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Prevention of Lymphocyte Apoptosis in Septic Mice with Cancer Increases Mortality

Amy C. Fox,* Elise R. Breed,†‡ Zhe Liang,†‡ Andrew T. Clark,* Brendan R. Zee-Cheng,* Katherine C. Chang,§ Jessica A. Dominguez,§ Enjae Jung,* W. Michael Dunne,‖ Eileen M. Burd,* Alton B. Farris,* David C. Linehan,* and Craig M. Coopersmith †,‡

Lymphocyte apoptosis is thought to have a major role in the pathophysiology of sepsis. However, there is a disconnect between animal models of sepsis and patients with the disease, because the former use subjects that were healthy prior to the onset of infection while most patients have underlying comorbidities. The purpose of this study was to determine whether lymphocyte apoptosis prevention is effective in preventing mortality in septic mice with preexisting cancer. Mice with lymphocyte Bcl-2 overexpression (Bcl-2-Ig) and wild type (WT) mice were injected with a transplantable pancreatic adenocarcinoma cell line. Three weeks later, after development of palpable tumors, all animals received an intratracheal injection of Pseudomonas aeruginosa. Despite having decreased sepsis-induced T and B lymphocyte apoptosis, Bcl-2-Ig mice had markedly increased mortality compared with WT mice following P. aeruginosa pneumonia (85 versus 44% 7-d mortality; p = 0.004). The worsened survival in Bcl-2-Ig mice was associated with increases in Th1 cytokines TNF-α and IFN-γ in bronchoalveolar lavage fluid and decreased production of the Th2 cytokine IL-10 in stimulated splenocytes. There were no differences in tumor size or pulmonary pathology between Bcl-2-Ig and WT mice. To verify that the mortality difference was not specific to Bcl-2 overexpression, similar experiments were performed in Bim−/− mice. Septic Bim−/− mice with cancer also had increased mortality compared with septic WT mice with cancer. These data demonstrate that, despite overwhelming evidence that prevention of lymphocyte apoptosis is beneficial in septic hosts without comorbidities, the same strategy worsens survival in mice with cancer that are given pneumonia. The Journal of Immunology, 2011, 187: 1950–1956.

Sepsis is the leading cause of death among critically ill patients in the United States, with >200,000 people dying from the disease annually (1). Despite many advances in understanding the pathophysiology of sepsis, mortality remains unacceptably high (2).

Apoptosis is theorized to have a critical role in the pathophysiology of sepsis (3). Human autopsy studies of sepsis demonstrate increased apoptosis in the spleen and the intestinal epithelium (4). In addition, apoptosis in circulating lymphocytes is markedly increased in septic patients (5–7), and this is associated with poor outcome (8). Animal models of sepsis replicate these findings of increased sepsis-induced lymphocyte and intestinal epithelial apoptosis (9–14). The functional significance of this finding is demonstrated in animal models (predominantly peritonitis-induced sepsis) demonstrating that prevention of apoptosis in lymphocytes, globally using knockout mice or siRNA or in the intestinal epithelium, improves survival following sepsis (15–35). Because apoptosis prevention has been repeatedly successful in improving survival when targeting a wide variety of mediators by a number of investigative groups, there is significant interest in translating these findings to the bedside (36–39).

There has been a longstanding disconnect between animal models of sepsis and therapeutic trials in patients (40). There are complex reasons why positive preclinical trials have not successfully translated into therapeutic benefit at the bedside, and one possibility is that the populations studied are different. Typical animal models use mice that were healthy prior to the onset of sepsis; however, the majority of septic patients have one or more preexisting comorbidities (1). Patients and animals subjected to a septic insult have increased mortality in the setting of additional comorbidities (41–44). This is consistent with a “two-hit” model of injury, where a chronic comorbidity is the first insult and an acute septic injury represents the second insult. Although each of these “hits” independently confers some risk, their combined effects are disproportionately harmful over what might have been predicted from either in isolation.

Cancer is one of the most common comorbidities that can afflict patients with sepsis. It is also associated with a high rate of mortality, with ~40% of septic patients with cancer dying from the disease (1, 45). In addition, patients with malignancy are nearly 10-fold more likely to develop sepsis than the general population (46). The factors that affect an individual’s susceptibility to developing sepsis can include tumor type, tumor size, presence of metastatic disease, and host immunologic response. Our laboratory recently described an animal model of sepsis and cancer in which mice that received a transplantable pancreatic adenocarcinoma were infected with P. aeruginosa. Despite the fact that mice with cancer alone had increased mortality compared with WT mice (29% 7-d mortality vs. 12% 7-d mortality), Bcl-2-Ig mice with cancer had markedly increased mortality compared with either septic WT mice with cancer (72% 7-d mortality) or Bcl-2-Ig mice without cancer (40% 7-d mortality; p = 0.004). The worsened survival in Bcl-2-Ig mice was associated with increases in Th1 cytokines TNF-α and IFN-γ in bronchoalveolar lavage fluid and decreased production of the Th2 cytokine IL-10 in stimulated splenocytes. There were no differences in tumor size or pulmonary pathology between Bcl-2-Ig and WT mice. To verify that the mortality difference was not specific to Bcl-2 overexpression, similar experiments were performed in Bim−/− mice. Septic Bim−/− mice with cancer also had increased mortality compared with septic WT mice with cancer. These data demonstrate that, despite overwhelming evidence that prevention of lymphocyte apoptosis is beneficial in septic hosts without comorbidities, the same strategy worsens survival in mice with cancer that are given pneumonia. The Journal of Immunology, 2011, 187: 1950–1956.
carcinoma cell line 3 wk prior to the onset of Pseudomonas aeruginosa pneumonia had a 24% increase in mortality compared with septic mice that were previously healthy (44).

In light of 1) the extensive literature demonstrating a survival benefit to preventing lymphocyte apoptosis in previously healthy mice and 2) the knowledge that mice with cancer (or other comorbidities) behave differently than previously healthy mice subjected to the identical septic insult, this study examined whether preventing lymphocyte apoptosis would improve survival in the clinically relevant model of sepsis in the setting of cancer.

Materials and Methods

Mice

Nine- to 16-wk-old mice were used for all experiments. Transgenic mice overexpressing human Bcl-2 in both T and B lymphocytes (Bcl-2-Ig mice) were generated as previously described (17, 47). Of note, Bcl-2 expression is significantly greater in the spleen than in the thymus in these animals. Bim−/− mice were initially generated at the Walter and Eliza Hall Institute of Medical Research (Melbourne, VIC, Australia) (48), but were subsequently bred for over 3 y at Washington University for experiments examining lymphocyte apoptosis and sepsis, where they were a gift from Dr. Richard Hotchkiss (Washington University School of Medicine) (21). Transgenic mice that overexpress Bcl-2 in the intestinal epithelium (Fahpl-Bcl-2 mice) were generated on an FVB/N background and were then backcrossed to C57BL/6 mice for >20 generations (49, 50). For all studies in this article, animals were compared with C57BL/6 littermates or controls bred in the same animal facility. All studies complied with the National Institutes of Health Guide for the Care and Use of Laboratory Animals and were approved by the Animal Studies Committee of both Washington University and Emory University.

Cancer model

The transplantable mouse pancreas adenocarcinoma cell line Pan02 was injected to induce cancer as described previously (51, 52). Pan02 cells were cultured in RPMI 1640 medium supplemented with 1% glutamine, 1% (2-hydroxyethyl)-1-piperazineethanesulfonic acid, 10% FBS, and 1% penicillin–streptomycin (Cellgro, Herndon, VA). A total of 250,000 Pan02 cells were injected s.c. into each animal’s right inner thigh. Mice were then housed for 3 wk in a barrier facility to allow tumors to grow prior to the induction of sepsis. Animals given Pan02 cells developed well-defined, circumscribed tumors at the injection site, but the tumors were not metastatic and did not cause mortality in the period studied in this set of experiments. The longest axis of the tumor was used for measuring tumor size. In a recent study from our laboratory (44), animals given Pan02 cells 3 wk earlier were compared with healthy mice. Animals had similar body weights, liver function, kidney function, lung histology, wet-to-dry lung ratios, blood cytokine levels (TNF-α, IL-6, IL-10, IL-12, and MCP-1), bronchoalveolar lavage (BAL) cytokines (IL-6, IL-10, IL-12, and MCP-1), gut apoptosis, intestinal villus length, intestinal proliferation, hematocrit, WBC count, absolute neutrophil count, absolute lymphocyte count, and platelet count. In contrast, the presence of cancer caused lower levels of T lymphocyte and B lymphocyte apoptosis compared with healthy mice and also induced higher levels of TNF-α in BAL fluid.

Sepsis model

Three weeks after the injection of Pan02 cells, mice were made septic via direct intratracheal injection of P. aeruginosa (American Type Culture Collection 27853) (53). A midline cervical incision was made while using isoflurane anesthesia, and 40 μl of a solution of bacteria diluted in 0.9% NaCl (final concentration, 6 × 10^6 CFUs/ml) was injected directly into the trachea using a 29-gauge insulin syringe. Animals were then held vertically for 10 s to enhance delivery of bacteria into the lungs. Mice received a single 1-ml s.c. injection of 0.9% NaCl to replace insensible fluid losses following incision closure. Animals were either sacrificed 24 h after induction of pneumonia for tissue harvest or followed 7 d for survival. Of

![FIGURE 1](http://www.jimmunol.org/) Effect of Bcl-2 overexpression on lymphocyte apoptosis in septic mice with cancer. T lymphocyte (A; n = 13–19 per group) and B lymphocyte apoptosis (C; n = 14–19 per group) was decreased in Bcl-2-Ig mice compared with WT mice whether assayed by active caspase 3 staining (A, C) or the TUNEL assay (B) by flow cytometry. Similar results were qualitatively seen on H&E-stained sections in which splenic apoptosis was elevated in septic WT mice with cancer (D), but lower in Bcl-2-Ig mice subjected to the same insult (E). Representative histomicrographs are shown at original magnification ×400. *p < 0.05.
extensively characterizing the effect of pneumonia superimposed on cancer.

FIGURE 2. Effect of Bcl-2 overexpression in lymphocytes on survival in septic mice with cancer. Mortality was nearly twice as high in Bcl-2-lg mice compared with WT mice 7 d after induction of P. aeruginosa pneumonia. \( n = 20–27 \) per group. *\( p < 0.05 \).

note, mortality is nearly twice as high in mice given Pan02 cells 3 wk prior to the onset of P. aeruginosa pneumonia compared with previously healthy mice given the identical insult (44). The rationale for studying P. aeruginosa pneumonia following cancer, as opposed to a more commonly studied model of sepsis such as cecal ligation and puncture, was a recent study extending extensively characterizing the effect of pneumonia superimposed on cancer (44).

Splenic apoptosis

Splenic apoptosis was quantified via flow cytometry using Abs against active caspase-3 (Cell Signaling Technology, Beverly, MA) and via the TUNEL assay (Phoenix Flow Apo-BrdU Kit, San Diego, CA) (21). T and B cell populations were identified using fluorescein-labeled anti-mouse CD3 (BD Pharmingen, Franklin Lakes, NJ) and PE-Cy5 conjugated anti-mouse CD45R/B220 (eBioscience, San Diego, CA), respectively. Flow cytometric analysis (50,000 events per sample) was performed on FACScan (BD Biosciences, San Jose, CA) as described previously (5).

Local, systemic, and stimulated cytokine analysis

BAL and whole blood were used to assess local and systemic cytokine levels, respectively (44). The trachea was lavaged with 1 ml sterile saline. Whole blood was collected retro-orbitally and centrifuged at 5000 rpm for 5 min in serum separator tubes. BAL and whole blood cytokine concentrations were then analyzed using the Bio-Plex Pro Mouse Cytokine Standard Group 1 Kit (Biorad, Hercules, CA) according to the manufacturer’s protocol. All samples were run in duplicate.

Table I. BAL cytokines

<table>
<thead>
<tr>
<th>Cytokine (pg/ml)</th>
<th>WT (n = 10–11)</th>
<th>Bcl-2-lg (n = 9–10)</th>
<th>( p ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNF-( \alpha )</td>
<td>346 ± 48</td>
<td>734 ± 115</td>
<td>0.03</td>
</tr>
<tr>
<td>IFN-( \gamma )</td>
<td>17 ± 1</td>
<td>43 ± 17</td>
<td>0.008</td>
</tr>
<tr>
<td>IL-10</td>
<td>179 ± 54</td>
<td>82 ± 33</td>
<td>ns</td>
</tr>
<tr>
<td>IL-6</td>
<td>11,813 ± 3,632</td>
<td>13,469 ± 2,325</td>
<td>ns</td>
</tr>
</tbody>
</table>

Table II. Blood cytokines

<table>
<thead>
<tr>
<th>Cytokine (pg/ml)</th>
<th>WT (n = 10–11)</th>
<th>Bcl-2-lg (n = 9–10)</th>
<th>( p ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNF-( \alpha ) 3,445 ± 392</td>
<td>2,908 ± 352</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>G-CSF         14,200 ± 1,236</td>
<td>14,349 ± 860</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>IL-10   187 ± 41</td>
<td>298 ± 138</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>IL-6    3,197 ± 584</td>
<td>3,828 ± 701</td>
<td>ns</td>
<td></td>
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</tbody>
</table>

Table III. Stimulated splenocyte cytokines

<table>
<thead>
<tr>
<th>Cytokine (pg/ml)</th>
<th>WT (n = 9)</th>
<th>Bcl-2-lg (n = 9)</th>
<th>( p ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL-10           187 ± 15</td>
<td>117 ± 15</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>TNF-( \alpha ) 56 ± 4</td>
<td>52 ± 5</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>IFN-( \gamma ) 10,492 ± 1,375</td>
<td>12,493 ± 1,364</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>IL-6            1,922 ± 189</td>
<td>1,509 ± 209</td>
<td>ns</td>
<td></td>
</tr>
</tbody>
</table>

the addition of substrate buffer containing O-dianisidine and 0.0055% hydrogen peroxide, myeloperoxidase (MPO) activity was measured at 470-nm wavelength over 6 min (Bio-Tek Instruments-\( \mu \)Quant Microplate Spectrophotometer, Winooski, VT). MPO activity was calculated as AOD/minute per microliter of BAL fluid.

Bacterial cultures

Blood was collected from the inferior vena cava, and BAL fluid was obtained as described above. BAL samples were serially diluted in sterile saline and plated on sheep blood agar plates. Plates were incubated overnight at 37°C and examined for colony counts 24 h later.

Intestinal epithelial apoptosis

Apoptotic cells were quantified in 100 contiguous, well-oriented crypt-villus units using H&E staining and active caspase-3 staining (53). Apoptotic cells were identified on H&E-stained sections by morphologic criteria. Cells with characteristic nuclear condensation and fragmentation were considered to be apoptotic. For active caspase-3 staining, intestinal sections were deparaffinized, rehydrated, and incubated in 3% hydrogen peroxide for 10 min. Ag retrieval was performed by placing slides in Ag Decloaker (Biocare Medical, Concord, CA) and heating them in a pressure cooker for 45 min. Slides were then blocked with 20% goat serum (Vector Laboratories, Burlingame, CA) and incubated with rabbit polyclonal anti-active caspase-3 (1:100; Cell Signaling Technology, Beverly, MA) overnight at 4°C. The following day, slides were incubated with goat anti-rabbit biotinylated secondary Ab (1:200; Vector Laboratories) for 30 min at room temperature followed by Vectastain Elite ABC reagent (Vector Laboratories) for 30 min. Slides were developed with diaminobenzidine and counterstained with hematoxylin.

Statistics

All data were tested for Gaussian distribution using the Shapiro-Wilk normality test. If data were found to have a Gaussian distribution, comparisons were performed using the Student t test, and results were presented as mean ± SEM. If data did not have a Gaussian distribution, comparisons were performed using the Mann–Whitney \( U \) test and were presented as median ± range. Survival studies were analyzed using the log-rank test. Data were analyzed using the statistical software program Prism 4.0 (GraphPad, San Diego, CA). A \( p \) value \( <0.05 \) was considered statistically significant.

Results

In all experiments, mice were injected with the transplantable pancreatic adenocarcinoma cell line Pan02. Three weeks later, animals were given P. aeruginosa pneumonia. As a result, all animals developed sepsis in the setting of preexisting cancer.

Bcl-2 overexpression in lymphocytes increases mortality despite preventing sepsis-induced lymphocyte apoptosis

Transgenic mice overexpressing human Bcl-2 in both T and B lymphocytes (Bcl-2-lg mice) had decreased levels of T lymphocyte apoptosis compared with wild type (WT) littermates by both...
the active caspase-3 staining and TUNEL assay as measured by flow cytometry (Fig. 1A, 1B). Bcl-2-Ig mice also had decreased levels of B lymphocyte apoptosis (Fig. 1C). A similar decrease in apoptosis was also observed on H&E-stained splenic sections (Fig. 1D, 1E).

A different set of Bcl-2-Ig and WT cancer mice were then followed for survival after the induction of sepsis. Despite the fact that Bcl-2-Ig mice had lower lymphocyte apoptosis, 85% of Bcl-2-Ig mice died 7 d after the onset of sepsis compared with 44% of WT mice ($p = 0.004$; Fig. 2).

**Bcl-2 overexpression in lymphocytes in septic mice with cancer induces an upregulation of Th1 cytokines in BAL fluid but not plasma**

To determine whether the local host response played a role in the elevated mortality in septic Bcl-2-Ig mice, BAL cytokines were measured in transgenic and WT mice (Table I). Concentrations of the Th1 cytokines TNF-$\alpha$ ($p = 0.008$) and IFN-$\gamma$ ($p = 0.03$) were significantly higher in Bcl-2-Ig than WT mice. In contrast, when plasma cytokines were assayed, no significant differences were detected between septic Bcl-2-Ig and WT mice with cancer (Table II).

**Bcl-2 overexpression in lymphocytes in septic mice with cancer decreases production of IL-10 in stimulated lymphocytes**

Lymphocytes isolated from the spleens of septic Bcl-2-Ig mice that were incubated ex vivo with anti-CD3/28 had lower production of the Th2 cytokine IL-10 compared with WT littermates ($p = 0.004$; Table III). Other stimulated cytokines were similar in septic mice with cancer, regardless of whether they overexpressed Bcl-2 in their lymphocytes.

**Bcl-2 overexpression in lymphocytes does not alter tumor size**

To determine whether overexpression of an antiapoptotic protein in lymphocytes caused a secondary effect on cancer growth, tumor size was measured in Bcl-2-Ig and WT mice. No difference in tumor size was identified, regardless of whether an animal overexpressed Bcl-2 in its lymphocytes (Fig. 3).
mice have increased survival if peritonitis is initiated in previously healthy mice (17, 21, 54), but have decreased survival if pneumonia is initiated in mice with preexisting cancer.

A differential host response appears to play a role in explaining this discrepancy. Bcl-2-Ig mice with cancer have increases in their Th1 cytokines TNF-α and IFN-γ in BAL fluid 24 h after the onset of pneumonia compared with WT septic mice with cancer. In addition, when their splenocytes are stimulated ex vivo, they have decreased production of the Th2 cytokine IL-10. These findings suggest that there is an exaggerated inflammatory response in septic mice with cancer when lymphocyte apoptosis is prevented. This increased proinflammatory response is both local and systemic in nature given the findings in BAL fluid and stimulated splenocytes.

The inflammatory response following sepsis is complex. Either too much or too little inflammation can damage the host by causing unintended organ failure or leaving the host susceptible to secondary infections, respectively. Some degree of inflammation is beneficial, because immunoparalyzed hosts are at risk for fatal infectious complications. However, the appropriate amount of inflammation varies with both the clinical scenario and the length of time elapsed after the initial insult. Too much inflammation can be as harmful as too little inflammation, and it is likely that the increased inflammatory state in the lungs and the decreased ability of splenocytes to secrete compensatory anti-inflammatory cytokines played a role in the excessive mortality seen in this study.

In our prior description of why septic mice with cancer were more likely to die than septic mice that were previously healthy (both WT C57BL/6 mice), we found that sepsis induced an increase in T and B lymphocyte apoptosis in all animals (44). However, septic mice with cancer had decreased T and B lymphocyte apoptosis compared with previously healthy septic mice. These findings imply that some degree of lymphocyte apoptosis may be beneficial in a subset of septic hosts in light of the fact that 1) mice with cancer have lower levels of sepsis-induced apoptosis than previously healthy mice despite higher mortalities, and 2) preventing this apoptosis leads to a further increase in mortality. Thus, an important implication of this study is that prevention of lymphocyte apoptosis may not always be a beneficial therapeutic strategy, and it may be a harmful strategy in select patient groups with a specific disease process. This issue is directly relevant because of the large amount of interest in translating anti-apoptotic therapies to the bedside of patients with sepsis based on overwhelming evidence in animal models and observational human studies suggesting that lymphocyte apoptosis is harmful in sepsis.

One possible explanation for the discrepancy between our results and those published in the existing literature is the difference in the model used. The vast majority of mouse studies demonstrating the benefit of preventing lymphocyte apoptosis use the cecal ligation and puncture model, and there is overwhelming evidence supporting apoptosis prevention in previously healthy mice with peritonitis. In contrast, this study uses a pneumonia model. To our knowledge, there is only one published study examining lymphocyte apoptosis prevention in pneumonia, in which overexpression of Bcl-2 in lymphocytes resulted in a trend toward improved survival in P. aeruginosa pneumonia (54). A similar experiment performed for this study also demonstrates a nonsignificant 16% improvement in survival in Bcl-2-Ig mice subjected to P. aeruginosa pneumonia compared with WT mice (data not shown). Based on this finding, it is possible that Bcl-2 overexpression confers either a small survival benefit or has no meaningful benefit in previously healthy mice subjected to pneumonia. Each of these results would be at least somewhat different from previously healthy mice subjected to peritonitis, where apoptosis prevention confers a marked survival benefit. Importantly, the results also differ significantly from mice with cancer that subsequently are given pneumonia, demonstrating that the addition of cancer as a comorbidity alters the host response by changing an intervention (i.e., lymphocyte apoptosis prevention) that may ordinarily be either beneficial or neutral into one that is detrimental to host survival. Although both peritonitis and pneumonia models induce sepsis, they do not induce an identical inflammatory response. Both Bcl-2-Ig mice and Bim−/− mice have increased basal numbers of lymphocytes compared with WT animals. In a pneumonia model, this baseline increase in effector cells could lead to profound changes in a stressed host. As such, this increase in effector cells might be more physiologically significant than prevention of lymphocyte apoptosis and functionally overwhelm it, resulting in the observed proinflammatory response. This explanation could help to explain the differential result.

**FIGURE 5.** Effect of knocking out the proapoptotic factor Bim on survival in septic mice with cancer. Mortality was higher in Bim−/− mice than in WT mice (n = 11–14 per group) 7 d after induction of P. aeruginosa pneumonia. *p < 0.05.

**FIGURE 6.** Effect of Bcl-2 overexpression on intestinal epithelial apoptosis and survival in septic mice with cancer. No difference in mortality was observed between Fabpl-Bcl-2 mice and WT mice 7 d after induction of P. aeruginosa pneumonia (A, n = 27–29 per group). Despite the fact that Bcl-2 was overexpressed in the intestinal epithelium in transgenic mice, intestinal epithelial apoptosis was similar by both H&E staining (B) and active caspase-3 staining (C) in Fabpl-Bcl-2 mice and WT mice. n = 12–13 per group.
between mice subjected to peritonitis versus those subjected to pneumonia, although it would not explain the difference in survival between Bcl-2 overexpression in mice that were healthy prior to the onset of pneumonia versus those that had cancer prior to the onset of pneumonia.

Although the vast majority of preclinical studies use healthy, 6–12-wk-old mice, these animals actually model a patient population that almost never gets septic and is unlikely to die of the disease in the rare instance that it develops. Sepsis is a disease that most commonly affects the elderly or patients with comorbidities, or both; however, the typical study using young, previously healthy mice is the equivalent of studying the disease in a 13 y old (55, 56) without any medical history. Interventions that may be beneficial in this age group may lose their efficacy or actually be harmful in either aged patients or those with chronic comorbidities, who have markedly different inflammatory milieus at baseline.

The findings in septic Fabpl-Bcl-2 mice reinforce the importance of cancer as a comorbidly. Previously healthy Fabpl-Bcl-2 mice do not have the increase in sepsis-induced gut epithelial apoptosis seen in WT animals subjected to the same insult and have improved survival following sepsis (24, 57). In contrast, when these animals have cancer prior to the induction of sepsis, they neither prevent sepsis-induced apoptosis nor improve survival. Although the finding that Bcl-2 was ineffective in preventing sepsis-induced gut apoptosis was surprising, we have previously described that these animals fail to prevent sepsis-induced intestinal apoptosis in the absence of lymphocytes (58), which suggests that the strength of apoptotic signaling (in the intestine at least) may be modifiable by host factors outside of the local environment. Furthermore, although the loss of the survival benefit conferred by gut-specific Bcl-2 was not as striking as the worsening of survival conferred by lymphocyte-specific Bcl-2 in septic mice with cancer, the results are consistent in that both the host response to sepsis and attempts to alter this response may be determined, at least in part, prior to the onset of infection. This study has a number of limitations. Because all nonsurvival studies were performed at a single time point (24 h), the experimental design did not allow for a dynamic assessment of the temporal changes in the host response. Next, although WT C57BL/6 mice were subjected to the same model of sepsis, mortality was significantly higher in experiments examining the effect of Bim1/−/− mice than in those examining the effect of Bcl-2-Ig mice. There is no clear explanation for this finding, because the experiments were performed by the same person (A.C.F.). Next, the decrease in sepsis-induced lymphocyte apoptosis in Bcl-2-Ig mice was small. We believe this decrease is small because sepsis-induced lymphocyte apoptosis is significantly lower in mice with cancer than in previously healthy mice (44). Previous work from our laboratory has shown that T lymphocyte apoptosis in Pan02-bearing septic mice is 10.4% and that T lymphocyte apoptosis in sham mice with cancer is 3.5% (44). In a comparison of these prior results with data shown in Fig. 1B, Bcl-2 decreased sepsis-induced T lymphocyte apoptosis to levels seen in sham mice. The fact that mortality was decreased in Bcl-2-Ig mice and Bim1/−/− mice, both of which have improved survival following cecal ligation and puncture in previously healthy mice (17, 21, 54), strengthens our findings. However, all transgenic and knockout mice used in this study have lifelong genetic alterations that could lead to chronic changes in other immune effector cells, which could affect the outcome when mice are subjected to pneumonia. As such, an alternate strategy initiating either Abs or drugs that inhibit apoptosis after the onset of pneumonia might have more clinical relevance and in theory a different effect on mortality.

Despite these limitations, these results lead to a new paradigm in understanding lymphocyte apoptosis in sepsis. There continues to be overwhelming evidence that lymphocyte apoptosis is harmful in hosts that were healthy prior to the onset of septic peritonitis. However, prevention of lymphocyte apoptosis by chronic genetic alterations in the mitochondrial pathway is harmful in mice with cancer that subsequently develop sepsis from pneumonia. Thus, the results do not support the view that sepsis-induced apoptosis is a maladaptive response independent of the host or insult; instead, they suggest a response that is modifiable by pre-existing host comorbidities and a model of sepsis used in which a basal level of lymphocyte cell death may be beneficial under the correct circumstances. These results should be repeated using other types of tumors, other comorbidities, other models of sepsis, and other apoptosis inhibitor strategies to determine their generalizability. These results should also be considered in designing entry criteria for future clinical trials aimed at preventing lymphocyte apoptosis in sepsis.

Disclosures
The authors have no financial conflicts of interest.

References