Accelerated Production of Antigen-specific T Cells for Preclinical and Clinical Applications Using Gas-permeable Rapid Expansion Cultureware (G-Rex)

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Summary: The clinical manufacture of antigen-specific cytotoxic T lymphocytes (CTLs) for adoptive immunotherapy is limited by the complexity and time required to produce large numbers with the desired function and specificity. The culture conditions required are rigorous, and in some cases only achieved in 2-cm^2 wells in which cell growth is limited by gas exchange, nutrients, and waste accumulation. Bioreactors developed to overcome these issues tend to be complex, expensive, and not always conducive to CTL growth. We observed that antigen-specific CTLs undergo 7 to 10 divisions poststimulation. However, the expected CTL numbers were achieved only in the first week of culture. By recreating the culture conditions present during this first week—low frequency of antigen-specific T cells and high frequency of feeder cells—we were able to increase CTL expansion to expected levels that could be sustained for several weeks without affecting phenotype or function. However, the number of 24-well plates needed was excessive and cultures required frequent media changes, increasing complexity and manufacturing costs. Therefore, we evaluated novel gas-permeable culture devices (G-Rex) with a silicone membrane at the base allowing gas exchange to occur uninhibited by the depth of the medium above. This system effectively supports the expansion of CTL and actually increases output by up to 20-fold while decreasing the required technician time. Importantly, this amplified cell expansion is not because of more cell divisions but because of reduced cell death. This bioprocess optimization increased T-cell output while decreasing the complexity and cost of CTL manufacture, making cell therapy more accessible.

Key Words: immunotherapy, antigen-specific cytotoxic T lymphocytes, large-scale expansion, novel gas-permeable cultureware

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Infusion of antigen-specific cytotoxic T lymphocytes (CTLs) has proven safe and apparently effective for the prophylaxis and treatment of infections with cytomegalovirus (CMV), adenovirus, and Epstein-Barr virus (EBV) in transplant recipients.[1–6] CTLs have also induced objective tumor responses and complete remissions in patients with advanced lymphoma, melanoma, and nasopharyngeal carcinoma.[7–15] The potential of T-cell therapy for cancer may be further improved by genetic modification to confer antigen specificity with recombinant T-cell receptors or chimeric antigen receptors (CARs), or by improving their homing and proliferative properties or their resistance to tumor immune evasion strategies.[16–26]

Although promising, most current protocols for the activation and expansion of antigen-specific CTL ex vivo are complicated and labor intensive, limiting the broad application of this therapy. These problems could be overcome by the optimization of conventional in vitro T-cell production to accelerate expansion and minimize cell handling, while ensuring that T-effector functions are maintained, thereby increasing the general enthusiasm for, and feasibility of, antigen-specific T-cell therapies.

Cell proliferation in culture is limited by requirements for nutrients and oxygen (O_2), and by accumulation of waste products such as carbon dioxide (CO_2) and lactic acid.[27] The volume of the medium used in conventional culture is restricted to the depth that allows sufficient O_2 diffusion from the medium surface to the cells growing at the base of the vessel. Both O_2 and nutrient requirements increase with cell concentration and rate of growth, so that cultures must be fed and split regularly. These frequent medium changes and cell manipulations are time-consuming, expensive, reduce the reproducibility of the production process and the consistency of the resultant T-cell product, and increase the risk of contamination.

One way of overcoming these limitations is to use bioreactors that provide mechanical rocking or stirring and medium and gas perfusion, thereby increasing the rate of cell expansion and maximum achievable cell density.[28–35] These machines are expensive, complex, and bulky, however, so that the number of cultures that can be maintained in parallel is limited by space and availability. Furthermore, although antigen nonspecific T-cell cultures have been grown with great success in these bioreactors,[31,34] antigen-specific CTLs have strict requirements for cell-to-cell contact and have proven difficult to consistently adapt to moving cultures, as production of functional cells occurs best under static culture conditions.

Many groups, including our own, have found that optimal expansion of antigen-specific CTL lines occurs in the 2-cm^2 wells of standard tissue culture-treated 24-well plates,[5,36] in which the volume of medium in the wells is restricted by gas diffusion to 1 mL/cm^2. This volume in turn limits the supply of nutrients that are rapidly consumed by the proliferating T cells. Consequent acidic pH and waste build-up rapidly impedes cell growth and survival, so that the maximum cell density that can be achieved is about $2 \times 10^6/cm^2$. As the minimum seeding density is around 2.5×10^5 T cells per cm^2, the maximum weekly cell expansion is about 8-fold. Continued expansion of CTLs requires weekly reseeding with antigenic restimulation, and twice weekly exchanges of medium and growth factors. As the rate of expansion is slow, these manipulations must be repeated over a 4-8 week propagation period to obtain sufficient numbers for cell infusions, and sterility, identity, and potency assays.[3,5,37,38]

To maintain the desirable static culture conditions needed for antigen-specific CTL expansion in the course of overcoming the obstacles of limited gas and nutrient supplies, we have evaluated a novel gas-permeable rapid expansion cultureware (G-Rex) system in which O_2 and CO_2 are exchanged across a silicone membrane at the base of the flask.[39] Gas exchange from below allows an increased depth of the medium above, providing more nutrients and diluting waste. We now show that the G-Rex device supports the expansion of antigen-specific CTLs and genetically modified T cells and a range of suspension cell lines, without significantly altering cell phenotype or function. The system is scalable and suited to good manufacturing practice-applications, and reduces the number of technician interventions approximately 4-fold while increasing the cell output by at least 3-fold and up to 20-fold when compared with conventional methods. As these benefits are predominantly mediated by improved cell survival, the device decreases the number of cell divisions required to achieve a given cell number, an important consideration for the expansion and long-term persistence of adoptively transferred T cells.[40]

MATERIALS AND METHODS

Generation of EBV-transformed B-cell Lines

After consent, we obtained peripheral blood from healthy donors. Then 5×10^6 peripheral blood mononuclear cells (PBMCs) were infected with concentrated B95-8 EBV supernatant in the presence of cyclosporin A (Sandoz, Broomfield, Co.) to establish an EBV-lymphoblastoid cell line (LCL).[5]

EBV-CTL Generation

Conventional CTL Generation Protocol (24-well Plates-2 cm^2 Surface Area and 2 mL Volume)

Day 0

CTLs were initiated by coculturing PBMCs from normal donors (1×10^6/mL) with γ-irradiated (40 Gy) autologous EBV-LCLs at a 40:1 ratio (PBMC:LCLs) in a total volume/well of 2-mL CTL medium [RPMI 1640 supplemented with 45% Click medium (Irvine Scientific, Santa Ana, CA), 2-mM GlutaMAX-I, and 10% fetal bovine serum (FBS)].

Days 9 to 12

CTLs were harvested, resuspended in fresh medium at 0.5×10^6 CTL/mL and restimulated with irradiated autologous EBV-LCLs at a ratio 4:1 (1×10^6:2.5×10^5—CTL:LCL).

Days 13 to 16

CTLs were fed with 1 mL of fresh medium containing recombinant human IL-2 (50 U/mL) (Proleukin; Chiron, Emeryville, CA)

Subsequent Stimulations

CTLs were restimulated weekly using CTL:LCL at a ratio 4:1 with twice weekly addition of IL-2.

Conventional CTL Generation Protocol (G-Rex)

Day 0

CTLs were initiated by coculturing 1×10^7 PBMC ($1 \times 10^6/cm^2$), with γ-irradiated (40 Gy) EBV-LCLs at a 40:1 PBMC to LCL ratio in a final volume of 30 mL of CTL medium in the G-Rex40 (10 cm^2).

Days 9 to 12

The second stimulation was performed by removing 15 mL of the medium, counting the T cells and adding 15 mL of fresh CTL medium containing irradiated EBV-LCLs, resuspended in at an appropriate concentration to stimulate T cells at a ratio 4:1.

Days 13 to 16

IL-2 (50 U/mL—final concentration) was added directly to the culture.

Subsequent Stimulations

Once the cells had expanded to a density of $> 5 \times 10^6/cm^2$ they were transferred to a G-Rex500 and stimulated with irradiated EBV-LCL (4:1) in a volume of 200-mL CTL medium containing IL-2 (50 U/mL). Antigen stimulation was performed every 7 days thereafter using a 4:1 CTL:LCL ratio and cells were plated in 200 mL of CTL medium and the cultures were supplemented twice weekly with 50 U/mL of IL-2. This was repeated until the culture reach about 7×10^8 cells per G-Rex500. After this, they could be split among G-Rex500s at 5×10^7 T cells per G-Rex500 until sufficient T cells were obtained.

Modifications to optimize this procedure were made as indicated in the results section and figure legends.

Cell Lines and Tumor Cells

BJAB and K562 were obtained from the American Type Culture Collection (ATCC, Rockville, MD). All cells were maintained in culture with RPMI 1640 medium (GIBCO-BRL, Gaithersburg, MD) containing 10% heat-inactivated fetal calf serum, 2-mM GlutaMAX, 25-IU/mL penicillin, and 25-mg/mL streptomycin (all from Bio-Whittaker, Walkersville, MD). Cells were maintained in a humidified atmosphere containing 5% CO_2 at 37°C.

Immunophenotyping

Cell Surface

Cells were stained with phycoerythrin (PE), fluorescein isothiocyanate, periodin chlorophyll protein, and allophycocyanin-conjugated monoclonal antibodies (MAbs) to CD3, CD4, CD8, CD56, CD16, CD62L, CD45RO, CD45RA, CD27, CD28, CD25, CD44 from Becton Dickinson (Mountain View, CA). PE-conjugated tetramers (Baylor College of

Medicine) and allophycocyanin-conjugated pentamers (Proimmune Ltd, Oxford, UK) were used to quantify EBV-CTL precursor frequencies.[3] For cell surface and pentamer staining 10,000 and 100,000 live events, respectively, were acquired on a FACSCalibur flow cytometer and the data were analyzed using the Cell Quest software (Becton Dickinson).

Carboxy-fluorescein Diacetate, Succinimidyl Ester Labeling

PBMC (2×10^7) or EBV-specific CTLs (EBV-CTLs) were washed twice and resuspended in 850 μL 1 × phosphate-buffered saline (PBS) containing 0.1% FBS (Sigma-Aldrich). Before staining, an aliquot of carboxy-fluorescein diacetate, succinimidyl ester (CFSE) (10 mM in dimethyl sulfoxide) [Celltrace CFSE cell proliferation kit (C34554) Invitrogen] was thawed, diluted 1:1000 with 1 × PBS and 150 μL of the dilution was added to the cell suspension (labeling concentration was 1 μM). Cells were incubated with CFSE for 10 minutes at room temperature. Subsequently, 1-mL FBS was added to the cell suspension followed by a 10-min incubation at 37°C. Afterward cells were washed twice with 1 × PBS, counted, and stimulated with antigen as described.

AnnexinV-7-AAD Staining

To determine the percentage of apoptotic and necrotic cells in our cultures, we performed Annexin-7-AAD staining as per the manufacturers' instructions (BD Pharmingen, #559763, San Diego, CA). In brief, EBV-CTL from the 24-well plates and the G-Rex were washed with cold PBS, resuspended in 1X Binding Buffer at a concentration of 1×10^6 cells/mL, stained with Annexin V-PE and 7-AAD for 15 min at room temperature (25°C) in the dark. After the incubation, the cells were analyzed immediately by flow cytometry.

Chromium Release Assay

We evaluated the cytotoxic activity of EBV-CTLs in standard 4-hour ^{51}Cr release assay, as described earlier.[25,38] As target cells, we used autologous and HLA classes I and II mismatched EBV-transformed LCL to measure MHC restricted and MHC unrestricted killing and the K562 cell line to measure natural killer activity. Chromium-labeled target cells incubated in medium alone or in 1% Triton × −100 were used to determine spontaneous and maximum ^{51}Cr release, respectively. The mean percentage of specific lysis of triplicate wells was calculated as follows: [(test counts spontaneous counts)/(maximum counts spontaneous counts)] × 100.

Enzyme-linked Immunospot Assay

Enzyme-linked Immunospot (ELIspot) analysis was used to quantitate the frequency and function of T cells that secreted interferon (IFN)-γ in response antigen stimulation.[3,41] CTL lines expanded in 24-well plates or in the G-Rex were stimulated with irradiated LCL (40 Gy) or LMP1, LMP2, BZLF1, and EBNA1 pepmixes (diluted to 1 μg/mL) (JPT Technologies GmbH, Berlin, Germany), or EBV peptides HLA-A2 GLCTLVAML = GLC, HLA-A2 CLG GLLTMV = CLG, HLA-A2-FLYALALLL = FLY, and HLA-A29 ILLARLFLY = ILL (Genemed Synthesis, Inc., San Antonio, TX), diluted to a final concentration of 2 μM, and CTLs alone served as a negative control. CTLs were resuspended at 1×10^6/mL in ELIspot medium [RPMI 1640 (Hyclone, Logan, UT) supplemented with 5% Human Serum (Valley Biomedical, Inc., Winchester, VA) and 2-mM L-glutamine (GlutaMAX-I, Invitrogen, Carlsbad, CA)].

Ninety-six-well filtration plates (MultiScreen, #MAHA S4510, Millipore, Bedford, MA) were coated with 10 μg/mL anti-IFN-γ antibody (Catcher-mAB91-DIK, Mabtech, Cincinnati, OH) overnight at 4°C, then washed and blocked with ELIspot medium for 1 hour at 37°C. Responder and stimulator cells were incubated on the plates for 20 hours, then the plates were washed and incubated with the secondary biotin-conjugated anti-IFN-γ monoclonal antibody [Detector-mAB (7–B6-1-Biotin), Mabtech] followed by incubation with Avidin:biotinylated horseradish peroxidase complex [Vectastain Elite ABC Kit (Standard), #PK6100, Vector Laboratories, Burlingame, CA] and then developed with AEC substrate (Sigma, St. Louis, MO). Each culture condition was run in triplicate. Plates were sent for evaluation to Zellnet Consulting, New York, NY. Spot-forming cells and input cell numbers were plotted.

Retrovirus Production and Transduction of T lymphocytes

Retroviral supernatant was produced and T cells transduced as described before.[23,25] CAR expression on T cells was measured 72 hours posttransduction and the cells maintained in culture in complete medium with the addition of rIL-2 (50 U/mL) every 3 days.

Statistical Analysis

All in vitro data are presented as mean ± 1SD. Student t test was used to compare the difference between the 2 groups after appropriate log-transformation. A P value of <0.05 was accepted as indicating a significant difference.

RESULTS

Antigen-specific CTLs Expand Inefficiently Using Conventional Cell Culture Conditions

Antigen-specific CTLs are traditionally activated and expanded by coculture with antigen-presenting cells (APCs) in a standard tissue culture-treated 24-well plates at fixed T-cell/APC ratios. For example, to activate and expand EBV-CTLs, PBMCs are stimulated with irradiated, autologous EBV-LCL at a responder to stimulator (R:S) ratio of 40:1. On day 9 and weekly thereafter, T cells are restimulated with the EBV-LCLs at an R:S ratio of 4:1 with twice weekly medium change with the addition of IL-2 from day 14. Under these culture conditions, antigen-specific T cells should undergo at least 7 cell doublings after each stimulation, as shown in Figure 1A. Thus, we expect a weekly T-cell expansion of 128-fold (as measured by the frequency of antigen-specific T cells × number of total cells). To test this assumption using EBV-CTLs as our model, we stimulated PBMC from EBV-seropositive donors with autologous EBV-LCL and measured the frequency of tetramer-positive cells after the first, second, and third stimulations. A representative experiment is shown in Figure 1B. On day 0 the frequency of T cells reactive against 2 EBV tetramers, RAK and QAK was 0.02% and 0.01%, respectively. After a single stimulation, we observed a 2.2-fold increase in total cell numbers (data not shown) on day 9, whereas the frequency of tetramer-positive T cells had increased to 2.7% and 1.5%, respectively, representing a 135-fold and 125-fold increase in the frequency of

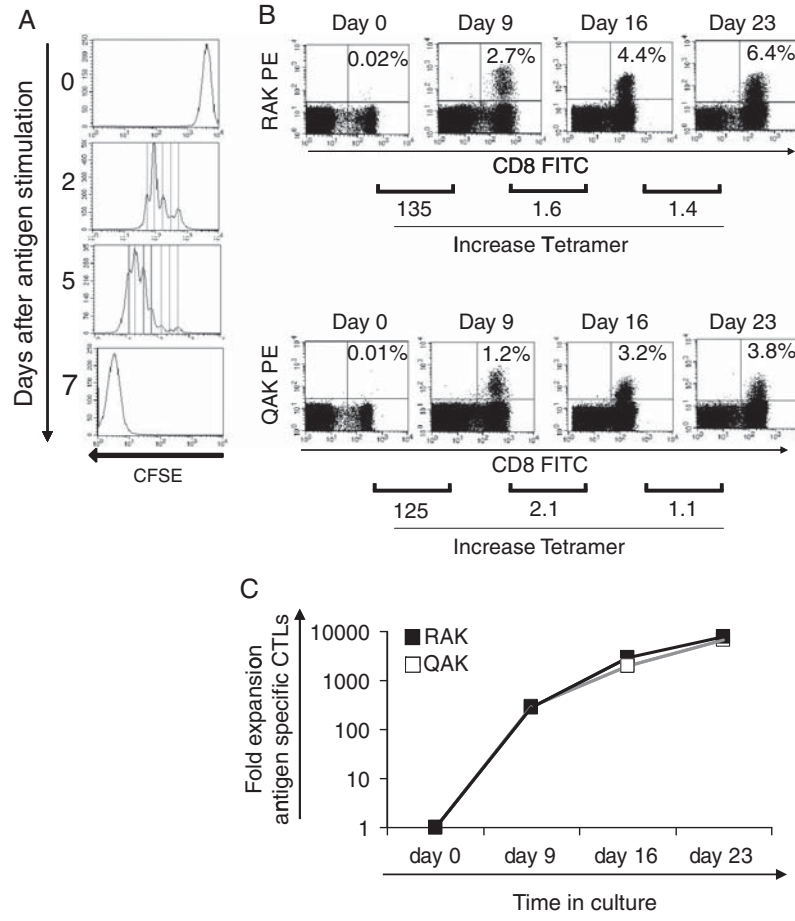


FIGURE 1. Expansion of antigen-specific cytotoxic T lymphocytes (CTLs) during the first week of culture in 24-well plates. A, CTLs labeled with CFSE undergo at least 7 doublings after antigenic stimulation, and this doubling rate was preserved through multiple rounds of stimulation. B, Enrichment of antigen-specific cells during the first week of culture, as shown by pentamer analysis using the Epstein-Barr virus (EBV)-specific HLA-B8-restricted RAK and QAK pentamers. The increase in the frequency of antigen-specific cells was superior during the first week of culture (from day 0 to 9) than in the subsequent weeks (day 16 and day 23). Fold increase in pentamer-positive cells is shown below the dot plots. This antigen-specific CTL enrichment, which preferentially occurs during the first week of culture, is reflected in the overall superior expansion of antigen-specific cells during the first week, as presented in (C).

antigen-specific tetramer-positive T cells. Thus, the fold expansion of the antigen-specific components was around 280 during the first stimulation, as shown in Figure 1C. Unfortunately, however, this rate of antigen-specific T-cell expansion was not sustained during the second and subsequent stimulations, after which the fold expansion of antigen-specific CTL was <5, even though the same number of cell doublings was observed during the first and subsequent weeks of culture, as measured by CFSE analysis. Table 1 illustrates the discrepancy between the expected and observed fold expansion of antigen-specific CTL (n = 3).

Minimal Cell Density Promotes Cell Expansion

We hypothesized that the decreased cell numbers obtained after the second T-cell stimulation compared with the first stimulation was due either to the increased susceptibility of activated T cells to activation-induced cell death (AICD) or to limiting cell culture conditions. For example, at the first stimulation, the EBV antigen-specific T-cell component of PBMCs represents, at most, 2% of the population and so the antigen-specific responder T-cell seeding density is less than $2 \times 10^4/cm^2$, with the remaining PBMCs acting as nonproliferating feeder cells (seen as the CFSE-positive cells in Fig. 2A) that sustain optimal cell-to-cell contact and antigen-specific CTL expansion (Fig. 2A, top panel). By contrast, at the second stimulation on day 9, a majority of T cells are antigen-specific, resulting in a much higher seeding density (up to 5×10^5 cells/cm^2) of responder cells. As a consequence, on restimulation a

TABLE 1. Expected and Observed CTL Expansion

Cell doubling	1	2	3	4	5	6	7
Expected fold expansion	2	4	8	16	32	64	128
Observed fold expansion (day 0 to 9)							258 range (48 to 409)
Observed fold expansion (day 9 to 16)							5.7 range (2.2 to 10.6)
Observed fold expansion (day 16 to 23)							4.3 range (4.1 to 14.9)

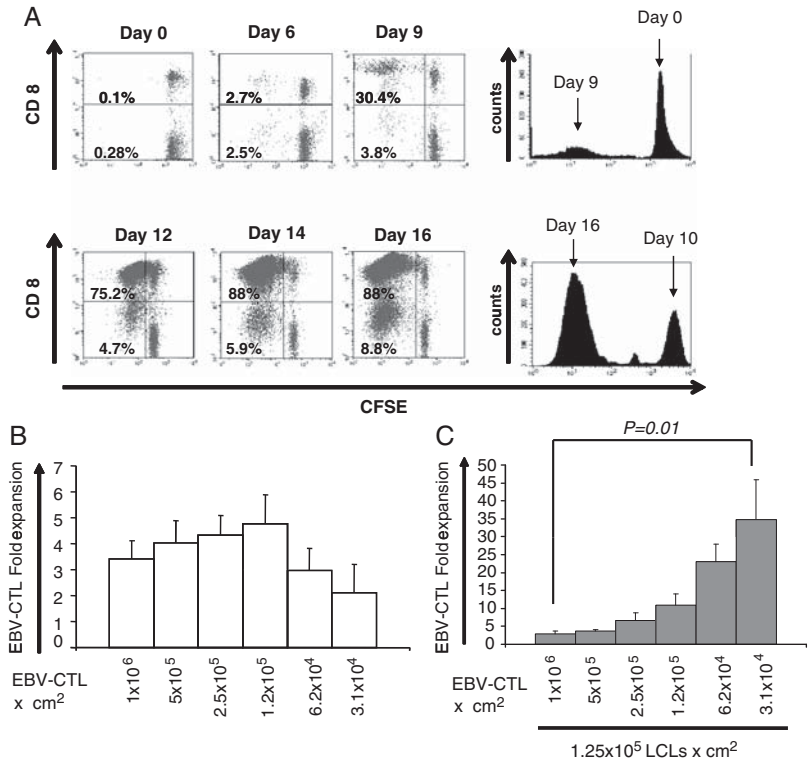


FIGURE 2. Antigen-specific cytotoxic T lymphocyte (CTL) expansion can be optimized by modifying the culture composition. As illustrated in (A) top panel, during the first week of culture only a small fraction of PBMC labeled with CFSE proliferate after antigen stimulation whereas the majority of cells, which are not antigen-specific, act as a feeder cell layer. In contrast, during subsequent stimulations, a majority of the cells in the culture are antigen-specific and proliferate after antigenic stimulation (A, bottom panel). B, Proliferation of established Epstein-Barr virus (EBV)-CTLs can be affected by decreasing the traditional seeding cell density (1×10^6 CTL) to 1.2×10^5 CTL, while conserving the R:S [CTL:lymphoblastoid cell line (LCL)] ratio of 4:1. However, by increasing the density of nonproliferating feeder cells (irradiated LCL), the fold expansion of EBV-CTL can be dramatically increased by decreasing the initial seeding effector cell density to as low as 3.1×10^4 (C).

majority of cells proliferate (Fig. 2A, bottom panel), and may therefore rapidly consume and exhaust their nutrients and O_2 supply.

To determine whether limiting culture conditions were responsible for the suboptimal T-cell growth rates, we measured the expansion of activated T cells plated at lower cell densities. We seeded activated EBV-CTL in 2-cm^2 wells at doubling dilutions from 1×10^6 to $3.1 \times 10^4/cm^2$ while maintaining an R:S ratio of 4:1 (Fig. 2B). The maximum CTL expansion (4.7 ± 1.1-fold) was achieved with a starting CTL density of $1.25 \times 10^5/cm^2$, but further dilution decreased the rate of expansion (Fig. 2B). As this limiting dilution effect was likely due to lack of cell-to-cell contact, we cultured doubling dilutions of EBV-CTL from 1×10^6 to 3.1×10^4 with a fixed number of feeder cells (EBV-LCL plated at $1.25 \times 10^5/cm^2$) and assessed cell expansion over a 7-day period. We observed a significant increase in the CTL expansion from 2.9 ± 0.8-fold using the conventional cell numbers (1×10^6 CTL:1.25×10^5 LCL) to 34.7 ± 11-fold expansion when 3.1 ± 10^4 CTL/cm^2 were incubated with 1.25×10^5 LCL/cm^2, as presented in Figure 2C ($P = 0.01$). Importantly, this modification of the culture conditions did not change the function or antigen specificity of the cells (see Supplementary Figure, Supplemental Digital Content 1, http://links.lww.com/JIT/A29). Activated antigen-specific T cells are therefore potentially capable of greater expansion than we were able to achieve using our traditional culture conditions. Of note, the maximum cell number achieved after stimulation (1.7 to $2.5 \times 10^6/cm^2$) was the same regardless of the starting cell density, suggesting that cell density is the limiting factor for cell growth.

Gas-permeable Rapid Expansion Cultureware (G-Rex) to Promote Gas Exchange and Decrease Medium Limitations

Although the improved expansion (34-fold) of antigen-specific CTL can be obtained in tissue culture wells as described above, the number of wells required to support such expansion is excessive. For example, 1×10^7 T cells cultured in tissue culture wells at $3.1 \times 10^4/cm^2$ could produce circa 3.5×10^8 CTL in 1 to 2 weeks, but would require 161 wells of a 24-well plate (>6 plates), making this protocol impractical for routine use or for scale up, due to the technician time and culture manipulations required. To determine whether the maximum T-cell density per centimeter square could be increased, we evaluated novel gas-permeable rapid expansion cultureware (G-Rex), developed by Wilson Wolf Manufacturing (New Brighton, MN). In conventional cultureware, gas exchange occurs across the surface of the medium, limiting medium depth to a maximum of only 1 mL/cm^2, (Fig. 3A). This restricted medium-to-surface area ratio limits nutrient and growth

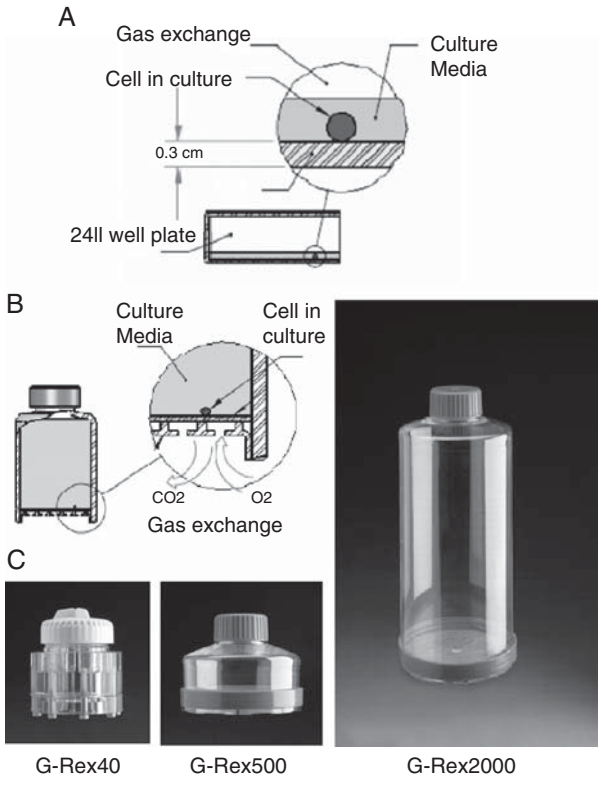


FIGURE 3. G-Rex overcomes the limited volume of medium per surface area in conventional cultureware. A, Illustrates that gas exchange in traditional cultureware is restricted to the surface area above the culture, which limits the depth of media. B, A blueprint of the G-Rex showing that gas exchange occurs from the bottom of the device that allows for an increase in the volume of the media per surface area. C, A photograph of the G-Rex40, G-Rex500, and G-Rex2000.

factors and facilitates the rapid build-up of metabolites such as CO_2 and lactic acid that increase the acidity of the culture. By contrast, in the G-Rex, O_2 and CO_2 are exchanged across a silicone membrane at the base of the device, removing the limitation of medium depth and allowing up to a 20-fold higher medium volume per unit area than in the conventional cultureware. A schematic of the G-Rex flask is shown in Figure 3B. We evaluated 3 different flask sizes with surface areas and maximum media volumes of $10\,cm^2$ (40 or $4\,mL/cm^2$) for the G-Rex40, $100\,cm^2$ (500 or $5\,mL/cm^2$) for the G-Rex500, and $100\,cm^2$ (2000 or $20\,mL/cm^2$)-G-Rex2000, respectively (Fig. 3C).

T Cells Cultured in the G-Rex Have Increased Viability and Expansion

To determine whether the maximum achievable cell density could be increased in G-Rex devices, we cocultured activated EBV-CTL with autologous EBV-LCLs at the conventional 4:1 ratio of T-cell:LCL. CTLs were seeded at 5×10^5 cells/cm^2 in the G-Rex40 and expansion was compared with CTL seeded at the same density in a 24-well plate. After 3 days, the cell numbers in the G-Rex40 had increased from $5 \times 10^5/cm^2$ to a median of $7.9 \times 10^6/cm^2$ (range 5.7 to $8.1 \times 10^6/cm^2$) without any medium exchange. This number further increased to 9.5×10^6 cells/cm^2 (range 8.5×10^6 to $11.0 \times 10^6/cm^2$) after replenishing the medium and IL-2 on day 7 (data not shown). In contrast, cells cultured for 3 days in conventional 24-well plates increased from $5 \times 10^5/cm^2$ to a median of only $1.8 \times 10^6/cm^2$ (range 1.7 to $2.5 \times 10^6/cm^2$) by day 3 (Fig. 4A) ($P = 0.005$); cell density/numbers were not further increased by replenishing medium or IL-2. The G-Rex can also be used to culture virtually any human suspension cells that we evaluated, including activated T-cell gene modified to express CAR molecules, EBV-LCLs, and other hematopoietic cell lines as shown in Supplemental Figures 2 and 3, Supplemental Digital Content 2, http://links.lww.com/JIT/A30; Supplemental Digital Content 3, http://links.lww.com/JIT/A313.

To understand the mechanism behind the superior cell expansion in the G-Rex device, we assessed the viability of OKT3-stimulated peripheral blood T cells using flow cytometric forward versus side scatter analysis on day 5 of culture. EBV-CTLs could not be assessed in this assay due to the presence of residual irradiated EBV-LCL in the cultures, which would interfere with the analysis. As shown in Figure 4B, cell viability was significantly higher in the G-Rex40 cultures (49.9% viability vs. 89.2% viability). We then analyzed the cultures daily for 7 days using Annexin-PI 7AAD to distinguish between live and apoptotic/necrotic cells, and observed consistently lower viability in T cells expanded in 24-well plates (Fig. 4C, top panel) compared with those in the G-Rex (Fig. 4C, lower panel). These data suggest that the cumulative improved survival of proliferating cells contributed to the increased cell numbers in the G-Rex devices compared with the plates.

To determine whether there was also a contribution from an increased number of cell divisions in the G-Rex versus the plates, T cells were labeled with CFSE on day 0 and divided between a 40-mL device and a 24-well plate. Daily flow cytometric analysis showed no differences in the number of cell divisions from days 1 to 3. From day 3 onward, however, cells cultured in the G-Rex continued to divide, whereas cell divisions were reduced in the 2-mL wells, suggesting that the culture conditions had become limiting (Fig. 4D). Thus, enhanced cell numbers in the G-Rex resulted from a combination of decreased cell death and prolonged proliferation.

CTL Stimulation Using Optimized Seeding Cell Density in the G-Rex Induces Maximum Expansion of Antigen-specific CTLs

To simplify and shorten the manufacture of EBV-CTLs for clinical use, we established an optimized standard operating procedure using the G-Rex for the initiation and expansion of antigen-specific T cells. For EBV-CTL initiation, we seeded PBMCs in the G-Rex40 at $1 \times 10^6/cm^2$ (total = 10^7 PBMCs) and stimulated them with EBV-LCL using a 40:1 ratio of PBMC:EBV-LCL; This 40:1 ratio is critical in the first stimulation to maintain the antigen specificity of the responder T cells. However, on day 9, 1×10^7 responder T cells were transferred to the G-Rex500 ($1 \times 10^5/cm^2$) with 5×10^7 LCL (5×10^5 per cm^2) (1:5 ration of T cells to LCLs) in a total of 200 mL CTL medium. This seeding density produced consistent CTL expansion in all donors screened and simplified cell calculations for good manufacturing practice staff. Four days later (day 13), IL-2 (50-U/mL final concentration) was added directly to the culture without medium change, and on day 16, the cells were harvested and counted. The median number of EBV-CTL obtained was 6.5×10^8 (range 2.4×10^8 to 3.5×10^9), which was approximately 4-fold more cells than would be

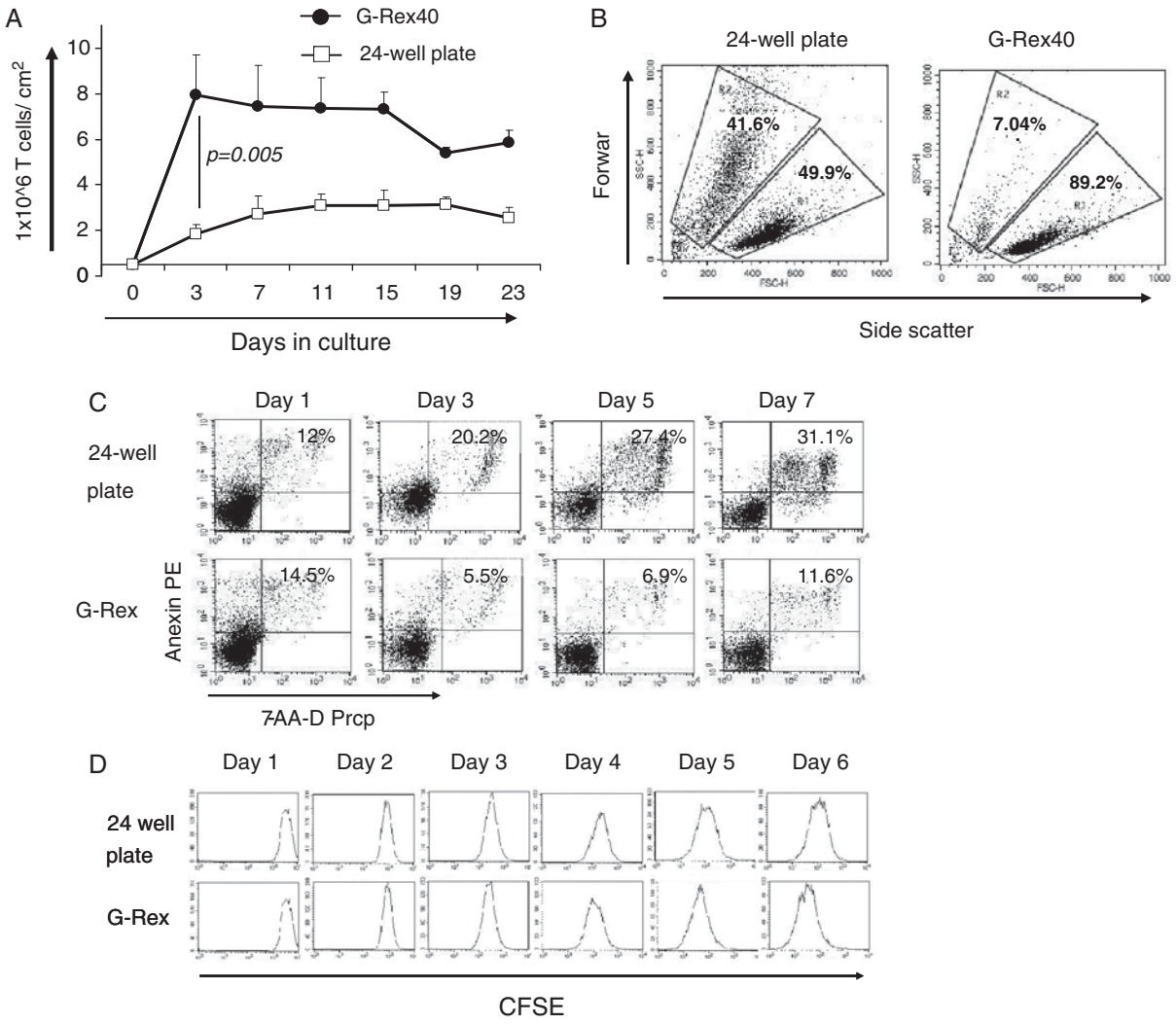


FIGURE 4. The G-Rex increases the cell output by improving the viability and the cell density. A, Increased numbers of EBV-CTLs per surface area can be attained in the G-Rex (solid circles) when compared with 24-well plates (open squares). This increase in the number of cells was achieved by an improvement in the cell viability as shown by the forward versus side scatter dot plot on day 7 and confirmed by daily Annexin-PI 7AAD flow cytometric analysis (B and C). The number of cell divisions in the cultures was evaluated by daily analysis of T cells labeled with CFSE as presented in (D).

achieved using our standard 4:1 ratio of T cells:APCs in the G-Rex and 26 times more cells than in 24-well plates (our current standard protocol) (Fig. 5A). The T cells continued to divide until days 27 to 30 without requiring additional stimulation provided the cultures were split when cell density was $>7 \times 10^8$, producing a median of 5.07×10^9 cells (range 1.1×10^9 to 2.5×10^{10}), generating 23.7-fold and 68.4-fold more EBV-specific cells than the G-Rex with the conventional R:S ratio ($P = 0.003$) and the 24-well plates ($P < 0.0001$), respectively (Fig. 5A).

Although in the G-Rex growing CTLs cannot be viewed clearly using light microscopy, clusters of CTLs can be visualized by eye or by inverted microscope and the appearance of the cells on days 9, 16, and 23 of culture is shown in Figure 5B. Culture in the G-Rex did not change the phenotype of the expanded cells (Fig. 5C), with > 90% $CD3^+$ cells (96.7 ± 1.7 vs. 92.8 ± 5.6; G-Rex vs. 24-well), which were predominantly $CD8^+$ (62.2% ± 38.3 vs. 75% ± 21.7). Evaluation of the activation markers CD25 and CD27, and the memory markers CD45RO, CD45RA, and CD62L, showed no substantive differences between CTL expanded under each culture condition. The antigen specificity was also unaffected by the culture conditions, as measured by ELIspot and pentamer analysis. Figure 5D shows a representative culture in which T cells stimulated with EBV pepmixes and/or peptide epitopes from LMP1, LMP2, BZLF1, and EBNA1 and stained with HLA-A2-LMP2 pentamers showed similar frequencies of peptide-specific T cells. Furthermore, the expanded cells maintained their cytolytic activity and specificity and killed autologous EBV-LCL (62% ± 12 vs. 57% ± 8 at a 20:1 E:T ratio; G-Rex vs. 24-well plate), with low killing of the HLA mismatched EBV-LCL (15% ± 5 vs 12% ± 7 20:1 ratio) as evaluated by ^{51}Cr release assays (Fig. 5E).

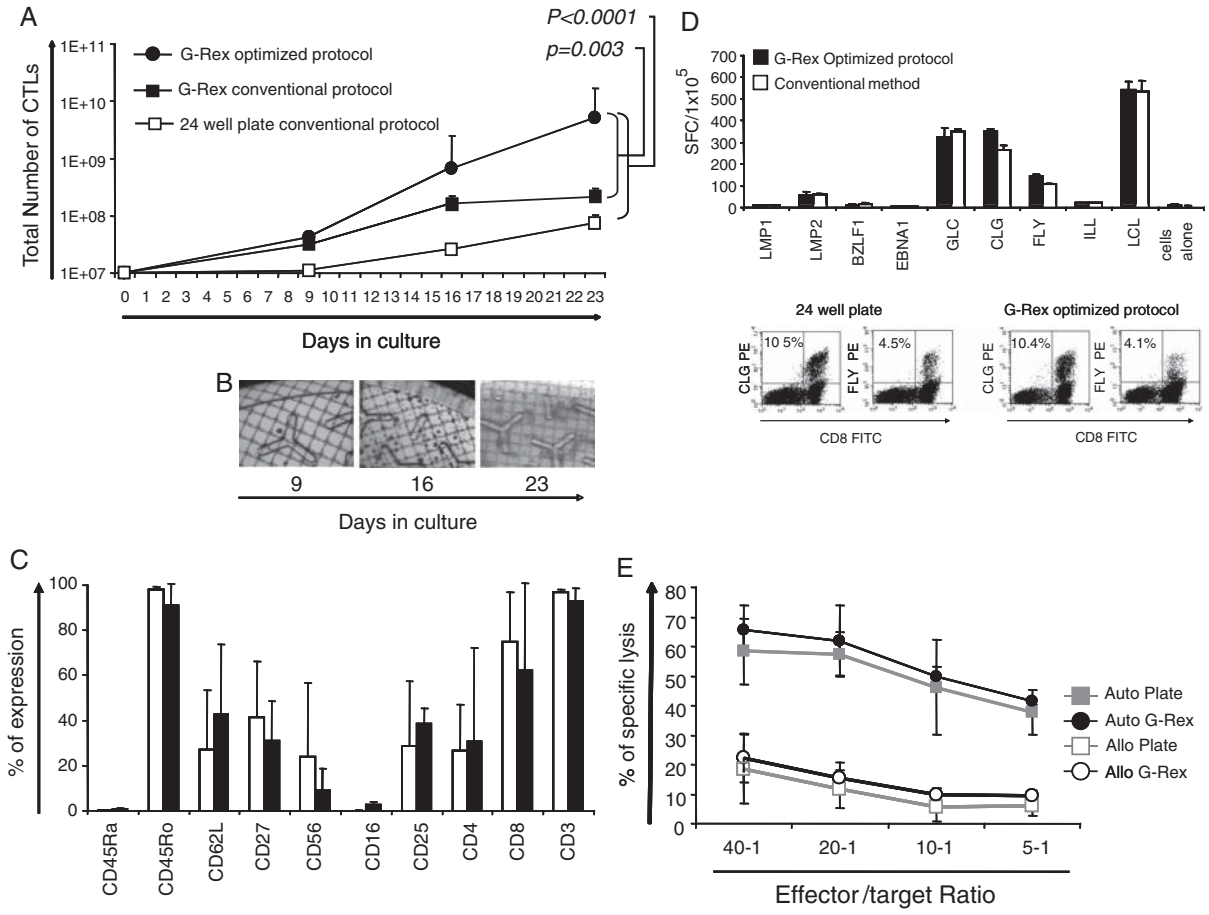


FIGURE 5. The use of an optimized APC:CTL ratio in the G-Rex dramatically improves the cell output without modifying CTL phenotype or function. Panel A shows the expansion of EBV-CTL using the conventional APC:CTL ratio and cell density in 24-well plates (open squares) in comparison with EBV-CTLs expanded in the G-Rex with the conventional and optimized APC:CTL ratio (solid squares and solid circles, respectively). B,CTL growth over time in the G-Rex, as evaluated by microscopy. C, Phenotypic comparison of EBV-CTLs cultured with the conventional method or with the optimized APC:CTLs ratio in the G-Rex. The antigen specificity of the expanded cells was evaluated by ELIspot and pentamer analysis and cytotoxicity assay, and a representative example is shown in (D) and (E).

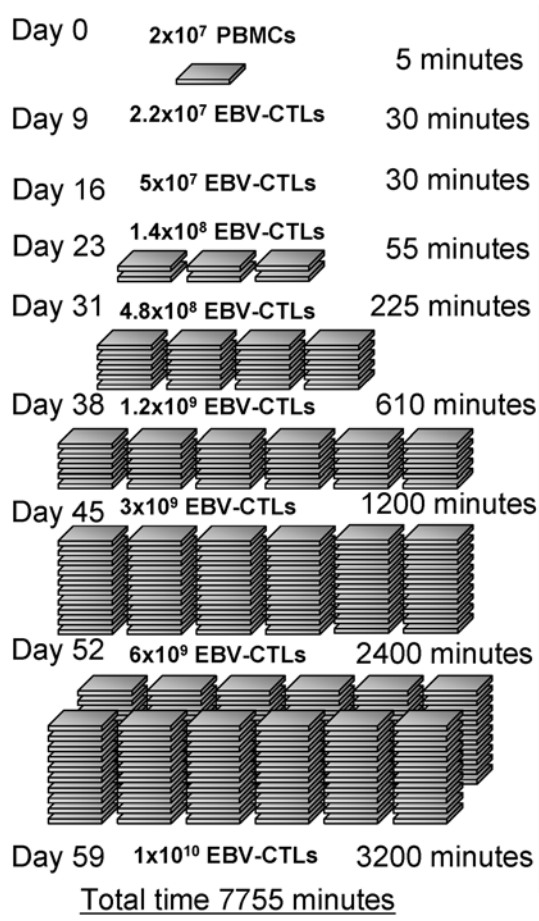
The G-Rex Reduces the Time, Complexity, and Cost Associated With CTL Production for Clinical Use

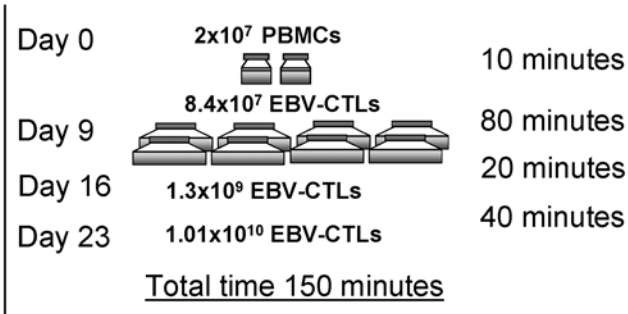
The broader implementation of T-cell immunotherapy is limited by (i) the cost of production; (ii) the complexity of production, including repeat feeding of open culture systems, and multiple skilled "judgment calls," thereby limiting scalability, and (iii) the time required for activation and expansion. Figure 6 shows the effects of the G-Rex on these obstacles. The "hands on" time for CTL manufacture is reduced because fewer cell manipulations are required, which consequently reduces the labor costs, decreases the complexity of manufacture, and diminishes the risk of contamination. The duration of CTL manufacture is also reduced by the increased rate of expansion. Hence production of 1×10^{10} CTLs, which would typically require approximately 60 days and 129 hours of technician time by conventional culture, is reduced to 23 days with 3 hours of labor and a reduction in the number of interventions from >200,000 to just 34, translating to a saving of >50% in CTL production costs (Fig. 6).

DISCUSSION

We have described an improved manufacturing system for producing EBV-CTL, using optimized cell-seeding densities and novel gas-permeable rapid expansion cultureware (G-Rex) to support the large-scale production of cells for clinical use. By using cultureware that promotes optimal O_2 and CO_2 exchange, the initial input volume of medium can be increased, which in turn increases the available nutrients and dilutes waste products without the need for culture agitation (which disrupts antigen-specific CTL expansion), frequent culture feeding, or continuous medium perfusion, facilitating large-scale CTL production. The G-Rex can also support the expansion of CTL with other antigen specificities including CMV and trivirus (CMV, EBV, adenovirus)-specific CTLs (data not shown), and can be adapted to the culture of virtually any human suspension cells including gene-modified-activated T cells, EBV-LCLs, and other hematopoietic cell lines as shown in supplementary Figures 2 and 3.

In our initial series of experiments, we measured the expansion of EBV-CTLs cultured in wells during the initial





	24 well plate		G-Rex	
Starting cell number	$2x10^7$ PBMCs		$2x10^7$ PBMCs	
Final cell number	$1x10^{10}$ CTLs		$1x10^{10}$ CTLs	
Technician time	129 hours	$ 3,096	2.5 hours	$ 60
GMP facility charge		$ 2,280		$ 300
Cultureware	310 plates	$ 2,325	2 (G-Rex40) 8 to 16 (G-Rex500)	$ 2200
Media / cytokines	11160 ml	$ 1,674	3280 ml	$ 492
Regular pipette use	618	$ 309	20	$ 10
product Testing		$ 1,843		$ 1,843
Final cost	$ 11,527($1.15 x $1x10^6$ cells)		$ 4,905 ($0.49 x $1x10^6$ cells)	

	24 well plate	G-Rex
Number of interventions	222720	34
Antigen stimulation	9	2
Risk of contamination	++++	+
Biohazard	++++	+
Time to generate the product	59 days	23 days

FIGURE 6. Bioprocess optimization for CTLs production decreases the complexity, risk of contamination, and cost of manufacture. The conventional method of CTL culture using 24-well plates is convoluted, demanding frequent manipulation to sustain culture growth. This increases the manufacture cost and risk of contamination. In contrast, CTL culture using the optimized APC:CTL ratio in the G-Rex can produce the same number of cells in a shorter period of time thus decreasing the cost and complexity of manufacture.

and subsequent stimulations using conventional APC:T-cell ratios and observed that CTL expansion was far greater during the first stimulation of PBMC than during subsequent stimulations (Fig. 1). This difference could not be ascribed to the propensity of activated T cells to undergo AICD after the T-cell stimulation, but rather to differences in the composition of the cultures. In PBMCs the frequency of antigen-specific T cells is low (<2% of all T cells), thus activation and subsequent amplification of this small population of cells during the initial stimulation is not limited by the available nutrients and O_2 in the 2-mL well. However, during subsequent stimulations, the frequency of antigen-specific T cells greatly increases to form >50% of the bulk population. Thus, upon antigenic restimulation a majority of specific cells are reactivated, and because of their high frequency, rapidly deplete O_2 and nutrients to limiting levels, accounting for the high rate of apoptosis seen in the cultures (Fig. 4B). By emulating the culture conditions present during the first week, we could successfully increase the expansion of antigen-specific CTLs during subsequent stimulation. This was achieved by simply reducing the seeding density of CTLs while preserving optimal cell-to-cell contact by introducing a constant number of feeder cells into the cell culture wells to support and promote cell expansion in a nonlimiting environment.

The above optimization approach using 2-cm^2 wells is not practical for large-scale cultures for multiple individuals. Thus, we determined whether optimal CTL activation and expansion could be achieved more simply and cost-effectively using the G-Rex device. When cells are grown in standard flasks or plates, the input volume of medium is restricted to the depth that permits O_2 diffusion (normally 1 mL/cm^2). This in turn limits the available nutrients (glucose and amino acids) present in the medium.[27,28] By augmenting O_2 diffusion, the G-Rex device allows an increased volume of medium to be added above the growing cells. This improved culture system increased the maximum cell density that could be obtained in static cultures from 2 to $3 \times 10^6/cm^2$ of plastic in wells or plates, to about 10×10^6 CTL/cm^2 of culture surface area in the G-Rex. This concentration of T cells was supported by the increased volume of medium, about 4 mL/cm^2 in the G-Rex40 and 5 mL/cm^2 in the G-Rex500 compared with 1 mL/cm^2 in wells. Although the volume of medium per cm^2 could be as high as 20 mL/cm^2 in the G-Rex2000, we found no increase in final cell density, although the viability of the

cells was maintained even at the maximum densities, indicating that the cell concentration was governed by gas exchange rather than by exhaustion of medium.

Although nonspecific T cells are amenable to culture in plates, flasks and closed-system cell bioreactors,[31,34] most groups report a requirement for either 2-cm^2 wells of 24-well plates or cell culture bags for the growth of antigen-specific CTL, which have strict requirements for interaction with APCs and feeder cells as their growth and specificity are disrupted by moving cultures. Thus, bioreactors, which are commonly used to generate large numbers of suspension cells and use rocking, stirring, and/or medium perfusion to increase cell density, are either not amenable to CTL generation or are prohibitively expensive to purchase and maintain and complex to run.[28,30,31] The requirement for 2-mL wells has made the preparation of CTL lines for adoptive immunotherapy time-consuming and complex, requiring 1 to 3 months to produce sufficient cells for therapeutic purposes and involving manipulations that increase the risk of contamination, and impede the broader clinical application of antigen-specific CTL. The G-Rex provides a substantial advance for the culture of CTL, requiring no mechanical shaking or stirring and no medium sampling, as medium requirements are fulfilled by the unlimiting volume allowed above the cells. The small footprint allows multiple devices to be cultured in a single incubator, so that the cultureware can efficiently produce antigen-specific CTL in a cost-effective way for at least 1×10^{10} CTLs.

Central memory T cells seem to be required for long-term in vivo repopulation, and there are concerns that excessive in vitro T-cell proliferation before infusion may lead to terminal differentiation and exhaustion. To determine whether the G-Rex would favor the unwanted production of exhausted, terminally differentiated effector cells,[40] we measured both cell proliferation and cell death. We found that the increased cell numbers were a result of improved survival rather than increased proliferation. In confirmation, phenotypic analysis of G-Rex-grown CTL revealed no apparent detrimental effects on the ratio of effector:memory phenotype.

Although the therapeutic significance of antigen-specific CTLs or genetically modified T cells will depend on their effectiveness in the clinical setting, the ability to extensively apply these therapies will be determined, in part, by the complexity of the cell manufacturing process. Widespread provision will require optimized bioprocesses that are scalable, sterile, and safe, and that reproducibly make a potent cell product. Our data suggest that the culture device we describe will be able to significantly contribute to these ends.

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