Characteristics of immunosuppressive macrophages induced in spleen cells by Mycobacterium avium complex infections in mice

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The profile of generation and characteristics of splenic macrophages (MΦs) which suppress the concanavalin A (Con A) mitogenic response of splenic T cells (designated as ‘immunosuppressive MΦs’) in host CBA/JN mice during the course of Mycobacterium avium complex (MAC) infection were investigated. In MAC-infected mice, reductions in some cellular functions of host splenic T cells, such as the Con A mitogenic response and mixed leucocyte reaction, were seen around 2 weeks after challenge of organisms, and this was accompanied by appearance of immunosuppressive MΦs in spleen cells. In this case, increase in immunosuppressive MΦ activity was seen in terms of both activity per spleen and activity per individual MΦ. In this phase of the infection, MAC-induced splenic MΦs showed a markedly increased ability to produce reactive oxygen radicals in response to phorbol myristate acetate. Thus, the expression of suppressor activity of MAC-induced MΦs seems to be closely linked to their activated state. A large proportion of the immunosuppressive MΦs exhibited suppressor activity dependent on prostaglandins and membrane functions related to microfilaments. It was also found that the generation of IL-2-reactive T cell populations in response to Con A was markedly inhibited by MAC-induced splenic MΦs, whereas they caused no significant reduction in the IL-2-producing ability of normal spleen cells.

Introduction

Mycobacterium avium complex (MAC) is one of the most prevalent pathogens in acquired immunodeficiency syndrome (AIDS) (Young et al., 1986). MAC is highly resistant to the majority of antituberculous and antimicrobial agents and frequently causes fatal infections (Wolinsky, 1979). It persists for long periods without producing the severe foci in target organs which are noted in cases of tuberculosis (Woods & Washington, 1987). In MAC, as well as in other mycobacterial infections, depression of delayed-type hypersensitivity, the blastogenic response of lymphocytes, and in vivo antibody response (Ellner, 1978; Wadee & Rabson, 1981; Orme & Collins, 1984; Watson & Collins, 1981) have been reported. Although suppressor T cells and immunosuppressive macrophages (MΦs) are thought to contribute to the impaired cellular immunity (Bullock et al., 1978; Turcotte & Lemieux, 1982; Edwards et al., 1986), the precise role of the latter cells in the establishment of immunosuppression (mainly antigen-specific immune unresponsiveness to MAC) remains to be elucidated. In this study, we examined the mode of generation and some properties of immunosuppressive MΦs during the course of MAC infection induced in mice.

Methods

Organisms. M. avium complex 31 F093 SmT and N-260 SmT variants were obtained from F. Kuze, Kyoto University, Kyoto, Japan, and T. Mitsui, Sanyo National Hospital, Yamaguchi, Japan, respectively. Before starting the experimental infection study, the organisms were transferred to mice. These strains were identified as M. intracellulare using the Gen-Probe Rapid Diagnostic System for MAC. Strain N-260 was found to belong to serovar 16 by a seroagglutination test.

Mice. Male CBA/JN mice were purchased from Charles River Japan.

Medium. RPMI 1640 medium (Nissui Pharmaceutical Co.) supplemented with 25 mM-HEPES, 2 mM-glutamine, 100 μg streptomycin ml⁻¹, 100 units penicillin G ml⁻¹, 5 × 10⁻⁴ M-2-mercaptoethanol and 5% (v/v) foetal bovine serum (FBS; M. A. Bioproducts) was used for cell cultures.
**Infection.** Bacteria grown for 5–8 d in Dubos Tween-albumin liquid medium were harvested by centrifugation and suspended in physiological saline. A 0.2 ml volume of bacterial suspension containing about $5 \times 10^5$ to $2 \times 10^8$ colony-forming units (c.f.u.) was given intravenously to CBA/JN mice. Almost 100% of the inoculum produced the smooth, transparent and irregularly shaped colonies characteristic of virulent variants, when plated on 7H10 agar (Kubica et al., 1963).

**Mitogenic response of splenic T cells.** The assay system was essentially as described previously (Tomioka & Saito, 1985). Briefly, spleen cells (SPCs) from normal and infected CBA/JN mice (2 weeks after infection, unless otherwise specified) were cultured in medium usually with or without addition of 2 μg concanavalin A (Con A) ml$^{-1}$ (Miles-Yeda) in triplicate wells of a flat-bottomed microtitre tray for cell culture (Corning) at 37 °C in a CO$_2$ incubator (5% CO$_2$ and 95% humidified air) for 72 h. The cultures were pulsed with 0.25 μCi per well of $[^{3}H]$thymidine (dThd) (2 Ci mmol$^{-1}$; 74 GBq mmol$^{-1}$; New England Nuclear) for the final 6–8 h. Cells were collected on glass-fibre filters and washed with physiological saline using an automatic cell harvester (Mitsumi Kagaku Co.). Radioactivity was counted in a Tri-Carb liquid scintillation counter (Packard Instrument Co.).

**Assay for suppressor activity of splenic Mφs per spleen.** SPCs of normal or infected mice were cultured in 0.2 ml medium in triplicate wells of a microtitre tray at concentrations of $5 \times 10^5$ to $2 \times 10^6$ cells per well in a CO$_2$ incubator for 2–3 h. The wells were then vigorously rinsed with a jet of Hanks' balanced salts solution (Nissui) (HBSS). This procedure usually gave Mφ monolayer cultures (more than 95% of the cells phagocytosed latex beads), containing about $2 \times 10^4$ and $5 \times 10^4$ cells per well from $2 \times 10^4$ normal and infected SPCs, respectively. The number of adherent cells on the culture well increased in a nearly linear fashion as the number of SPCs seeded was increased from $5 \times 10^5$ to $2 \times 10^5$ cells per well. Usually $1 \times 10^5$ normal SPCs in 0.2 ml medium containing 2 μg Con A ml$^{-1}$ were poured on to the resultant adherent cell monolayer culture. The cells were cultured at 37 °C for 72 h. The culture was pulsed with $[^{3}H]$dThd for the final 6–8 h of cultivation and the radioactivity was measured.

**Per-organ activity of suppressive Mφs, designated as 'suppressive MΦ units per spleen' was calculated as: suppressive MΦ units per spleen = (number of SPCs per spleen) $\div$ (number of SPCs seeded to prepare the MΦ monolayer which caused 50% inhibition of Con A blastogenesis of target splenic T cells).**

**Per-cell suppressive activity of splenic MΦs.** Suppressive activity of individual Mφs against mitogenesis of splenic T cells was determined as follows. SPCs ($7 \times 10^5$) of MAC-infected mice were cultured in 7 ml medium in an 80 mm plastic culture dish (Corning) at 37 °C for 2 h. Nonadherent cells were removed by vigorous vibration on an S/IUL mixer at a maximum speed for 15 s followed by rinsing with HBSS containing 1% (v/v) FBS and 5 × 10$^5$ cells per well. Usually 1–2 × 10$^5$ normal SPCs in 0.2 ml medium containing 2 μg Con A ml$^{-1}$ were poured on to the resultant adherent cell monolayer culture. The cells were cultured at 37 °C for 7 h. The culture was pulsed with $[^{3}H]$dThd for the final 6–8 h of cultivation and the radioactivity was measured.

**Treatment of spleen MΦs with indomethacin and cytochalasin B.** MAC-induced Mφs (2 weeks after infection) in monolayer culture on microtitre wells were treated with either indomethacin or cytochalasin B at 37 °C for 2 h. After washing the MΦ monolayer with HBSS, 1 × 10$^7$ normal SPCs were co-cultured with the indicated number of MΦs so obtained for 72 h in the presence of 2 μg Con A ml$^{-1}$ and $[^{3}H]$dThd incorporation during the final 8 h of incubation was measured. In some experiments, SPCs were co-cultured with MAC-induced splenic MΦs in the presence or absence of 1 μg indomethacin ml$^{-1}$ for 72 h. In this case, indomethacin alone did not affect the splenic T cell mitogenesis in response to 2 μg Con A ml$^{-1}$.

**Superoxide anion (O$_2^-$) generating ability of splenic adherent cells.** SPCs (1 × 10$^5$) of normal or infected mice were cultured in 1 ml medium in 16 mm culture wells containing a 14 mm plastic sheet (Wako Chemical Ind.) at 37 °C for 3 h and washed three times with a jet of HBSS. The resulting monolayer culture on the sheet was incubated in 1 ml medium containing 1 mg nitroblue tetrazolium (NBT) ml$^{-1}$ in the presence or absence of 100 ng phorbol myristate acetate (PMA; Sigma) ml$^{-1}$ at 37 °C for 30 min, then fixed with 4% (v/v) HCHO, and the number of NBT-reducing cells counted. Cells with more than 20 blue granules were counted as positive for NBT reduction.

**Chemiluminescence.** Test SPCs (4 × 10$^5$) or plastic-dish-adherent cells prepared from MAC-infected SPCs (2 × 10$^5$) were suspended in 1 ml HBSS (pH 7.4; free of phenol red) containing 10 mM-HEPES and 0.1 mM-luminol (Wako), then 100 ng PMA dissolved in 10 μl dimethylsulphoxide was added to the incubation mixture and photoemission was measured in a lumiphotometer, (Lumicounter ATP-237; Toyо Kagaku Ind.) at 37 °C.

**Results**

**Changes in some cellular functions of splenic T cells during the course of MAC infection**

SPCs from MAC-infected mice at various phases of infection (week 1 to week 6) were measured for mitogenic response, IL-2 production, and generation of IL-2-reactive T cells in response to Con A (data not shown). Mitogenesis induced by Con A (2 μg ml$^{-1}$) was reduced most markedly around 2 weeks after infection,
with concomitant reductions in IL-2-producing ability and generation of IL-2-reactive T cells. A marked reduction in SPC mitogenesis was usually found when the SPCs were cultured at cell densities higher than $5 \times 10^5$ cells per well. In this phase of infection, the number of SPCs as well as spleen weight increased markedly. In a separate experiment, we also observed a 44% and 72% reduction in the mixed leucocyte reaction of MAC-infected SPCs (2 weeks after infection) against mitomycin-C-treated BALB/c SPCs, when the responder cells were cultured at densities of $5 \times 10^5$ and $1 \times 10^6$ cells per well, respectively.

**Role of immunosuppressive MΦs in reduction of Con A mitogenesis of MAC-infected SPCs**

Fig. 1 shows that SPCs of MAC-infected mice (2 weeks after infection) contained two types of suppressor cells against the Con-A induced mitogenesis of normal splenic T cells.

Firstly, plastic-adherent cells and Thy-1,2- cells inhibited SPC mitogenesis in the same fashion (Fig. 1a, b). In separate experiments, more than 95% of the adherent cells were identified as MΦ on the basis of morphology and strong phagocytic ability against latex beads and sheep erythrocytes. Therefore, one component of the suppressor cell population in the MAC-infected SPCs is immunosuppressive MΦs. In this case, suppressive activity was noted only for the adherent cells from MAC-infected SPCs, and not for those from normal SPCs.

Secondly, a cell population which passed through a Sephadex G-10 column (MΦ-depleted cell population) also suppressed SPC mitogenesis (Fig. 1c). In this case, MΦ-depleted cells from SPCs of normal mice showed the same level of suppressive activity as those from MAC-induced SPCs. Therefore, MAC infection at this phase (2 weeks after bacterial challenge) is thought mainly to elicit immunosuppressive MΦs.

The observed suppression of splenic T cell mitogenesis by co-culture with MAC-induced splenic MΦs was not due to depletion of nutrients, because daily half medium changes did not overcome the suppression (data not shown). MAC-induced splenic MΦs also inhibited phytohaemagglutinin-induced mitogenesis of splenic T cells in the same manner as Con-A-induced mitogenesis (data not shown). Furthermore, treatment of MAC-induced splenic MΦs with anti-I-A, I-E, or I-J antibody plus complement failed to abolish the suppressor activity of the MΦs, although a partial reduction in suppressive activity was seen after anti-I-E or anti-I-J antibody treatment (statistically insignificant; $P > 0.1$). This suggests that the main cell populations of the suppressor MΦs do not express I-A, I-E or I-J antigen.

Fig. 2 shows the suppressive effect of MAC-induced splenic MΦs against Con A mitogenesis of normal or MAC-infected SPCs and splenic T cells. The MAC-induced MΦs inhibited Con A mitogenesis of normal and
MAC-infected SPCs in the same fashion (Fig. 2a). The MAC-induced Mφs inhibited the mitogenic response of splenic T cells prepared from normal and from MAC-infected mice in nearly the same fashion (Fig. 2b). However, it is noteworthy that splenic T cells were more resistant to the suppressive action of the MAC-induced Mφs, than were SPCs. This suggests that certain types of cell populations in SPCs amplify the suppressive action of the MAC-induced immunosuppressive Mφs. In this experiment, MAC-infected SPCs seeded at a density of $2 \times 10^5$ cells per well showed similar levels of proliferation to that of normal SPCs. However, this is not entirely surprising, since in many experiments MAC-induced SPCs showed a somewhat higher mitogenic response than that of normal SPCs, when the SPCs were seeded at densities lower than about $2 \times 10^5$ cells per well. MAC-infection-induced reduction in the mitogenic response of the host SPCs was much more evident when SPCs were seeded at higher cell densities ($>5 \times 10^5$ cells per well) (data not shown).

**Kinetics of generation of the immunosuppressive Mφs**

Table 1 shows changes in per-organ suppressive activity of the MAC-induced splenic Mφs during the course of MAC infection. As described in Methods, this value represents the total activity of suppressive Mφs in the host spleen, that is (number of suppressive Mφs) × (activity of individual Mφ). The value was markedly increased around 2 weeks after infection; it decreased rapidly thereafter and was almost zero by week 10. Table 1 also shows changes in per-cell suppressive activity of the splenic Mφs during the course of infection. This value also markedly increased around 2–4 weeks after infection. The value could not be determined for mice 10 weeks after infection, since sufficient numbers of the adherent cells could not be obtained.

In this experiment, transient reductions in the number of organisms in the host spleen were also observed around week 2 ($4.4 \times 10^6$, $1.0 \times 10^6$, $3.3 \times 10^6$ and $4.6 \times 10^6$ per spleen at 1, 2, 4 and 10 weeks after infection, respectively). Therefore, we expected that the splenic Mφs in this phase (week 2) would have an enhanced microbicidal capacity against MAC, and thus be in the 'activated' state. In fact, splenic Mφs induced in this phase (week 2) showed significantly enhanced spontaneous and PMA-triggered O$_2^-$ production. In the case of normal splenic Mφs, the percentages of NBT-reducing...
cells in the presence and absence of 100 ng PMA ml⁻¹ were 43 ± 3% and 0.5 ± 0.5% (mean ± SEM, n = 3), respectively, and in the case of MAC-infected splenic MΦs (2 weeks after infection), the values were increased to 77 ± 3% and 12 ± 1%, respectively. As shown in Table 1, PMA-triggered chemiluminescence was also markedly elevated around week 2. Moreover, PMA-triggered chemiluminescence (the peak value seen during 90–120 s after PMA triggering) of splenic MΦs (2 × 10⁵ cells) from MAC-infected mice was changed as follows during the early phase of infection; 304 ± 26 c.p.s. (week 1; mean ± SEM, n = 3), 976 ± 9 c.p.s. (week 2), and 187 ± 7 c.p.s. (week 4). Thus, significant activation of splenic MΦ functions as determined on the basis of oxidative metabolism (Tomioka & Saito, 1980; Saito et al., 1981) is also seen around 2 weeks after MAC infection. The functional activation in the early phase of MAC infection was also seen in peritoneal MΦs (Saito et al., 1986).

Mechanisms of action of MAC-induced immunosuppressive MΦs

Fig. 3(a) compares the effects of normal and MAC-induced splenic MΦs on the IL-2-producing ability of splenic T cells. Neither population of splenic MΦs significantly inhibited IL-2 production. As shown in Table 2, IL-2 production was not changed by the MAC-induced MΦs in the SPC culture at high cell density (1 × 10⁶ cells per well), but it was enhanced in the SPC culture at low cell density (2.5 × 10⁵ cells per well). Therefore, it seems that neither MAC-induced splenic MΦs nor normal MΦs cause a marked reduction in the IL-2-producing ability of splenic T cells. In separate experiments, the suppressive activity of the MAC-induced MΦs was not overcome, even when a sufficient amount of exogenous IL-2 was added (data not shown). Therefore, the possibility can be excluded that the suppressor MΦs inactivated or absorbed the IL-2 molecules by binding with specific receptors.

To elucidate the effect of the MAC-induced immunosuppressive MΦs on generation of IL-2 reactive T cells in SPC culture in response to Con A signals, we carried out the following experiments.

Firstly, normal SPCs were cultured in medium containing 2 µg Con A ml⁻¹ in the presence or absence of either normal or MAC-induced MΦs for 48 h, then the nonadherent cells were harvested, transferred to new wells, and thoroughly rinsed with HBSS containing FBS and 10 mg methyl α-D-mannoside ml⁻¹. Then, the resultant cells were cultured in the presence of exogenous IL-2 for a further 72 h and [³H]dThd uptake during the final 8 h of cultivation was measured (Figs 3b and 4a). In this case, the MAC-induced MΦs, but not normal MΦs (Fig. 3b), inhibited the generation of IL-2-reactive cell populations in the SPC culture.

Secondly, Con A blastoid cells separately prepared from normal SPCs were overlaid on to the monolayer

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Table 2. Influence of MAC-induced splenic MΦs on IL-2-producing ability of splenic T cells

<table>
<thead>
<tr>
<th>No. of SPCs</th>
<th>No. of MAC-induced splenic MΦs</th>
<th>IL-2 production by splenic T cells (c.p.m.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 × 10⁵</td>
<td>–</td>
<td>1227 ± 50</td>
</tr>
<tr>
<td>2.5 × 10⁶</td>
<td>1.8 × 10⁴</td>
<td>5189 ± 145</td>
</tr>
<tr>
<td>2.5 × 10⁷</td>
<td>4.8 × 10⁴</td>
<td>8488 ± 734</td>
</tr>
<tr>
<td>2.5 × 10⁸</td>
<td>7.2 × 10⁴</td>
<td>10753 ± 902</td>
</tr>
<tr>
<td>4.0 × 10⁶</td>
<td>–</td>
<td>25625 ± 279</td>
</tr>
<tr>
<td>4.0 × 10⁷</td>
<td>1.8 × 10⁴</td>
<td>29318 ± 435</td>
</tr>
<tr>
<td>4.0 × 10⁸</td>
<td>4.8 × 10⁴</td>
<td>36830 ± 726</td>
</tr>
<tr>
<td>4.0 × 10⁹</td>
<td>7.2 × 10⁴</td>
<td>33515 ± 1950</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 ± 6</td>
</tr>
<tr>
<td></td>
<td>1.8 × 10⁴</td>
<td>36 ± 5</td>
</tr>
<tr>
<td></td>
<td>4.8 × 10⁴</td>
<td>68 ± 13</td>
</tr>
<tr>
<td></td>
<td>7.2 × 10⁴</td>
<td>281 ± 17</td>
</tr>
</tbody>
</table>

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T cells without causing reduction in the IL-2-induced proliferation of the IL-2-reactive T cells by the MAC-induced splenic MOs. (a) Normal SPCs (1.25 × 10^5 cells per well) were cultivated in medium containing 2 µg Con A ml⁻¹ in the presence or absence of MAC-induced splenic MOs for 48 h. Nonadherent cells were then harvested, and transferred to new wells. After washing with HBSS containing 1% (v/v) FBS and 20 mg methyl α-D-mannoside ml⁻¹, their proliferative response to exogenous IL-2 (0.97 units ml⁻¹) during the final 8 h of further 72 h cultivation was measured. (b) The remaining monolayer MOs in (a) were examined for the effect on proliferative responses of Con A blastoid cells (5 × 10⁴ per well) in response to exogenous IL-2 (0.97 units ml⁻¹) during the final 8 h of a further 72 h cultivation. The Con A blastoid cells were separately prepared from normal SPCs by activation with 5 µg Con A ml⁻¹. Each point plotted indicates the mean ± SEM (n = 3).

**Table 3. Effects of indomethacin (indo.) and cytochalasin B (cyt B) on the activity of MAC-induced splenic MΦs**

<table>
<thead>
<tr>
<th>MAC-ΜΦ treatment</th>
<th>No. of MΦs added</th>
<th>Con A mitogenesis of SPCs cocultured with MAC-ΜΦs (c.p.m.)*</th>
<th>Residual activity of suppressive MΦs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indo. 3.2 µg ml⁻¹</td>
<td>6 × 10³</td>
<td>45,581 ± 604</td>
<td>100</td>
</tr>
<tr>
<td>Indo. 12.5 µg ml⁻¹</td>
<td>6 × 10³</td>
<td>21,317 ± 558</td>
<td>100</td>
</tr>
<tr>
<td>Indo. 50 µg ml⁻¹</td>
<td>6 × 10³</td>
<td>27,712 ± 3154</td>
<td>74</td>
</tr>
<tr>
<td>Indo. 3.2 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>37,591 ± 1,482</td>
<td>33</td>
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<tr>
<td>Indo. 12.5 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>44,541 ± 1,374</td>
<td>0.2</td>
</tr>
<tr>
<td>Indo. 50 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>29,090 ± 655</td>
<td>97</td>
</tr>
<tr>
<td>Indo. 3.2 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>29,602 ± 2,491</td>
<td>36</td>
</tr>
<tr>
<td>Indo. 12.5 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>4,758 ± 1,163</td>
<td>97</td>
</tr>
<tr>
<td>Indo. 50 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>28,035 ± 3,523</td>
<td>100</td>
</tr>
<tr>
<td>Indo. 3.2 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>19,020 ± 1,895</td>
<td>100</td>
</tr>
<tr>
<td>Indo. 12.5 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>31,189 ± 2,517</td>
<td>100</td>
</tr>
<tr>
<td>Indo. 50 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>43,512 ± 1,038</td>
<td>99</td>
</tr>
<tr>
<td>Indo. 3.2 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>361 ± 62</td>
<td>100</td>
</tr>
<tr>
<td>Indo. 12.5 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>1,022 ± 485</td>
<td>99</td>
</tr>
<tr>
<td>Indo. 50 µg ml⁻¹</td>
<td>1.5 × 10⁴</td>
<td>28,467 ± 2,771</td>
<td>41</td>
</tr>
</tbody>
</table>

* The results are means ± SEM (n = 3)
Cells per well) were cultivated in the presence or absence of the MAC-induced splenic MOs in medium containing 2 pg/ml Con A per well. This indicated the mean activity per well and the SEM. Fig. 5. Effect of indomethacin on the suppressive activity of the MAC-induced splenic MOs against Con A mitogenesis of SPCs. SPCs (1.25 x 10^5 cells per well) were cultivated in the presence or absence of MAC-induced splenic MOs in medium containing 2 pg/ml Con A per well. The addition of 1 pg/ml indomethacin did not markedly inhibit the suppressive activity of MAC-induced MOs. Although this dose of indomethacin did not affect the Con A mitogenesis of splenic T cells, it markedly inhibited the suppressive activity of MAC-induced MOs. This suggests the possible presence of some accessory cells for Con A mitogenesis in the MAC-induced splenic MO populations.

Discussion

In this study, we obtained evidence for the following.

Firstly, immunosuppressive MOs active against Con A mitogenesis of SPCs are induced in the host spleen cells at a relatively early phase of MAC infection (around 2 weeks after bacterial challenge) in mice. In this case, increase in the suppressive activity of the MAC-induced MOs was considerably enhanced by the addition of indomethacin in the SPC culture with a small number of MAC-induced MOs. This suggests the possible presence of some accessory cells for Con A mitogenesis in the MAC-induced splenic MO populations.

Secondly, the MAC-induced splenic MOs inhibited generation of IL-2-reactive T cell populations in response to Con A without suppressing IL-2-producing ability in helper T cells. Moreover, the suppressor MOs inhibited the expression of IL-2 receptors on the Con-A-activated T cell subpopulations. We interpret these findings to mean that the immunosuppressive MOs induced in the early phase of MAC infection, and possibly also in other mycobacterial infections, preferentially target the activation process of Lyt-1,2,3+ T cells to the IL-2-reactive state in response to signals given by mitogens including Con A. This finding differs from commonly reported observations that immunosuppressive MOs induced by microbial infections reduce the IL-2-producing activity of T cells (Hoffenbach et al., 1983; Tarleton & Kuhn, 1984; Tossi et al., 1986). Since IL-2 production in whole SPCs decreased in the case of MAC-infected mice, some types of immunosuppressive cells other than MOs may be induced by MAC infection.

The peculiarity of immunosuppressive MOs induced by MAC infection as compared with those induced by other mycobacterial infections could be a consequence of the course of infection of the different mycobacterial species studied. For instance, M. lepraemurium shows a progressive increase in bacterial load (Bullock et al., 1978), whereas MAC infection appears to be controlled at a plateau level.

The possibility that the MAC-induced splenic MOs exhibit a mitogenic inhibitory action through cytotoxic effects on the target T cells, including release of some cytotoxic substances, such as arginase (Kung et al., 1977) and other toxic proteins (Chen et al., 1977), has to be considered. However, this can be excluded because the spleen cells were not killed by contact with the suppressor MOs for 24 h (data not shown). Also, the MAC-induced MOs showed a selective inhibitory action...
on T cell functions. Although the IL-2-producing ability was not depressed, the T cell activation to the IL-2 reactive state was inhibited (Figs 3 and 4). The selective depression of IL-2-reactive T cell generation also excluded the possibility of participation of unlabelled dThd (Opitz et al., 1975) in the suppression of apparent [³H]dThd incorporation of splenic T cells by MAC-induced MΦs. It has been demonstrated that human monocytes phagocytosing M. tuberculosis suppress lymphocyte blastogenesis by releasing bacterial-cell-derived phospholipids which act as a suppressor cell activating factor (Wadie et al., 1983). However, the physical presence of MAC in the splenic MΦs could not have caused the suppressor cell activity, since the number of bacilli in the MΦs was very low (four bacilli in 100 MΦs).

Thirdly, the activity of the MAC-induced splenic MΦs was largely mediated by prostaglandins, as already noted in other types of immunosuppressive MΦs (Edwards et al., 1986; Metzger et al., 1980; Stout & Fisher, 1983). However, indomethacin could not entirely overcome the suppressive action of the present MΦs, when the number of MΦs added to the SPC culture was increased. This suggests that there is a prostaglandin-independent mechanism for the expression of the suppressor activity of MAC-induced splenic MΦs in addition to the prostaglandin-mediated mechanism. In fact, it is known that prostaglandins cause a relatively slight inhibition of mitogenic proliferation of T cells when Con A is used as the mitogen (Novogrodsky et al., 1979). Strong but incomplete dependency of the action of the present immunosuppressive MΦs on prostaglandins may indicate the presence of other mediators in the suppressor activity, such as MΦ-derived suppressor factors (SFs) (Fujiiwara & Ellner, 1986; Wadie & Rabson, 1981). It is also possible that the MAC-induced MΦs exert their suppressive function through direct cell-to-cell contact with the target cells.

Fourthly, the suppressive action of the MAC-induced splenic MΦs was dependent on microfilament functions, because it was abolished by treatment with cytochalasin B. Microfilament inhibitors are known to inhibit some functions of MΦs, such as spreading, phagocytosis, and respiratory burst in response to some triggering ligands including PMA (Axline & Reaven, 1974; Nathan & Cohn, 1980; Tomioka & Saito, 1987), which are dependent on membrane function of MΦs. Thus, the mechanism of expression of suppressive activity of the immunosuppressive MΦs seems to be linked to certain membrane functions, such as those prerequisite for the signal transduction system or cell-to-cell interaction with target cells.

Studies are now under way using various strains of mice having the Bcg⁻ (MAC sensitive) and Bcg⁺ (MAC resistant) genotypes, with special regard to the role of immunosuppressive MΦs in the establishment of suppressor T-cell-mediated immune unresponsiveness.

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References


