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Culturing Aerobic and Anaerobic Bacteria and Mammalian Cells with a Microfluidic Differential Oxygenator

Raymond H. W. Lam,† Min-Cheol Kim,‡‡ and Todd Thorsen*†

Department of Mechanical Engineering, Hatsopoulos Microfluids Laboratory, Massachusetts Institute of Technology, Room 3-246, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, and Biomedical Microdevices and Microenvironments Laboratory, Boston University, Room 723, 44 Cummington Street, Boston, Massachusetts 02215

In this manuscript, we report on the culture of anaerobic and aerobic species within a disposable multilayer polydimethylsiloxane (PDMS) microfluidic device with an integrated differential oxygenator. A gas-filled microchannel network functioning as an oxygen—nitrogen mixer generates differential oxygen concentration. By controlling the relative flow rate of the oxygen and nitrogen input gases, the dissolved oxygen (DO) concentration in proximal microchannels filled with culture media are precisely regulated by molecular diffusion. Sensors consisting of an oxygen-sensitive dye embedded in the fluid channels permit dynamic fluorescence-based monitoring of the DO concentration using low-cost light-emitting diodes. To demonstrate the general utility of the platform for both aerobic and anaerobic culture, three bacteria with differential oxygen requirements (E. coli, A. viscosus, and F. nucleatum), as well as a model mammalian cell line (murine embryonic fibroblast cells (3T3)), were cultured. Growth characteristics of the selected species were analyzed as a function of eight discrete DO concentrations, ranging from 0 ppm (anaerobic) to 42 ppm (fully saturated).

Monitoring and controlling the dissolved oxygen (DO) concentration in medium are critical for biological culture and tissue engineering applications. Cellular growth, especially biofilm formation, involves the complex correlations of growth environment1,2 and cell—cell communications among cellular species.3,4 For cellular growth analysis, including the single cells/small cell clusters5 monitoring, precise control of the cellular environment is clearly desirable. Several microscale silicone-based chemostats6–8 bioreactors,9–12 and other microfluidic platforms13,14 containing multiple cell chambers have been developed for this purpose. Such platforms were engineered to provide moderate to long-term control (on the order of hours to days) of the microenvironment, including elements such as temperature, pH value, dissolved gas concentration, nutrient delivery, and waste removal. Due to the reproducibility and biocompatibility of soft lithography,15 the structural material choice of many microfluidic platforms is polydimethylsiloxane (PDMS), which has an oxygen diffusivity (D_{O_2,PDMS} \approx 6 \times 10^{-5} \text{ cm}^2/\text{s})16 on the same order as water at standard temperature and pressure (STP) (20 °C, 101.325 kPa).17

Controlling local DO levels in PDMS microfluidic devices can be achieved by flowing oxygen through dedicated gas microchannels that are in close proximity to the fluid-filled microchannels. Using conventional soft lithography methods,15,18 a small separation between gas and fluid microchannels on the order of tens of micrometers can readily be achieved. Several methods to regulate medium oxygenation using integrated microfluidic gas channels have been recently reported.6,19–22 A double-layer gas perfusion network structure fabricated above the cell culture region was

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of culture growth dynamics versus medium oxygen levels. The ability to vary and tune $p_{O_2}$ in a microfluidic environment has practical applications in areas such as microbiology and cancer research, where fluctuations in DO concentration impact not only cell viability but also the regulation of key biochemical pathways. The multilayer microfluidic device consists of a gas-based analog of a microfluidic solution gradient generator similar to the design utilized by Polinkovsky et al., with a network of branching gas-filled microchannels that overlap the underlying microfluidic culture channels. Similar to the chemical solution gradient generator, which has been applied in chemotaxis studies and continuous cell culture, gases like oxygen and nitrogen are mixed like liquids, with a parallel output of streams containing a stepwise gradient of oxygen concentrations. By varying the dimensions of the individual microchannels within the mixer network, the output oxygen concentration(s) can be finely tuned for the target application.

Oxygenation of culture media is achieved by the double-layer gas perfusion channel structure along the cell culture region. While the Polinkovsky platform used an inverted fluorescent microscope to monitor oxygenation with a solution-based fluorescent dye, the monitoring in our platform is achieved with an array of optical (Pt-porphyrin) oxygen sensors embedded in each culture channel that provides a real-time medium DO measurement with low-cost light-emitting diodes. To validate such platform, the growth characteristics of murine embryonic fibroblast cells (3T3) and bacteria with different DO requirements, including *Escherichia coli* (facultative anaerobe), *Actinomyces viscosus* (aerobe) and *Fusobacterium nucleatum* (anaerobe), have been analyzed as a function of eight discrete DO concentrations, ranging from anaerobic to fully saturated.

### EXPERIMENTAL SECTION

#### Oxygen-Sensing System.

Real-time oxygen concentration measurement is achieved by an optical oxygen-sensing system. Platinum(II) octaethylporphine ketone (PtOEPK) was selected as the optical sensing element, because of its long lifetime, high photostability, and low photobleaching rate among other fluorescent dyes. The excitation (570 nm) and emission (760 nm) wavelengths of PtOEPK induce a large Stokes shift to reduce the signal-to-background ratio. A schematic diagram of the oxygen-sensing scheme is illustrated in Figure 1a. The excitation light is generated by a yellow light-emitting diode (LED) with a bandpass color filter (CVI laser, BG-39) placed between the LED and the optical sensing element, because of its long lifetime, high photon stability, and low photobleaching rate among other fluorescent dyes. The excitation (570 nm) and emission (760 nm) wavelengths of PtOEPK induce a large Stokes shift to reduce the signal-to-background ratio.

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to the oxygen concentration. The emitted light is detected by a photodiode (OPT101) with a long-pass color filter (CVI laser, LP-720). After further signal processing, the signal is fed to computer via a data acquisition unit.

To minimize the oxygen measurement sensitivity to ambient light, we applied an oscillating voltage to drive the LED instead of a direct current (DC) voltage. The photodiode receives an oscillating intensity with a frequency matched to the driving signal. By choosing a high oscillating frequency (on the order of kilohertz), the ambient intensity can be filtered out by a high-pass signal filter (with a cutoff frequency of 1.6 kHz). Afterward, the amplitude of the extracted oscillating signal is converted to a steady voltage by the signal conditioning circuit, which contains a rectifier, low-pass filters, and amplifiers. (The circuit diagrams for the light excitation module and the infrared detection module are available as Supporting Information.) The modified signal is fed into the serial port of a computer, where the mean signal output voltage is correlated with the oxygen concentration using a data acquisition module (DI-194RS, DataQ Instruments). The packaged oxygen sensing system is shown in Figure 1b. The overall sampling rate of the oxygen-sensing system is 240 Hz, which is sufficient given the equilibration time of DO in the embedded sensors (∼1–3 min, depending on the media flow rate).

Post-analysis of the measured data was performed using a script written in Visual C++.

**Microfluidic Oxygenator Device Fabrication.** The PDMS microfluidic oxygenator consists of an array of eight microchannels (20 µm (height) × 100 µm (width)) that provides differential DO concentrations (channel-to-channel) for cell culture. The chip has a double-layer channel structure, with the design layout illustrated in Figure 2a. The fabrication process was based on previously reported multilayer soft lithography methods. The mold with medium channel patterns was prepared by patterning two layers of 10-µm-thick positive AZ4620 photoresist (AZ Electronic Materials) on a 3-in. silicon wafer (James River Semiconductors), followed by a 1-min. reflow at 150 °C. Photolithography (12 s × 3 exposure) was performed using a high-resolution transparency mask (∼20 000 dpi). SU-8 negative photoresist was selected for the gas channel mold. A 40-µm-thick SU-8 (Microchem SU-8 50) layer was spin-coated on a 3-in. wafer and patterned by photolithography (Karl Suss Mask Aligner MJB3, 75 s exposure). Afterward, the molds were silanized with a high-molecular-weight trichloro-perfluorooctyl saline (Aldrich) for ∼5 min to facilitate PDMS mold release. The silanization process reduces the adhesion of PDMS to Si/SU-8 and Si/AZ4620 surfaces, to increase the mold lifetime.

The oxygen sensor array was prepared by wet-etching the sensor pad regions on a glass substrate, followed by deposition of a Pt0EPK film. To initiate the process, a sacrificial layer of

AZ4620 photoresist (10 µm) was spin-coated on the surface and patterned by photolithography. The exposed sensor regions were then etched with buffered hydrofluoric acid (7:1 ratio of H₂O to HF) for 15 min. After etching, the protective photoresist layer was stripped with acetone, and a droplet (~1 µL) of PtOEPK dye solution was applied using a pipet tip to each sensor region. The stock PtOEPK dye solution in the polymer matrix was prepared by mixing PtOEPK (1 mg) with polystyrene (50 mg) and toluene (950 µL). After applying the dye droplets, the solvent rapidly evaporated, leaving behind a thin film (2–4 µm) of dye-embedded polymer.

The molding and assembly of the gas and fluidic channels networks was achieved via multilayer soft lithography. A 1:10 A:B two-part PDMS compound (Silgard 184, Dow Corning) was mixed and poured onto the SU-8/silicon mold that contained a multiplexor and gas channels to a thickness of ~6 mm. The mold was subsequently degassed in a vacuum bell jar for ~10 min before it was baked in an oven for 1 h at 80 °C. For the fluid channel mold, 10:1 PDMS was spin-coated (2300 rpm, 50 s) to a thickness of ~40 µm and baked for 10 min at 80 °C. After the initial bake, both molds were removed from oven for alignment. The ~6-mm-thick PDMS gas mold replicate was released from the mold and cut to size with a razor blade. A blunt-tipped 20G surgical steel Luer stub was used to punch gas inlet and outlet holes in the PDMS. After punching, an isopropyl alcohol wash was applied to remove debris, followed by drying under a nitrogen stream. The processed thick PDMS gas layer was then aligned over the spin-coated fluid layer under a dissecting scope (Olympus, Model SZX9). To bond the two layers, the composite PDMS substrate was post-baked in an oven for >2 h at 80 °C. The devices were then cut from the flow mold and the fluid layer inlet/outlet holes were punched as previously described. The assembled PDMS was subsequently bonded to the prepared glass substrate that contained the sensor film, using oxygen plasma (Plasmof, Model SZX9). To bond the two layers, the composite PDMS substrate was post-baked in an oven for >2 h at 80 °C. The devices were then cut from the flow mold and the fluid layer inlet/outlet holes were punched as previously described. The assembled PDMS was subsequently bonded to the prepared glass substrate that contained the sensor film, using oxygen plasma (Plasmof, Tegal Corporation, 600 mTorr) for 15 s, with the composite device presented in Figure 3. Figure 3 shows the emitting signal intensity (I) in terms of output voltage as a function of time, for a panel of oxygen/nitrogen ratios ranging from nitrogenated to fully oxygenated. Typical equilibration time for the sensor is on the order of 3 min, based on the diffusivity of oxygen in the polystyrene sensor matrix. Figure 3 shows that the DO level in water has a good agreement with the Stern–Volmer relation.

Cell Seeding. 3T3 Murine Embryonic Fibroblast. The microfluidic oxygenator was sterilized by flushing fluid channels with 70% ethanol, followed by baking at 80 °C for 2 h. After baking, the fluid channels were rinsed with 1x phosphate-buffered saline (PBS), with pH 7.4, and degassed by forcing trapped air through the walls of the gas-permeable oxygenator with pressurized PBS buffer. The glass surface along flow channels was subsequently precoated with 20 mg/mL gelatin (Sigma) in 1x PBS for 1 h to promote cell attachment. Excess gelatin was removed by rinsing with 1x PBS. In preparation for device loading, the cell line was trypsinized, spun down in a centrifuge (1000 rpm, 5 min), and reconstituted in Leibovitz’s L-15 medium (Invitrogen 11415064) at a density of ~10⁶ cells/mL. To load cells into the oxygenator, a syringe pump (PicoPlus, Harvard Apparatus) was used to inject cells into each culture channel (flow rate = 0.01 µL/min, load time = 3 min), activated by an integrated microfluidic multiplexor. (Detailed protocols for culturing all cell lines, mammalian and bacteria, are available as Supporting Information.)

E. coli, A. viscosus, and F. nucleatum. The microfluidic devices were sterilized, rinsed, and degassed, following the aforementioned protocol for mammalian cells. Confluent bacteria cultures of each species (OD600 0.95) were diluted in their respective media to a cell density of ~10⁶ cells/mL. Following dilution, cells were loaded into the oxygenator at a flow rate of 0.01 µL/min for 3 min. Prior to on-chip oxygenated culture, the microfluidic devices for E. coli and A. viscosus were placed in a 37 °C aerobic incubator for 2 h to promote adhesion between the bacteria

$$\frac{I_0}{I} = 1 + K_{SV}P_{O_2}$$

(1)

where I is the emitting fluorescence intensity, I₀ the intensity in a deoxygenated state, and K_SV is the Stern–Volmer constant. The Stern–Volmer constant and the deoxygenated state intensity of PtOEPK are unique for each sensor, because of the
and glass microchannel wall, while the devices for F. nucleatum were anaerobically cultured by flowing pure nitrogen through the gas-layer microchannel network.

**RESULTS AND DISCUSSION**

**Design of Oxygen Gradient Generator.** The gas layer in microfluidic oxygenator is composed of microchannels with a constant height (40 μm) and variable width (ranging from 20 μm to 2 mm), and a summary of the calculated equivalent resistances is listed in Table 1. Different oxygen levels are generated by continuously flowing gases with constant input pressure. With corresponding scaled Reynolds numbers ($Re^*$) in the range of $10^{-3}$-$10^{-1}$, viscous effect dominates over the inertial one; and the fluidic resistance $R$ of an individual microchannel can be estimated as a rectangular channel, given by

$$\frac{1}{R} = \frac{WH^3}{12\mu L} \left[1 - 192H \sum_{n=0}^{\infty} \frac{\tanh[(2n + 1)\pi W/(2H)]}{(2n + 1)^5}\right]$$

where $\mu$ is the fluid viscosity, $L$ the channel length, $W$ the channel width, and $H$ the channel height. The value of $\mu$ is dependent on the ratio of oxygen and nitrogen along an individual channel, and it is approximated as

$$\mu \approx \left(\frac{C_{O_2}}{\mu_{O_2}} + \frac{C_{N_2}}{\mu_{N_2}}\right)$$

where $C_{O_2}$ and $C_{N_2}$ are the volumetric concentrations of oxygen and nitrogen, respectively; $\mu_{O_2}$ and $\mu_{N_2}$ are the respective viscosities of oxygen and nitrogen.

Modeling each individual channel as the fluid equivalent of an electrical resistor, the gas-layer network is simplified to an equivalent circuit, as illustrated in Figure 4. In the circuit model, the electrical voltage represents the gas pressure while the current represents the gas flow rate. The gas supplies were regulated to the same gauge pressure. By adjusting the effective fluidic resistance of each individual channel, a gradient generator requiring low input gas pressures (i.e., $P_1 = P_2 = 1$ kPa) can be achieved. The resistances of folded channels ($R_n$) are set to be much larger than the common resistance of interconnecting channels ($R_l$), such that a linear distribution of oxygen concentrations at the respective series of microchannel outlets can be obtained by adjusting only the $R_l$ values.

Using the assumption that nitrogen and oxygen are fully mixed in every folded microchannel, the volumetric ratios of oxygen along the outlet channels can be estimated. The validity of such assumption is supported by the low scaled Peclet number in the gas microchannels (i.e., $Pe^* \ll 1$), with diffusion dominating over convective fluxes. For a folded channel that has two inlets with different flow rates and oxygen concentrations, the corresponding oxygen concentration $C$ after mixing can be estimated based on the conservation of mass:

$$C = \frac{Q_1 C_1 + Q_2 C_2}{Q_1 + Q_2}$$

where $Q_1$ and $Q_2$ are the flow rates of the channel inlets, which are resolved by the circuit model; and $C_1$ and $C_2$ are the corresponding oxygen concentrations.

The oxygen ratios along outlet channels ($C_{out1}$-$C_{out8}$ in Figure 4) were calculated as 0%, 14.2%, 28.49%, 42.82%, 57.18%, 71.53%, 85.81%, and 100%, respectively. This result has also been validated by computational software, as described in the Supporting Information. This implies a homogeneous discrete oxygen gradient can be achieved by mixing $N_2$ and $O_2$ with the proposed gradient generator, which is equivalent to the approach described in ref 24.

**Generation of DO Concentrations.** The distribution of DO concentrations along cell culture channels under continuous flow was investigated experimentally. In each measurement, the multiplexor valve array was used to open a single medium channel...
with steady flow rate controlled by a syringe pump (PicoPlus, Harvard Apparatus). The culture channels are located at the middle sections in the diffusion region, as shown in Figure 2a. The scaled Peclet number along the culture channels is \(<0.03\) (see Table 1). Consequently, the medium DO level will be fully diffused within \(\sim 100\ \mu\text{m}\), and, therefore, the cell culture and sensor regions will have steady oxygenation conditions. With sensors located outside the culture region, the DO sensing mechanism can obtain the simultaneous \(p_{\text{O}_2}\) monitoring and cell density analysis. The experimental results (Figure 5) show that the oxygenator can generate different DO levels along channels, which correlate with the oxygen concentrations from the gradient generator mentioned in the previous section. In addition, repeatable results were obtained with a low variation \((R^2 > 0.99)\) between separate runs.

**Mammalian Cell Culture.** To study the effect of DO concentration on mammalian cell culture, the oxygenator chip was used for parallel culture of BALB murine embryonic fibroblast cells (3T3). Cells were first seeded into culture channels and precultured in an incubator (~21% \(O_2\) and 5% \(CO_2\) gas supply) for one day to allow cell spreading and attachment to the treated glass surface. During on-chip cell culture, oxygen and nitrogen (supply pressure \(\approx 1\ \text{kPa}\) ), humidified by bubbling through water reservoirs, were flowed through the gradient generator to generate different DO levels in the underlying medium-filled channels (0–42 ppm). A syringe pump (Harvard Apparatus) was used to supply fresh medium continually (flow rate = 0.003 \(\mu\text{L/min}\) ) to each fluid channel in turn, switching channels every minute under the control of an integrated microfluidic multiplexor. This operation provides a consistent medium supply along every channel, even when there were inconsistencies in the channel cross sections and fluidic resistances developed by different cell growth rates. After 4 h, the effect of DO on 3T3 cell growth in the culture region could be observed (see Figure 6). The cells exhibited good viability and proliferation at a DO concentration of 12 ppm (Figure 6b). Under low \(p_{\text{O}_2}\) (~6 ppm), 3T3 cells shrank and started detaching from the channel wall (Figure 6a), while in high \(p_{\text{O}_2}\) (>36 ppm),
cell necrosis was observed (Figure 6d). A comparative traditional culture experiment of 3T3 cells in flasks incubated at 37 °C under pure nitrogen, 21% O2 and 100% O2 yielded morphological results consistent with that of the microfluidic oxygenator, in which 3T3 cells grown under nitrogen detached, while pure O2 resulted in necrosis. (Micrographs of traditional cell culture under variable oxygenation levels are provided as Supporting Information).

**Bacteria Cell Culture.** Culture Experiments were also performed with the facultative anaerobe *E. coli*, the aerobe *A. viscosus*, and the obligate anaerobe *F. nucleatum*. Fresh medium was supplied with the same protocol as the mammalian cell culture. To estimate the cell density of bacteria over different culture durations, phase-contrast microscopy images of the culture channel were obtained and compared to control images in which the cell densities (10⁶–10⁸/mL) were measured by a hemocytometer. In the culture region, bacterial communities, which were darker in microscopic images, were extracted by thresholding on image intensity. Results (Figure 7) show that *E. coli* (Figure 7a) cells grew under both aerobic and anaerobic conditions, with the shortest doubling time (T_d = 1.9 h) under ambient condition (pO2 ≈ 12 ppm). *A. viscosus* (Figure 7b) grew only under aerobic conditions, with the shortest doubling time (T_d = 14.1 h) at pO2 ≈ 18 ppm. *F. nucleatum* (Figure 7c) exhibited maximum growth under anaerobic conditions (T_d = 9.67 h), with some growth observed up to pO2 ≈ 12 ppm.

**CONCLUSION**

In this manuscript, the application of a microfluidic differential oxygenator system to the culture of mammalian cells and bacteria with different oxygen demands has been described. Integrating the multiplexor, oxygen–nitrogen gas mixer, and double-layer diffusion channels, the oxygenator generates a step function of repeatable DO concentrations in an array of parallel microchannels containing aqueous media. Integrated polymeric oxygen sensors provide a robust method for real-time monitoring of the DO levels in culture media within the microchannels. To validate its potential for the culture of both eukaryotic and prokaryotic cells, on-chip growth profiles of a model mammalian cell line (3T3), as well as anaerobic and aerobic bacteria, were demonstrated. The culture experiments showed differential cellular growth response verses DO concentrations. Microfluidic oxygenator chips, representing a robust and low-cost method to regulate DO levels in culture, are anticipated to be of wide appeal not only to cancer researchers, but also to public health laboratories for bacteria that are difficult to culture using established microbiology protocols.

**SUPPORTING INFORMATION AVAILABLE**

Information regarding the circuit design of oxygen sensing system, the cell culture, the cell extraction of *Actinomyces viscosus*, the simulation of oxygen gradient generation, and bulk culture of murine embryonic fibroblast cells under different oxygen conditions, including referenced literature. This material is available free of charge via the Internet at http://pubs.acs.org.

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