

# Macrophage Deactivation by Interleukin 10

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## Summary

Recombinant mouse interleukin 10 (IL-10) was exceedingly potent at suppressing the ability of mouse peritoneal macrophages (m $\phi$ ) to release tumor necrosis factor  $\alpha$  (TNF- $\alpha$ ). The IC<sub>50</sub> of IL-10 for the suppression of TNF- $\alpha$  release induced by 0.5  $\mu$ g/ml lipopolysaccharide was 0.04  $\pm$  0.03 U/ml, with as little as 1 U/ml suppressing TNF- $\alpha$  production by a factor of 21.4  $\pm$  2.5. At 10 U/ml, IL-10 markedly suppressed m $\phi$  release of reactive oxygen intermediates (ROI) (IC<sub>50</sub> 3.7  $\pm$  1.8 U/ml), but only weakly inhibited m $\phi$  release of reactive nitrogen intermediates (RNI). Since TNF- $\alpha$  is a T cell growth and differentiation factor, whereas ROI and RNI are known to inhibit lymphocyte function, it is possible that m $\phi$  exposed to low concentrations of IL-10 suppress lymphocytes. m $\phi$  deactivated by higher concentrations of IL-10 might be permissive for the growth of microbial pathogens and tumor cells, as TNF- $\alpha$ , ROI, and RNI are major antimicrobial and tumoricidal products of m $\phi$ . IL-10's effects on m $\phi$  overlap with but are distinct from the effects of the two previously described cytokines that suppress the function of mouse m $\phi$ , transforming growth factor  $\beta$  and macrophage deactivation factor. Based on results with neutralizing antibodies, all three m $\phi$  suppressor factors appear to act independently.

IL-10, originally termed cytokine synthesis inhibitory factor (CSIF),<sup>2</sup> was discovered as a product of Th2 cells that suppresses IFN- $\gamma$  production by Th1 cells (1-3). IL-10 joins TGF- $\beta$  as one of the few lymphocyte suppressor factors to be purified and cloned (4, 5). The mechanisms by which suppressor factors affect lymphocyte function are not well understood. IL-10 inhibits Th1 cells only in the presence of accessory cells, especially macrophages (m $\phi$ ) (6). This raises the possibility that IL-10 might act primarily on m $\phi$  to alter the balance between their lymphocyte-stimulating and lymphocyte-inhibiting secretory products (7), thereby affecting lymphocytes secondarily.

As is the case for lymphocytes, only a few purified cytokines are known to suppress the function of m $\phi$  (8-14). In fact, only two cytokines are known to block or reverse the activation of mouse m $\phi$ : TGF- $\beta$  (including TGF- $\beta$ -1, -2, and -3) and m $\phi$  deactivating factor (MDF) (8-10, 15-18; for review see reference 19). The present experiments were designed to test whether IL-10 is a new m $\phi$  deactivation factor, and if so, whether it mediates the m $\phi$ -deactivating effects of TGF- $\beta$  or MDF.

<sup>1</sup> Christian Bogdan and Yoram Vodovotz contributed equally to the experiments described in this paper.

<sup>2</sup> Abbreviations used in this paper: CSIF, cytokine synthesis inhibitory factor; MDF, macrophage deactivating factor; m $\phi$ , macrophage; RNI, reactive nitrogen intermediates; ROI, reactive oxygen intermediates.

## Materials and Methods

**Mice.** Female CD1 mice (8-12 wk old) were from the Charles River Breeding Laboratories (Wilmington, MA).

**Cytokines and Other Reagents.** Supernatants from COS7 cells transfected with mIL-10 cDNA (1,000 U/ml, where 1 U caused half-maximal response of the MC/9 mast cell line as described [20]; LPS content at 100 U/ml < 10 pg/ml) and control supernatants from mock transfected cells (LPS content at a 1:10 dilution < 10 pg/ml) were kindly provided by Dr. K. Moore (DNAX, Palo Alto, CA); 1 MC/9 U/ml is equal to 1 CSIF U/ml, personal communication). MDF was purified from the culture supernatants of P815 mouse mastocytoma cells as described (10) or directly extracted from these cells following a similar procedure (Y. Vodovotz, C. Bogdan, and C. Nathan, unpublished results). A unit of MDF is defined as that amount of MDF in a final culture volume of 0.125 ml that causes 50% suppression of PMA-triggered m $\phi$  H<sub>2</sub>O<sub>2</sub>-releasing capacity after a 48-h incubation (10). rmIFN- $\gamma$  (protein concentration 1.1 mg/ml; sp act 5.2  $\times$  10<sup>6</sup> U/mg; LPS content <10 pg/ml) and rmTNF- $\alpha$  (protein concentration 0.98 mg/ml; sp act 1.2  $\times$  10<sup>7</sup> U/mg; LPS content <52 pg/ml) were kindly provided by Genentech (South San Francisco, CA). rhTGF $\beta$ 1 was a gift of Amgen, Inc. (Thousand Oaks, CA). Ascites fluid containing a neutralizing rat IgM mAb against mIL-10 (SXC1 [21]; LPS content <10 pg/ml at a 1:100 dilution) was a gift from Dr. S. Reed (Seattle, WA). A 1:1,000 dilution of this antibody preparation completely neutralized the effect of IL-10 at concentrations  $\leq$ 100 U/ml and was used in all experiments. Purified rat IgM as an isotype control antibody was obtained from Calbiochem-Behring Corp. (La Jolla, CA). Turkey anti-TGF- $\beta$ 1 IgG and nonimmune turkey IgG were kindly provided by Dr. M. Sporn (National Cancer Institute, Bethesda, MD). LPS, prepared by phenol extraction from *Esche-*

*richia coli* O111:B4, was from List Biological Laboratories (Campbell, CA).

**M $\phi$  Cultures.** Periodate- and thioglycolate-elicited m $\phi$  were harvested from the peritoneal cavity with  $\alpha$ MEM medium (JRH Biosciences, Cambridge, MA) and cultured as published (22).

**H<sub>2</sub>O<sub>2</sub> Release Assay.**  $1.5 \times 10^5$  Periodate-elicited peritoneal cells were triggered for H<sub>2</sub>O<sub>2</sub> release by PMA. H<sub>2</sub>O<sub>2</sub> secretion/mg adherent cell protein was determined as described (10).

**Reactive Nitrogen Intermediates (RNI) Production and NO<sub>2</sub><sup>-</sup> Determination.** Monolayers of thioglycolate-elicited m $\phi$  were stimulated for RNI production by IFN- $\gamma$ , IFN- $\gamma$ /TNF, or IFN- $\gamma$ /LPS for 48 h. Nitrite concentration in the cell-free m $\phi$  supernatants served as a reflection of nitric oxide production and was measured by the colorimetric Griess reaction as described (18, 22).

**TNF- $\alpha$  Production and TNF- $\alpha$  Assay.** Monolayers of thioglycolate-elicited m $\phi$  were obtained by seeding the cells in 24-well plastic tissue culture plates (Costar, Cambridge, MA) at  $10^6$ /well (final volume of 0.5 ml) for 2–3 h at 37°C in 5% CO<sub>2</sub>/95% air. Nonadherent cells were removed by three washes with PBS (37°C) and the monolayers were then stimulated with LPS ( $\pm$  rmIL-10) either in the presence or absence of rmIL-10 as indicated in the text. 20 h later, the supernatants were harvested and stored at –20°C. The TNF- $\alpha$  content of the test supernatants was determined in a bioassay with the highly specific and sensitive subclone 13 of the WEHI 164 fibrosarcoma line (23) (kindly provided by Dr. S. Kunkel, Ann Arbor, MI, with permission of Dr. T. Espevik, Trondheim, Norway) as published previously (24). Data from at least 10 serial twofold dilutions per supernatant were subjected to probit analysis using a rmTNF- $\alpha$  standard curve as described (25). Finally, the fold suppression of TNF release in the test supernatants was determined [(ng/ml TNF in medium control)/(ng/ml TNF in test supernatant)]. Use of a polyclonal rabbit anti-TNF- $\alpha$  antiserum (Genzyme, Boston, MA) demonstrated that the cytotoxic activity was completely dependent on TNF- $\alpha$ .

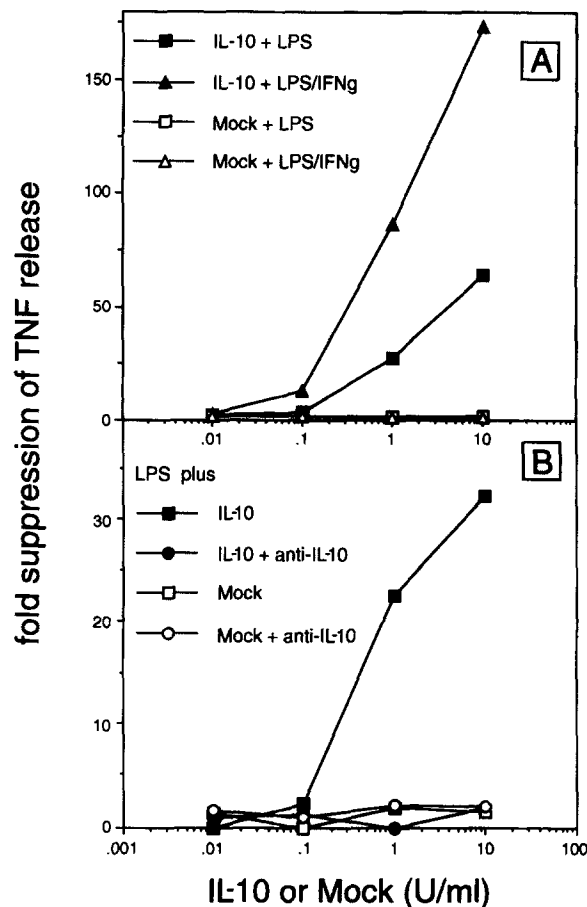
**SDS-PAGE and Western Blot.** IL-10-containing and mock control COS cell supernatants and partially purified MDF were separated on 20% SDS-PAGE and transferred to nitrocellulose membranes (26, 27).

**Protein Synthesis.** Monolayers ( $2 \times 10^6$ /well) of periodate-elicited m $\phi$  were incubated for 48 h in complete RPMI 1640 in the presence or absence of rmIL-10. During the last 6 h of incubation, the medium was exchanged for methionine-free RPMI 1640 with 1% FCS (Gibco, NY), and 50  $\mu$ Ci [<sup>35</sup>S]-methionine (> 1,000 Ci/mmol; Amersham Corp., South Clearbrook, IL) was added per  $2 \times 10^6$  m $\phi$ . The cells were then washed and lysed in 1% triton X-100 and processed for determination of radiolabeled protein as described (15). Additional aliquots of the lysates were subjected to SDS-PAGE autoradiography.

## Results

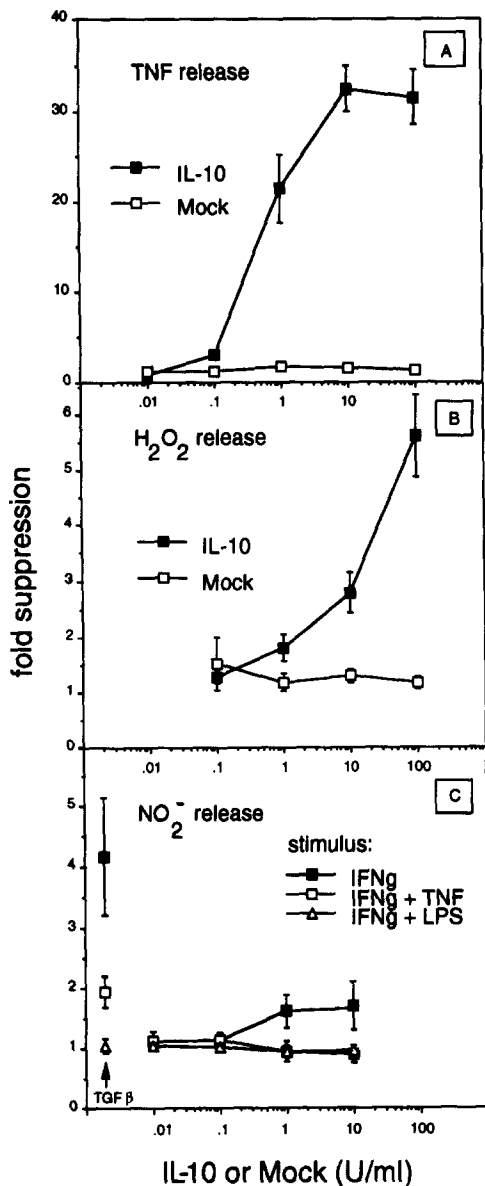
TGF- $\beta$  and MDF can prevent m $\phi$  from releasing all three of their major cytotoxic products: TNF- $\alpha$  (28, and Bogdan, C., Y. Vodovotz, and C. Nathan, manuscript in preparation), reactive oxygen intermediates (ROI) (8, 10, 15–17), and RNI (18, 29). Accordingly, we tested the effects of IL-10 in each of these assays.

**Suppression of TNF- $\alpha$  Release.** IL-10 was an exceedingly potent inhibitor of m $\phi$  TNF- $\alpha$  release (Fig. 1; Fig. 2 A). The inhibitory effect was concentration dependent, reaching its plateau upon exposure of m $\phi$  to 10 U/ml IL-10, which cause 32.4 ( $\pm$  2.8)-fold (97%) suppression (mean  $\pm$  SEM



**Figure 1.** IL-10 suppresses TNF- $\alpha$  release by monolayers of thioglycolate-elicited m $\phi$ . (A) M $\phi$  were stimulated with LPS (0.25  $\mu$ g/ml) or LPS (0.25  $\mu$ g/ml) plus IFN- $\gamma$  (10 ng/ml) in the absence or presence of IL-10 or an identical amount of COS-cell control supernatant (mock transfectant). (B) M $\phi$  were stimulated with LPS (0.5  $\mu$ g/ml) alone or together with IL-10 or an identical amount of COS-cell control supernatant (mock transfectant) in the absence or presence of anti-IL-10. (A and B) After 20 h, the TNF content in the cell-free supernatants and the fold suppression of TNF- $\alpha$  release were determined as described in Material and Methods. The TNF release in the medium controls was 4.6 ng/ml (LPS alone) and 41.6 ng/ml (LPS plus IFN- $\gamma$ ) in the experiment shown in A and 43.3 ng/ml (LPS alone) in B.

of three experiments) of m $\phi$  TNF- $\alpha$  release induced by 0.5  $\mu$ g/ml LPS. 50% suppression required only  $0.044 \pm 0.031$  U/ml (mean  $\pm$  SD from four experiments). Preincubation of the m $\phi$  with IL-10 before stimulation by LPS was not necessary. Anti-IL-10 mAb abolished the suppression afforded by IL-10-containing COS cell supernatant (Fig. 1 B), whereas a rat IgM control antibody failed to do so (not shown). Mock-transfected COS cell supernatant had no effect (Fig. 1 B). IL-10 abolished TNF- $\alpha$  release induced by LPS at concentrations of 0.25 or 0.5  $\mu$ g/ml (Fig. 1), 1 or 10  $\mu$ g/ml (not shown), or when TNF- $\alpha$  release was induced by the combination of LPS (0.25  $\mu$ g/ml) and IFN- $\gamma$  (10 or 20 ng/ml) (Fig. 1 A). In control experiments, IL-10 did not stimulate the indicator cells in the TNF bioassay; protect them from inhibition by



**Figure 2.** Comparison of the effect of IL-10 on mφ TNF- $\alpha$  production, H<sub>2</sub>O<sub>2</sub> secretion, and RNI release. (A) Adherent thioglycolate-elicited mφ (10<sup>6</sup>/well) were stimulated with LPS (0.5  $\mu$ g/ml) for TNF- $\alpha$  release in the presence of IL-10 or a mock-transfectant control supernatant as described in the legend to Fig. 1. (B) Periodate-elicited cells (1.5  $\times$  10<sup>5</sup>/well) were incubated in medium alone, IL-10, or a mock-transfectant control supernatant. After 48 h, H<sub>2</sub>O<sub>2</sub> release was triggered, the adherent cell protein determined, and the H<sub>2</sub>O<sub>2</sub> release/mg adherent cell protein calculated. (C) Adherent thioglycolate-elicited mφ (2  $\times$  10<sup>5</sup>) were stimulated with IFN- $\gamma$  (1 ng/ml), IFN- $\gamma$  (1 ng/ml) plus TNF- $\alpha$  (20 ng/ml), or IFN- $\gamma$  (1 ng/ml) plus LPS (100 ng/ml) in the presence of IL-10, supernatant of mock transfectants, TGF- $\beta$  (10 ng/ml), or medium. After 48 h, the cell-free supernatants were processed for NO<sub>2</sub><sup>-</sup> determination (nmol release per 2  $\times$  10<sup>5</sup> mφ) (22). The mean NO<sub>2</sub><sup>-</sup> release in the control cultures was 6.2 (IFN- $\gamma$ ), 7.8 (IFN- $\gamma$  + TNF- $\alpha$ ), and 12.0 (IFN- $\gamma$  + LPS) nmol/2  $\times$  10<sup>5</sup> mφ. The symbols next to the y-axis denote the values for the TGF- $\beta$ -treated cultures. The remaining symbols are all for cells treated with the indicated concentration of IL-10. The mock-transfectant supernatant-treated cultures revealed <10% suppression and the values are not shown here for the sake of clarity. (A, B, and C) The fold suppression of TNF- $\alpha$ , H<sub>2</sub>O<sub>2</sub>, and NO<sub>2</sub><sup>-</sup> release was calculated by comparing the values of the IL-10-, mock-transfectant control supernatant-, or TGF- $\beta$ -

exogenous TNF- $\alpha$ ; nor induce mφ to release a factor that could block the action of TNF- $\alpha$  (not shown).

**Suppression of H<sub>2</sub>O<sub>2</sub> Release.** Concentrations of IL-10 50–100-fold higher than those suppressing TNF- $\alpha$  release suppressed the ability of PMA-triggered mφ to release H<sub>2</sub>O<sub>2</sub> (IC<sub>50</sub> = 3.7  $\pm$  1.8 U/ml, mean  $\pm$  SD, three experiments) (Fig. 2 B). The range of suppression caused by 10 U/ml IL-10 was 55–79% with a mean ( $\pm$  SEM) of 65% ( $\pm$  4.1; four experiments). This action of IL-10-containing COS cell supernatant was abolished by anti-IL-10 mAb and was lacking in mock-transfected COS cell supernatant (Fig. 3).

**Relation between IL-10 and MDF or TGF- $\beta$ .** Since suppression of mouse peritoneal mφ H<sub>2</sub>O<sub>2</sub> releasing capacity has been the cardinal assay for characterization of MDF (10, 15–17), it was important to test whether MDF consists in, or acts through the induction of, IL-10. As shown in Fig. 3, anti-IL-10 mAb had no effect on the respiratory burst-suppressing action of MDF. Moreover, anti-IL-10 mAb immunoblotted IL-10 in COS cell supernatant, but not a preparation of semi-purified MDF containing a twofold higher bioactivity as determined in the H<sub>2</sub>O<sub>2</sub> release assay (Fig. 4).

Likewise, the suppressive action of TGF- $\beta$  on the mφ respiratory burst (8, 17) or TNF- $\alpha$  release (28) was unaffected by anti-IL-10 mAb (not shown). Finally, abs that neutralize TGF- $\beta$  but not MDF in the H<sub>2</sub>O<sub>2</sub> release assay (10) had no effect on suppression by IL-10 (Fig. 5). Anti-MDF abs are not yet available.

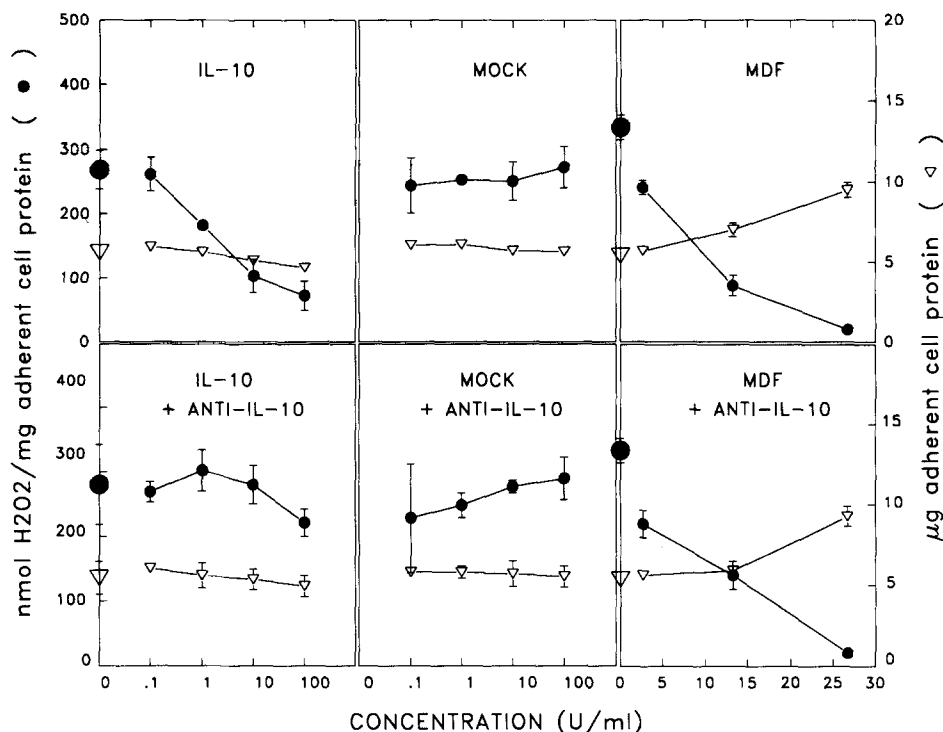
**Effect of IL-10 on RNI Release.** The above results indicated that IL-10 appears to act independently of TGF- $\beta$  and MDF. Thus, the spectrum of action of IL-10 on mφ may differ from that of TGF- $\beta$  and MDF. Indeed, unlike TGF- $\beta$  and MDF (18), IL-10 only variably and weakly inhibited the induction of RNI release by IFN- $\gamma$  (range of suppression by 10 U/ml in six experiments: 0–60%; mean  $\pm$  SEM = 37  $\pm$  15%) and was unable to suppress RNI release induced by the combination of IFN- $\gamma$  and TNF- $\alpha$  (Fig. 2 C). Higher concentrations of IL-10 (100 U/ml) did not further increase the suppression of RNI release (three experiments; data not shown). As found for MDF and TGF- $\beta$ , IL-10 also failed to inhibit RNI release induced by the combination of IFN- $\gamma$  plus LPS (Fig. 2 C).

**Effect of IL-10 on mφ Protein Synthesis.** The selectivity of IL-10 effects on mφ was further demonstrated by its inability to alter the incorporation of <sup>35</sup>S-methionine into protein, or to affect the overall pattern of protein synthesis as evaluated by one-dimensional SDS-PAGE (not shown).

## Discussion

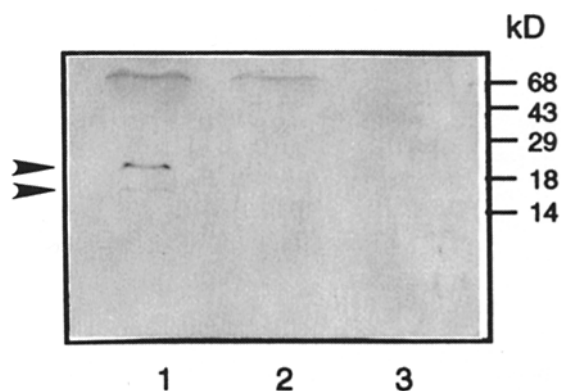
IL-10 appears to be even more potent as a suppressor of mφ TNF- $\alpha$  release than as a suppressor of Th1 cell IFN- $\gamma$  synthesis (1). A concentration of IL-10 (1 U/ml) that almost completely suppressed mφ TNF- $\alpha$  release (95.4% suppres-

reated cultures with those of the medium control. Data represent mean values ( $\pm$  SEM) of three (TNF- $\alpha$  release), four (H<sub>2</sub>O<sub>2</sub> release) or five (NO<sub>2</sub><sup>-</sup> release) experiments, respectively.



**Figure 3.** IL-10 suppresses m $\phi$  H<sub>2</sub>O<sub>2</sub> release, but does not appear to account for the activity of MDF.  $1.5 \times 10^5$  periodate-elicited cells were incubated either in medium alone or in IL-10, mock COS cell supernatant, or in MDF (C18-RPHPLC-purified) in the presence or absence of anti-IL-10. After 48 h, H<sub>2</sub>O<sub>2</sub> release was triggered with PMA and the adherent cell protein ( $\nabla$ ) was determined to exclude toxicity. H<sub>2</sub>O<sub>2</sub> release is expressed as nmol H<sub>2</sub>O<sub>2</sub>/mg adherent cell protein ( $\bullet$ ). Control values are given on the y-axis of each panel. Data represent mean ( $\pm$  SD) from triplicate cultures of a representative experiment. Where error bars are not visible, they fall within the symbols denoting the means.

sion) had little effect on H<sub>2</sub>O<sub>2</sub> release (42% suppression) and on the secretion of RNI (36% suppression). TNF- $\alpha$  is a potent growth and differentiation factor for mouse T cells (30–32). In contrast, ROI and RNI suppress lymphocyte function (33–35). Thus, activated m $\phi$  exposed to low concentrations of IL-10 are likely to produce ROI and RNI but not TNF- $\alpha$ , and thus may display a suppressor phenotype toward lymphocytes. This may contribute to the CSIF activity of IL-10.

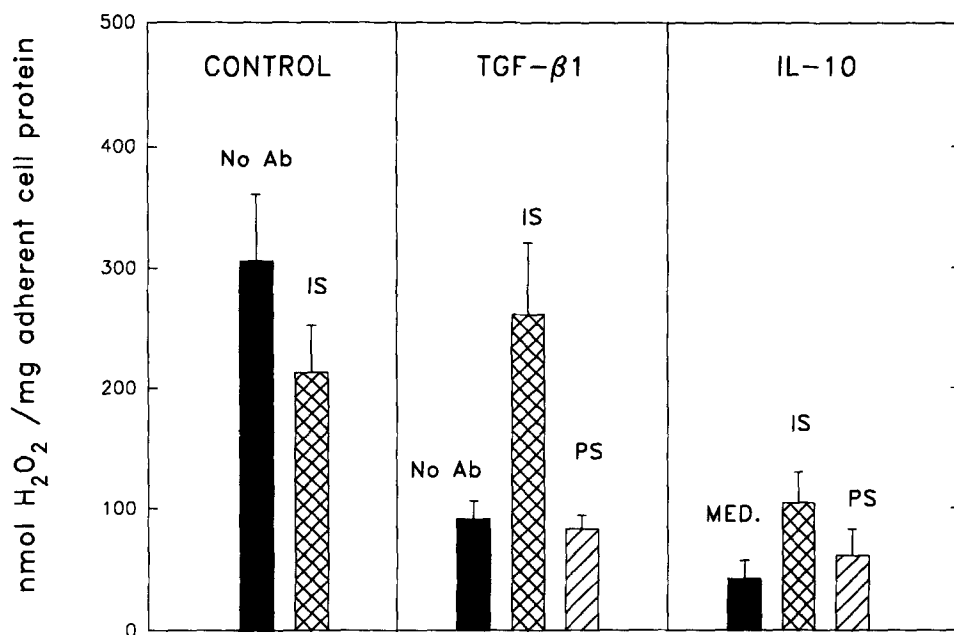


**Figure 4.** Anti-IL-10 mAb fails to recognize MDF. IL-10 containing COS cell supernatant (50 U, corresponding to  $\sim 100$  U in the standard H<sub>2</sub>O<sub>2</sub> release assay) (lane 1), an equivalent amount of mock transfectant supernatant (lane 2), and MDF (200 U in the H<sub>2</sub>O<sub>2</sub> release assay) (lane 3) were separated on 20% SDS-PAGE, electrotransferred to nitrocellulose, immunoblotted with anti-IL-10 mAb (1:100 dilution), and developed with a goat anti-rat IgM antiserum conjugated to alkaline phosphatase. The arrows indicate rmIL-10 in its expected size heterogeneity (2, 21).

On the other hand, at higher concentrations (10 U/ml), IL-10 markedly suppressed not only m $\phi$  TNF- $\alpha$  release but also the release of ROI. Finally, although IL-10 only weakly suppressed RNI release induced by IFN- $\gamma$ , IL-10 might be more effective at suppressing RNI release indirectly in situations where RNI release depends on an autocrine action of TNF- $\alpha$ . Ingestion of pathogens is a strong stimulus for m $\phi$  to release TNF- $\alpha$  (24, 36), which in turn helps to induce RNI by interacting synergistically with IFN- $\gamma$  (22, 37). Since ROI, RNI, and TNF- $\alpha$  are among the major antimicrobial (for review see references 38 and 39) and antitumor products of m $\phi$  (for review see reference 40), a second phenotype of the IL-10-treated m $\phi$  may be that of a cell permissive for the growth of pathogens and tumor cells. IL-10, therefore, may suppress the antimicrobial and tumoricidal function of m $\phi$  in two ways: first, indirectly through inhibition of IFN- $\gamma$  production by Th1 cells, which then impairs m $\phi$  activation; and second, directly through deactivation even in the presence of IFN- $\gamma$ .

IL-10's actions on m $\phi$  function were selective and nontoxic. At the same time that IL-10 abolished TNF- $\alpha$  release and decreased H<sub>2</sub>O<sub>2</sub> release, it had only little effect on their release of RNI. IL-10 did not affect the number of m $\phi$  remaining adherent to vigorously washed plates (Fig. 3), their overall synthesis of protein, nor their synthesis of major proteins.

IL-10, TGF- $\beta$ , and MDF appeared to act independently, since abs that neutralized either IL-10 or TGF- $\beta$  had no effect on the actions of the other two proteins in the same assays. Although MDF remains to be cloned, it appears to be distinct from IL-10 by the following criteria. MDF migrates at  $\sim 13$  kD on denaturing SDS-PAGE and is purified on the basis of its acid stability (10), while IL-10 migrates at 16–21



**Figure 5.** H<sub>2</sub>O<sub>2</sub> suppression by IL-10 is not mediated through TGF-β1. Periodate-elicited cells ( $1.5 \times 10^5$ /well) were cultured in medium alone (control) or in TGF-β1 (10 ng/ml) or in IL-10 (10 U/ml), in the presence of preimmune (PS) or immune (IS) anti-TGF-β1 antiserum or in the absence of antiserum (no Ab). After 48 h, H<sub>2</sub>O<sub>2</sub> release was triggered and the adherent cell protein determined. Data represent mean ( $\pm$  SD) from triplicate cultures of a representative experiment.

kD on SDS-PAGE and is acid labile (2). MDF (Vodovotz, Y., C. Bogdan, and C. Nathan, manuscript in preparation) but not IL-10 inhibits lymphocyte proliferation (1, 2, 41). Moreover, MDF is much more potent in suppressing RNI release (18). Like TGF-β (8) but unlike MDF (10, 15), IL-10 tends to cause adherent mφ to round up in culture (not

shown). Finally, anti-IL-10 mAb neither neutralizes nor immunoblots MDF.

Several cytokines activate mφ in ways that are overlapping but distinct, giving rise to diverse phenotypes. The same can now be said of cytokines that deactivate mφ.

We are grateful to S. Kunkel (University of Michigan, Ann Arbor, MI), K. Moore (DNAX Research Institute, Palo Alto, CA), M. Palladino (Genentech, South San Francisco, CA), S. Reed (Biomedical Research Institute, Seattle, WA), M. Sporn (National Cancer Institute, Bethesda, MD), and H. Yeganegi (Amgen Biologicals, Thousand Oaks, CA) for gifts of reagents and cells, and to Erika Bach for excellent technical assistance.

This study was supported by National Institutes of Health grant CA-43610. C. Bogdan is supported by grant Bo-996/1-1 from the Deutsche Forschungsgemeinschaft.

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Received for publication 25 June 1991 and in revised form 5 August 1991.

*Note added in proof:* After this paper was submitted, we learned of other studies in press or in preparation describing deactivating effects of IL-10 on mouse macrophage or human monocyte MHC class II expression, cytokine release, nitrite production, or killing of parasites (de Waal Malefyt, R., J. Haanen, H. Spits, M.-G. Roncarolo, A. te Velde, C. Fidgor, K. Johnson, R. Kastelein, H. Yssel, and J. E. de Vries. 1991. *J. Exp. Med.* 174:915; de Waal Malefyt, R., J. Abrams, B. Bennett, C. Fidgor, and J. E. de Vries. 1991. *J. Exp. Med.* 174:1209; Fiorentino, D. F., A. Zlotnik, T. R. Mosmann, M. Howard, and A. O'Garra. 1991. *J. Immunol.* In press; Silva, J. S., P. J. Morrissey, K. H. Grabstein, K. M. Mohler, D. Anderson, and S. G. Reed. 1992. *J. Exp. Med.* In press; Gazzinelli, R. T., I. P. Oswald, S. L. James, and A. Sher, personal communication).

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