amounts to those patients desiring oral feedings. Carnation Instant Breakfast (Carnation Co., Los Angeles, CA) (laboratory analysis showed < 0.3 mg of NO2- per serving), or other low NO3-/NO2- foods were supplied, based on limited information on food NO3-/NO2- content (38, 39). The following food groups were excluded: cured meats, malt, vegetables raw or cooked, including potatoes, melons, fish, imported cheese, and any fermented foods. The diet included milk, ice cream and domestic cheese, eggs, breads and cereals (including whole kernel corn), fresh meats (chicken, turkey, beef and pork), legumes, other fruits, hard candy and carbonated beverages, sugar, coffee, salt, and pepper. Daily enteral intake was also recorded and included in the calorie counts.

Measurement of urine and blood NO3-. Sequential 24-h urine specimens were collected throughout the study period. Bacterial growth in the urine during the collection period was prevented by placing 200 ml of 2-propanol into a 3-liter collection bottle. The samples were frozen at −80°C until a 1:10 dilution of urine was assayed for NO3- as previously described (24, 40). The 2-propanol did not affect the enzymatic conversion of NO2- to NO3- by the E. coli NO3- reductase. Serum was diluted 1:1 with NO2-/NO3- free distilled water and then ultrafiltered (Ultraframe MC microcentrifuge device, UFC3 LGC NB, Millipore Corp., Bedford, MA) at 2,000 g for 120 min. NO2- in the filtrate was reduced to NO3- by mixing 80 ml with 80 ml E. coli NO3- reductase suspension prepared and then incubated for 1 h at 37°C. The E. coli NO3- reductase had no NO2- reductase activity when prepared as described (24). The reaction mixture was centrifuged (12,000 rpm, Microfuge, Beckman Instruments, Inc., Fullerton, CA) for 5 min. Supernatant (50 ml) was added to 100 ml of Griess reagent (24). Absorbance (A540) was measured on a microplate reader (Dynatech Laboratories, Inc., Chantilly, VA).

Administration of the stable nonradioactive isotope L-arginine HCl (guanidino 15N, 70%). The material supplied by Cambridge Isotope Laboratories, Woburn, MA, contained 70% L-[guanidino-15N]-arginine (L-15N[15N]arginine) as determined by potentiometric titration (Galbraith Laboratories, Knoxville, TN). HPLC and nuclear magnetic resonance analysis showed 1.5% l-ornithine and < 2% of the optical isomer d-[guanidino-15N]arginine which is not a substrate for the cytokine-induced L-arginine/NO pathway (11, 12). The remaining and major other component was unlabeled ammonium chloride. A 70 mM stock solution of L-15N[15N]arginine prepared in sterile pyrogen-free water contained < 1 ng/ml of lipopolysaccharide (LPS) as measured by the Limulus amebocyte lysate assay. This stock solution was filtered three times (0.22 mM, Millipore Corp.) and sterility was confirmed by culture on blood agar. L-15N[15N]arginine HCl was added to a TPN solution containing a 1:1 mixture of 5.4% Nephramine (an essential amino acid mixture that lacks l-arginine; Kendall McGraw Laboratories, Inc. Inc, Irvine, CA) and 50% dextrose plus vitamins/electrolytes. The standard TPN mixture was discontinued and the L-15N[15N]arginine/Nephramine containing TPN mixture (2,400 ml) infused over a 24-h period. The standard TPN regimen was resumed upon completion of the L-15N[15N]arginine infusion. The patients tolerated the L-15N[15N]arginine infusions without incident or adverse effects. All calculations of 15N enrichment of serum NO2-, urine NO3-, and urine urea were based on the administration of a 70% L-15N[15N]arginine solution.

15N enrichment of serum NO3-, urine NO3-, and urine urea. Atom percent excess of urine and serum [15N]NO3- and [15N]urea was measured by gas chromatography-mass spectrometry (GC/MS) (model 5971, Hewlett-Packard Co., Palo Alto, CA), using electron ionization as previously described (41, 42). GC/MS analysis was performed by Dr. David A. Wagner, Metabolic Solutions Inc., Acton, MA.

Determination of renal function. Glomerular filtration rate was monitored throughout by daily determination of endogenous creati-
nine clearance. Renal handling of NO\textsuperscript{3}, urea, sodium, and water was assessed as previously reported (43, 44).

Statistical analysis. Statistical analysis was conducted using stepwise regression to evaluate differences among patients, followed by isolation of treatment effects as post-patient factors. Stepwise analysis of covariance procedure was used to compare periods of IL-2 administration vs. periods when patients were not receiving the drug. Two levels of prior comparisons were used. The first level tested for the presence of a linear (monotonically increasing or decreasing) trend within the four treatment phases of the study (two IL-2 and two off-drug) (45, 46). In the second level, paired comparisons for differences among treatments were conducted, each averaging across the 5 d of observations within a treatment phase. The first compared the first IL-2 treatment with the first off-drug phase. The second compared the second IL-2 treatment with the second off-drug phase. The third contrast compared the first two treatment phases with the second two treatment phases and constituted a test of the reversibility and reproducibility of IL-2 therapy. Additional analyses were conducted to compare all possible pairs of treatments. Means for the four treatment phases were subjected to analysis of variance for repeated measurements. In case of overall significance, Newman-Keul’s pairwise comparison of the differences between treatments was performed. All data are expressed as mean±SE. A P value of < 0.05 was taken to indicate significant differences.

Results

Baseline serum NO\textsuperscript{3} and 24-h urine NO\textsuperscript{3} output. Serum NO\textsuperscript{3} levels in six normal control individuals (four males and two females; mean age 38 yr) was 32±4 μmol/liter. The control individuals consumed a low nitrite (NO\textsuperscript{2}/NO\textsuperscript{3}) oral diet for 24 h and then fasted overnight (12 h) before donating blood for the NO\textsuperscript{3} assay. In the current study, pretreatment sera were assayed for NO\textsuperscript{3}. Baseline serum NO\textsuperscript{3} for MM patients was 32±3.3 μmol/liter (n = 9) and for RCC patients 36±3.2 μmol/liter (n = 5). The mean 24-h urinary NO\textsuperscript{3} output for the patients on TPN before initiation of IL-2 therapy was 600±80 μmol (n = 5) for MM patients and 521±71 μmol (n = 3) for RCC patients. This was similar to urinary NO\textsuperscript{3} excretion (690 μmol/24 h) in eight healthy subjects with unrestricted activity (mean age 21 yr) on a low protein and low NO\textsuperscript{2}/NO\textsuperscript{3} oral diet (daily NO\textsuperscript{3} ingestion < 180 μmol) (47).

Effect of IL-2 therapy on serum NO\textsuperscript{3} levels. The 5-d induction course of IL-2 therapy caused a significant rise of serum NO\textsuperscript{3} levels in both RCC patients (Fig. 2, left, panel a) and MM patients (Fig. 2, right, panel a). The results for RCC and MM patients are presented separately because of the possible effects of unilateral nephrectomy on serum and urinary NO\textsuperscript{3} levels. Serum NO\textsuperscript{3} of RCC patients increased from a baseline level of 36±3.2 to 106±16 μmol/liter on day 3 of therapy, followed by a further increase on day 5 (313±55 mmol/liter), and peaked on day 7 (353±31 μmol/liter). This 10-fold rise in serum NO\textsuperscript{3} was highly significant (P < 0.001). The overall pattern of serum NO\textsuperscript{3} changes in MM patients was similar to that observed in RCC patients. Serum NO\textsuperscript{3} levels increased from the baseline of 32±3.3 μmol/liter to 57±35, 189±48, and 247±96 on days 4, 5, and 6, respectively (P < 0.003). The highest individual serum NO\textsuperscript{3} level recorded was 646 μmol/liter on day 7. Serum NO\textsuperscript{3} decreased to 25±4 μmol/liter by day 11 when consolidation IL-2 therapy was started. During the interval between the induction course and consolidation course of IL-2, serum NO\textsuperscript{3} levels fell more slowly in RCC patients than in MM patients. During the second half of the treatment course peak serum NO\textsuperscript{3} for MM patients was 122±23 μmol/liter (day 15). The peak serum NO\textsuperscript{3} level during the consolidation course of IL-2 was significantly less than during the induction course both in RCC (P < 0.02) and MM (P < 0.05) patients.

Effect of IL-2 therapy on endogenous NO\textsuperscript{3} synthesis as determined by 24-h urinary NO\textsuperscript{3} excretion. Daily NO\textsuperscript{3} excretion paralleled serum NO\textsuperscript{3} levels. Fig. 2, both panels b, show the mean 24-h urinary NO\textsuperscript{3} excretion for patients with RCC and MM, respectively. 24-h NO\textsuperscript{3} excretion rose significantly (P < 0.001) from a baseline value of 521±71 μmol to a peak of 3,376±470.4 μmol/24 h on day 7 (P < 0.001) in five patients with RCC. By day 11, when the second course of IL-2 was started, NO\textsuperscript{3} excretion returned to 637.5±72.85 μmol/24 h, a value close to the control level. As was observed during the first IL-2 course, NO\textsuperscript{3} excretion increased during the second IL-2 infusion, again peaking (2,014.9±608.5 μmol/24 h; P < 0.05) 2 d after completion of therapy. Thereafter, NO\textsuperscript{3} excretion returned toward baseline. The consolidation course of IL-2 or IL-2 plus LAK cell therapy produced a significantly smaller increase in 24-h mean urine NO\textsuperscript{3} output than the induction course (P < 0.001).

In eight treatment courses in seven patients with MM (patient 5 had two complete courses of IL-2 therapy separated by a 3-mo interval), the excretion of NO\textsuperscript{3} increased significantly from baseline (600±80 μmol/24 h) to 1,372±271 μmol/24 h during the first 24 h of IL-2 therapy (P < 0.05) and stabilized at this level until day 6 when urine NO\textsuperscript{3} excretion rose (3,368±1,041 and 5,401±1,436 μmol/24 h on days 6 and 7, respectively [P < 0.001]). The mean 24-h output of NO\textsuperscript{3} then fell gradually to near baseline level (766 μmol/24 h) by day 11. The highest 24-h urine excretion of NO\textsuperscript{3} by an individual patient was 11,824 μmol on day 7. After reinstitution of IL-2 and without LAK cell administration (days 11–17), urine NO\textsuperscript{3} again increased (mean values of 2,041 μmol/liter on day 16 and 2,670 μmol/liter on day 17) but did not reach levels observed during the priming course of IL-2 (P < 0.003). The differences in 24-h urine NO\textsuperscript{3} output and serum NO\textsuperscript{3} levels between the induction and consolidation courses of IL-2 could be related, in part, to the fact that both MM and RCC patients received fewer infusions of IL-2 during the consolidation course because of more severe toxic side effects. MM and RCC patients received a mean of 12.5 and 10.6 priming IL-2 infusions and 8.5 and 5 consolidation infusions of 14 possible doses in each treatment course (Table I).

Effect of IL-2-induced changes in renal function on serum NO\textsuperscript{3} levels and 24-h urine NO\textsuperscript{3} excretion. The data were further analyzed in order to determine whether the IL-2-induced increase in serum NO\textsuperscript{3} resulted from a primary rise in NO\textsuperscript{3} production or from decreased renal NO\textsuperscript{3} excretion (see Fig. 2, panels c, d, e). This distinction was important since IL-2 administration caused reproducible decreases in creatinine clearance that could have contributed to NO\textsuperscript{3} retention and thus elevation of serum NO\textsuperscript{3} levels (36, 37). The data summarized in Fig. 2 (left) demonstrate that the observed increases in serum NO\textsuperscript{3} levels of RCC patients resulted from a primary rise in NO\textsuperscript{3} production and not from a major decrease in renal NO\textsuperscript{3} excretion. This is concluded because the increases in serum and urine NO\textsuperscript{3} (panels a and b) were accompanied by parallel elevations in serum NO\textsuperscript{3}/creatinine (threefold increase; P < 0.005), serum NO\textsuperscript{3}/blood urea nitrogen (BUN) (eightfold increase; P < 0.001) and urine NO\textsuperscript{3}/creatinine (fivefold increase; P < 0.02) ratios (panels c through e). In MM patients
(Fig. 2, right) serum NO\textsubscript{3} (panel a) and urinary NO\textsubscript{3} excretion (panel b) also increased in parallel with the ratios of serum NO\textsubscript{3}/creatinine (panel c; \(P < 0.005\)), serum NO\textsubscript{3}/BUN (panel d; \(P < 0.003\)) and urine NO\textsubscript{3}/creatinine (panel e; \(P < 0.004\)) ratios. The significant rise of the former two ratios indicates that the elevation in serum NO\textsubscript{3} exceeded simultaneous increases in creatinine and BUN induced by IL-2. The portion of filtered NO\textsubscript{3} that is excreted, remained relatively unchanged in RCC patients as evidenced by the fractional excretion (FE) of NO\textsubscript{3} (Fig. 2, left, panel f). The pattern of the FE NO\textsubscript{3} for MM differed somewhat from that observed for the RCC patients. Fig. 2, right, panel f, shows that the fractional excretion of NO\textsubscript{3} fell significantly during both courses of IL-2 therapy and rose during the first recovery period. These results suggest that marked IL-2–induced generation and modest NO\textsubscript{3} retention contributed to the overall rise in serum NO\textsubscript{3} levels.

**Origin of NO\textsubscript{3} synthesized in response to IL-2 treatment in humans.** Inorganic nitrogen oxides synthesized by cytokine–treated rodent macrophages are derived from a terminal guanidino nitrogen atom of L-arginine (see Fig. 1). In order to determine whether NO\textsubscript{3} synthesized by humans in response to IL-2 originated from the same precursor molecule, we administered intravenous L-[\textsuperscript{15}N]arginine to two patients. The synthesis of [\textsuperscript{15}N]NO\textsubscript{3} from L-[\textsuperscript{15}N]arginine was compared to that of [\textsuperscript{15}N]urea, a molecule known to be exclusively derived from the guanidino portion of L-arginine via the arginase reaction of the urea cycle (19). Fig. 3, panels a and b, shows the serum NO\textsubscript{3} levels and the 24-hr urine output of NO\textsubscript{3} of patient 10 with MM who was administered intravenous L-[\textsuperscript{15}N]arginine. Patient 10 had the characteristic increase of IL-2–induced NO\textsubscript{3} synthesis as reflected by total 24-hr urine NO\textsubscript{3} output and serum NO\textsubscript{3} levels. L-[\textsuperscript{15}N]arginine (18.4 mmol) was administered to patient 10, both before (day 0) and after (day 6) the induction course of IL-2, as shown in Fig. 3, panels c–e. A total of 17.6 μmol of [\textsuperscript{15}N]NO\textsubscript{3} and a total of 3.1 mmol of [\textsuperscript{15}N]urea (derived from 0.1% and 17%, respectively, of the L-[\textsuperscript{15}N]arginine molecules infused) were excreted in the urine during the subsequent 24-hr period (day 1). The second infusion of L-[\textsuperscript{15}N]arginine was ad-
ministered to patient 10 after completion of the induction course of IL-2 on day 6. There were 126 μmol of [15N]NO3 and 2.9 mmol of [15N]urea (derived from 0.7% and 16%, respectively, of L-[15N]arginine infused) excreted in the urine during the 24-h period after the L-[15N]arginine infusion was terminated (day 7). This represented a seven-fold increase in incorporation of 15N-labeled terminal guanidino nitrogen atoms of L-arginine into urine [15N]NO3 and no change in the synthesis of [15N]urea after the 5-d induction course of IL-2.

The synthesis of unlabeled NO3 and urea-N from endogenous sources of L-arginine was compared to the synthesis of [15N]NO3 and [15N]urea-N from L-[15N]arginine infused before and after administration of the induction course of IL-2 to patient 10 (see Fig. 3). This analysis determines the percentage of total urea and NO3 molecules in the 24-h urine sample containing 15N label derived from L-[15N]arginine. Unlabeled 24-h urinary urea-N increased from a pretreatment level of 321 mmol/24 h to a post-IL-2 treatment level of 430 mmol/24 h. The corresponding values for 15N-labeled urea-N was 3.1 mmol on day 1 and 2.9 mmol on day 7 resulting in a ratio of 15N-labeled to unlabeled urea-N of 0.97% (3.1 mmol [15N]urea-N/321 mmol urea-N ×100) and 0.67% (2.9 mmol [15N]urea-N/430 mmol urea-N ×100) on days 1 and 7, respectively. Corresponding measurements of urinary NO3 demonstrated a 10-fold increase of 24 h urine NO3 derived from endogenous sources of L-arginine (669 mmole NO3 on day 1 and 6,848 mmol NO3 on day 7) and a sevenfold increase of labeled [15N]NO3 (17.6 mmol on day 1 and 126.2 mmol on day 7) during IL-2 treatment. The ratio of labeled and unlabeled urinary [15N]NO3 was 2.6% (17.6 mmol [15N]NO3/669 mmol NO3 ×100) and 1.8% (126.2 mmol [15N]NO3/6,848 mmol NO3 ×100) on days 1 and 7, respectively. These results show that a similar proportion of total urea and total NO3 molecules excreted in the 24-h urine sample contained 15N label derived from L-[15N]arginine (pre- and post-IL-2).

Fig. 3, panel c, shows serum [15N]NO3 levels in patient 10. After the pre-IL-2 infusion of L-[15N]arginine the serum [15N]NO3 concentration reached a maximum of 0.5 μmol/liter (day 1). However, the serum [15N]NO3 of patient 10 was 3.5 μmol/liter (1% of 354 μmol/liter total serum NO3) 12 h after starting the L-[15N]arginine infusion (day 6). Immediately after terminating the L-[15N]arginine infusion (day 7), the serum [15N]NO3 was 7.3 μmol/liter (2.2% of 331 μmol/liter total serum NO3) and declined thereafter.

A second patient was administered L-[15N]arginine. The results confirmed that the IL-2-induced increase in urine and serum NO3 was derived from a terminal guanidino nitrogen atom of L-arginine (data not shown). In summary, the 15N-labeling studies demonstrate that (a) IL-2 induces a marked increase in synthesis of NO3 but not urea from a terminal guanidino nitrogen atom of L-arginine, and (b) the ratio of 15N-labeled molecules to unlabeled molecules remains constant regardless of whether synthesis was enhanced by IL-2 (NO3) or whether synthesis remained relatively unaltered (urea).

Effects of IL-2 on peripheral vascular resistance and renal tubular function. Despite progressive declines in creatinine clearance (days 3–6; panel a), Fig. 4 (left) urine output of RCC patients receiving IL-2 was maintained with intravenous fluids, albumin infusions, furosemide, and dopamine as needed. Mean blood pressure (panel e) fell from 85±4 mmHg before IL-2 therapy to a nadir of 67±3 mmHg (P < 0.004) by day 4. This IL-2–induced decrease in creatinine clearance and blood pressure was associated with a marked increase in weight (from 69±5.2 to 73.7±5.7 kg on day 6 and profound reversible sodium retention (see Fig. 4, left, panel b, P < 0.001). 2 d after discontinuation of IL-2, urine volume rose strikingly (from 1.9±0.5 to 6.4±0.6 liter/24 h on day 7; P < 0.001). This diuresis persisted until day 11, when the second course of IL-2 was begun. Predictably, body weight fell and creatinine clearance and blood pressure rose simultaneously (both P < 0.01). The second course of IL-2 produced a similar decrease in urine output and milder fall in blood pressure and again caused salt and water retention and thus weight gain. All alterations were readily reversible when IL-2 was discontinued. Both panels c of Fig. 4 illustrate the FE of urea, another variable that can be used to assess changes in tubular reabsorption. Within 3 d of beginning IL-2 therapy, FE of urea decreased modestly, rose as

![Figure 3. (left) NO3 and urea excretion and serum (right) values by patient 10 administered L-[15N]arginine HCl (arrows). See legend to Fig. 2 for an explanation of the symbols. Panels a and b show total serum NO3 levels and 24-h urinary NO3 excretion, respectively. Patient 10 received two 3.9-g (18.4 mmol) infusions of L-[15N]arginine. The first was administered during the 24-h period before beginning induction IL-2 therapy (day 0) and again during the 24-h period immediately after terminating induction IL-2 therapy (day 6). L, liter.](image-url)
IL-2 was discontinued, and fell again when IL-2 was readministered. This pattern demonstrates that IL-2 caused both enhanced Na and urea reabsorption. Panel d of Fig. 4 (left) depicts the urine to plasma ratio of creatinine. As creatinine clearance and sodium excretion declined with IL-2 therapy (days 3–5), the urine to plasma ratio of creatinine fell from 40.7±4.4 to 23.3±9.8 (P < 0.003). A further decrease to a low of 11.2±3.2 occurred by day 7, a time when IL-2 had been discontinued and when creatinine clearance, blood pressure, urine volume, and salt excretion increased dramatically.

Readministration of IL-2 on day 11 raised the urine to plasma ratio of creatinine to 70.1±3.0 (P < 0.001). Taken together, these data demonstrate that proximal renal tubular function and the urinary concentrating capacity of patients with unilateral nephrectomies were preserved and not grossly affected by IL-2.

Fig. 4 (right) summarizes the corresponding data from the MM patients. In general, the hemodynamic and renal responses to IL-2 administration were similar to those observed in RCC patients. It is of note, however, that virtually all functional changes were less severe when compared to those in RCC patients, whose baseline renal function was reduced because of prior unilateral nephrectomy. Finally, there was no evidence of major nephrogenous NO₃ production in either MM or RCC patients. The FE of NO₃ (panels f in Fig. 2) was never greater than ~ 40% indicating that ~ 60% of the filtered NO₃ was reabsorbed. Significant renal vascular or tubular NO₃ production during IL-2 therapy would have caused the FE of NO₃ to rise further.

Discussion

In 1981 Green and co-workers (48), while studying the biology of nitrosamine carcinogenesis, reported metabolic balance studies that showed that conventional and germ-free rats synthesize NO₃. This confirmed an earlier study suggesting that mammals, in addition to certain procaryotes, synthesized inorganic nitrogen oxides (49). These workers also investigated NO₃ metabolism in long-term metabolic balance studies on healthy humans (47). During one of these studies a human subject on a low NO₃ diet developed an unexpected increase of NO₃ biosynthesis that occurred simultaneously with the onset of fever and diarrhea (50). Compared to baseline levels, urinary NO₃ excretion increased ninefold during the illness. After this observation, Wagner et al. examined the effect of lipo polysaccharide (LPS) treatment on NO₃ excretion in rats (51). The results showed that LPS caused a marked (ninefold) increase in NO₃ excretion. Stuehr and Marletta (52) followed up these observations with experiments that demonstrated that murine macrophages cultured in vitro and exposed to LPS synthesized NO₃ and NO₂. These studies defined inorganic nitrogen oxide syn-

![Figure 4. Renal function and blood pressure in (left) RCC patients (n = 5) and (right) MM patients (n = 7) treated with two courses of IL-2. See legend to Fig. 2 for details and explanation of the symbols.](image-url)
thesis as a mammalian process but left open the question of precursor molecule identity and biological significance.

In 1987 our laboratory reported that L-arginine was the only amino acid in the culture medium required by cytotoxic activated macrophages to inhibit DNA replication and to cause inhibition of mitochondrial (4Fe-4S) enzymes in tumor target cells (11). L-Arginine was converted to NO\textsubscript{2} and L-citrulline without loss of the guanidino carbon atom (12). These experiments identified L-arginine as the precursor molecule for mammalian inorganic nitrogen oxide synthesis, L-citrulline as an additional product, and established a role for the L-arginine/NO pathway as an effector mechanism of cell-mediated immunity. NO was then demonstrated to be the precursor of the NO\textsubscript{2} and NO\textsubscript{3} previously shown to be synthesized from L-arginine by activated macrophages (13, 15, 16). In 1987, two vascular physiology laboratories reported that NO released by endothelial cells accounted for the biological activity of endothelium-derived relaxing factor (53, 54). This was followed by a second report in 1988 that demonstrated that NO synthesized by endothelial cells is also derived from a terminal guanidino nitrogen atom of L-arginine (30). Therefore, similar L-arginine/NO pathways were shown to exist in cytotoxic activated macrophages and endothelial cells but the pathways appeared to have been adapted for different physiological functions (e.g., a cytokine-inducible isoenzyme that synthesizes large quantities of NO during cell-mediated immune responses and a constitutive isoenzyme that synthesizes small quantities of NO that functions as an intercellular message).

There is limited information to date on L-arginine/NO pathways in humans. The metabolic balance studies of Green et al. demonstrated that normal adult humans with unrestricted activity endogenously produce ≈ 690 \textmu mol of nitrate/24 h (47). After the discovery of the L-arginine/NO pathways, this basal endogenous synthesis was explained by activity of the constitutive low-output NO synthase in maintenance of vascular tone (30), neural transmission (31–33), and in other functions such as chemotaxis (55). NO appears to be an important regulator of resting and stimulated regional blood flow in humans. N\textsuperscript{3} monomethyl-L-arginine, a potent inhibitor of both NO-synthesizing pathways (11, 12, 30), was infused into the brachial arteries of healthy volunteers to study the role of NO in the control of forearm blood flow (56). This agent caused a 50% fall in basal blood flow and attenuated the dilator response to acetylcholine but not to glycerol trinitrate. Taken together these studies provided evidence for the existence of a constitutive pathway in humans. Until now clinical studies evaluating human subjects for cytokine-inducible NO synthase activity have not been performed. We and others have not been successful in inducing high-output NO synthase from human cells cultured in vitro by treatment protocols with cytokines that are highly effective with rodent cells (57; Hibbs et al., unpublished data). However, a recent report describes the induction of high-output nitrite synthesis by cytokine-treated human blood monocyte–derived macrophages infected with Mycobacterium avium (29). The reason why it is difficult to detect activity of the cytokine-inducible pathway in human cells in vitro is not clear. However, results reported in this study demonstrate that IL-2 is a potent inducer of high-output NO synthase from L-arginine in human subjects with advanced malignancy.

There is evidence to suggest the IL-2 may not directly induce toxic effects or antitumor effects but may act as a factor that mobilizes and amplifies cell-mediated immunity by induc-
against bacteremic shock [64]). Further support for this concept is derived from recent reports that NO may mediate TNF-induced vascular changes. NO\textsuperscript{\textsuperscript{1}}-monomethyl-L-arginine reversed TNF (65) and endotoxin (66) induced decreased peripheral vascular resistance and mean arterial pressure in dogs. These studies provide evidence for a role for NO in the pathogenesis of decreased vascular resistance and hypotension observed in LPS- or TNF-treated dogs. It also has been demonstrated recently that IL-1 induces L-arginine-dependent cyclic GMP and NO production in rat vascular smooth muscle cells (67). Therefore, it is reasonable to suggest that NO synthesis from L-arginine could play a major role in development of decreased vascular resistance and hypotension in IL-2-treated patients.

The current study provided an opportunity to evaluate renal function in humans under pathophysiologic conditions that closely simulate endotoxin/LPS induced shock (hypotension and renal hypoperfusion) in a clinical setting associated with elevated levels of TNF in tissues. The data are consistent with the suggestion made by Marsden and Ballermann (68) that TNF-induced NO produced within the renal parenchyma actually protects against development of acute tubular necrosis by maintaining postglomerular circulation. This is also consistent with the observation that synthesis of NO from L-arginine lessens hepatic damage in a murine model of endotoxin-induced shock (69). NO reduces renal vascular resistance and inhibits platelet activation (aggregation and adhesion [70, 71]). Thus NO has the potential to promote maintenance of renal perfusion under normal and pathological conditions (30, 53, 54, 70–74). It is likely that cyclic GMP, a second messenger induced by NO, is elaborated by the kidney during IL-2 therapy (68, 73, 74). It has been shown that atrial natriuretic factor, a peptide with vasodilating and diuretic/natriuretic properties, ameliorates, via cyclic GMP, the severity of acute renal failure (75, 76).

The reversible form of IL-2–induced acute renal failure differs significantly from that observed in endotoxicemic patients and animals (77–82). In the latter, acute and sometimes irreversible tubular necrosis is common. Specifically patients with endotoxin-induced acute tubular necrosis lose their capacity to retain salt (high FE of sodium) and to concentrate their urine (low urine to plasma creatinine ratio). These alterations were not observed in the IL-2–treated patients evaluated in this study (see Fig. 4). Since IL-2–treated patients resemble patients with endotoxemia in many regards (elevated TNF levels, hypotension, elevated cytokine levels, etc.), it is of interest that acute tubular necrosis is a rare consequence of IL-2 therapy. This observation is even more surprising since all patients received indomethacin, an agent that predisposes to the development of acute tubular necrosis (83). In conclusion, the results reported here show highly significant 

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Cytokine-inducible Nitric Oxide Synthesis


