High-Throughput Methods for Culturing Microorganisms in Very-Low-Nutrient Media Yield Diverse New Marine Isolates

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Microbial diversity studies based on the cloning and sequencing of DNA from nature support the conclusion that only a fraction of the microbial diversity is currently represented in culture collections. Out of over 40 known prokaryotic phyla, only half have cultured representatives. In an effort to culture the uncultured phytypes from oligotrophic marine ecosystems, we developed high-throughput culturing procedures that utilize the concept of extinction culturing to isolate cultures in small volumes of low-nutrient media. In these experiments, marine bacteria were isolated and cultivated at in situ substrate concentrations—typically 3 orders of magnitude less than common laboratory media. Microtiter plates and a newly developed procedure for making cell arrays were employed to raise the throughput rate and lower detection sensitivity, permitting cell enumeration from 200-μl aliquots of cultures with densities as low as 10³ cells/ml. Approximately 2,500 extinction cultures from 11 separate samplings of marine bacterioplankton were screened over the course of 3 years. Up to 14% of the cells collected from coastal seawater were cultured by this method, which was 14- to 1,400-fold higher than the numbers obtained by traditional microbiological culturing techniques. Among the microorganisms cultured were four unique cell lineages that belong to previously uncultured or undescribed marine Proteobacteria clades known from environmental gene cloning studies. These cultures are related to the clades SAR11 (α subclass), OM43 (β subclass), SAR92 (γ subclass), and OM60/OM241 (γ subclass). This method proved successful for the cultivation of previously uncultured marine bacterioplankton that have consistently been found in marine clone libraries.

The term “the great plate count anomaly” was coined by Staley and Konopka in 1985 (31) to describe the difference in orders of magnitude between the numbers of cells from natural environments that form colonies on agar media and the numbers countable by microscopic examination (18). Marine ecosystems are a well-studied example of this phenomenon: only 0.01 to 0.1% of oceanic marine bacterial cells produce colonies by standard plating techniques (19). There are numerous explanations for this anomaly. For example, species that would otherwise be “culturable” may fail to grow because their growth state in nature, such as dormancy, prevents adjustment to conditions found in the medium used for the plate counts (13). This hypothesis does not explain the substantial discrepancy between 16S rRNA genes recovered from seawater directly by cloning and those of the readily cultured marine taxa (22, 34). Another explanation for the “great plate count anomaly” is that many of the microbial species that dominate in natural settings are not adapted for growth in media containing high concentrations of complex organic carbon. Many microorganisms may need oligotrophic or other fastidious conditions to be successfully cultured. There are many examples of microbial strains that are common in nature, but can only be cultivated by specialized techniques (3, 7, 9, 12, 15, 20, 25, 26, 29, 30, 37, 40).

Button and colleagues pioneered an approach that has been successful in isolating novel oligotrophic, heterotrophic cells from marine ecosystems (10). This method uses unamended environmental water as the medium and is often referred to as “extinction culturing” to distinguish it from dilution culturing, which also uses natural water, but involves complex microbial communities (1, 11, 23). Their approach was to dilute natural communities of microorganisms to a known number, ranging from 1 to 10 cells per tube, and then examine these potential cultures for microbial growth by flow cytometry, which is effective for counting very dilute populations of cells. By this method, bacterioplankton culturability from 2 to 60% was reported for marine waters around Alaska and The Netherlands (10). This work resulted in the description of two new oligotrophic bacterioplankton, *Sphingomonas alaskensis* and “Cyclcoclastus oligotrophus” (9, 29, 37, 39). However, this extinction culturing method is relatively laborious. The isolates that have been obtained by this method are of considerable scientific interest, but they are few in number.

The goal of this study was to develop high-throughput culturing (HTC) methods that would enable a large number of extinction cultures to be identified so that the efficacy of this approach could be assessed with a larger sampling of isolates. Over the course of 3 years and 11 separate samplings of marine bacterioplankton, 2,484 extinction wells were examined for growth. The results indicate that these newly developed HTC techniques yield isolates of many novel microbial strains, including members of previously uncultured groups that are believed to be abundant in coastal seawater.

MATERIALS AND METHODS

HTC technique. A series of protocols and techniques were developed to allow the efficient screening of a large number of extinction culture attempts for growth

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Direct count of the inoculum by fluorescence microscopy

\[
\text{Dilute inoculum into prepared medium at 1-5 cells per ml and fill 48-well microtiter plate with 1 ml per well}
\]

\[
\text{Incubate under the desired time and conditions}
\]

\[
\text{Screen for positive growth by fluorescence microscopy}
\]

\[
\text{Array 200\mu l aliquots onto a 48 sector filter manifold, stain and transfer to a microscope slide}
\]

\[
\text{Identify cultures by PCR, RFLP and sequencing}
\]

\[
\text{Transfer to fresh medium}
\]

\[
\text{Store cultures with DMSO and/or glycerol in liquid N2}
\]

FIG. 1. Flow chart of HTC procedures. DMSO, dimethyl sulfoxide.

and subsequent identification (Fig. 1). Slight variations of the method were performed during the development of these HTC techniques over the course of 3 years, but the overall approach remained constant. Microtiter plates were used to culture cells, and cell arrays were made to allow efficient screening of the plates for growth. The cultures acquired were designated with HTC collection (HTCC) numbers.

Preparation of media. Water for media was collected on the south side of the southern jetty in Newport, Oreg., at high tide with a bucket on 19 March 1998 8 km (44°39.1N, 124°10.6W) offshore from the mouth of Yaquina Bay, Oreg., with a Niskin bottle deployed at 5 m on 7 June 2000. On the day water was collected, it was filtered through a 0.2-μm-pore-diameter Supor membrane and immediately autoclaved. In order to restore the bicarbonate buffer lost during autoclaving, the seawater was sparged with sterile CO2 for at least 6 h, followed by sterile air for at least 12 h. Acid-washed polycarbonate containers were used for media and live samples whenever possible. Dissolved organic carbon concentrations of the seawater media were 107.1 μM (standard deviation [SD], 1.1) for the 19 March 1998 collection, determined with a Shimadzu TOC-5000A (Shimadzu Co., Kyoto, Japan). Before each use, the liquid media were checked for sterility by directly counting cells stained with 4',6-diamidino-2-phenylindole (DAPI) as described by Turley (36), except that 1% formaldehyde was used.

Inoculum collection, dilution, and incubation. Water samples for inocula were collected on the south side of the southern jetty in Newport, Oreg., at high tide with a bucket and at 8 km (44°39.1N, 124°10.6W) and 25 km (44°39.1N, 124°24.7W) offshore from the mouth of Yaquina Bay, Oreg., with a Niskin bottle deployed at 5 m. The water was held in darkness at ambient sea surface temperatures until the processing of samples began, within 1 to 4 h after collection from the jetty and within 9 h after collection off the boat to avoid bottle effects (14). To determine the bacterioplankton cell densities of the inocula, direct cell counts were done by DAPI staining, where at least 300 cells were counted per filter to be representative. To determine viable cell counts (i.e., culturability) by traditional methods, inocula of 50 or 100 μl of seawater were applied to spread plates of MA2216 (Difco Laboratories, Detroit, Mich.), Marine R2A (R2A) (34), and a 1/10 dilution of Marine R2A (1/10R2A). Inoculum samples were diluted into the prepared seawater medium and distributed as 1-ml aliquots into 48-well non-tissue-culture treated PolyStyrene plates (Becton Dickinson, Franklin Lakes, N.J.) to a final average inoculum ranging from 1.1 to 5.0 cells per well. At least one control plate was made for each sample collection by distribution of 1-ml aliquots of uninoculated medium. The 48-well plates and agar plates were incubated in the dark at 16°C. The extinction cultures were incubated for 3 weeks, and the agar cultures were incubated until colonies were large enough to count, about 1 week for MA2216 and up to 8 weeks for 1/10R2A.

Detection of growth by using cell arrays. A cell array was made from each 48-well plate to examine wells for growth. Two hundred microliters from each well in the plate was filtered into the corresponding chamber of a 48-array filter manifold of custom design manufactured by HyTek Plastics, Corvallis, Oreg. Cells were then DAPI stained and vacuum filtered onto a 48-by-60-mm 0.2-μm-pore-diameter white polycarbonate membrane (cut from 8-by-10-in. sheets; Whatman Nuclepore, Newton, Mass.). The membrane was laid on an oilied 75-by-50-mm slide (Corning Glass Works, Corning, N.Y.) and covered with a 48-by-60-mm coverslip (Erie Scientific, Portsmouth, N.H.). The diameter of each sector of the array was 2 mm, which enabled the detection of a culture with a cell titer as low as 1.3 × 10³ cells/ml when 200 μl of sample was filtered. The array was then scored for growth by fluorescence microscopy. Cell titer was estimated by counting five random fields within each positive sector.

Culturability statistics. Percent culturability was determined by the equation for estimation of culturability, \( V = -\ln(1-p)/X \), and the theoretical number of pure cultures was estimated by the equation \( n = n p(1-p)\ln(1-p)\ ) described by Button and colleagues (10), where \( n \) is an estimate of the expected number of pure cultures, \( n \) is the number of inoculated wells, \( V \) is estimated culturability, \( p \) is the proportion of wells positive for growth (wells positive for growth/total inoculated wells), and \( X \) is the initial inoculum of cells added per well. To calculate the error, first, the exact lower and upper 95% confidence limits for the binomial proportion (p) were determined by using the SAS package version 6.12 (SAS Institute Inc.). Next, these exact limits were inserted into the culturability equation and pure culture equation in place of the term \( p \) to give the exact lower and upper 95% confidence limits for percent culturability and the theoretical number of pure cultures.

RFLP analysis and sequencing of HTCC isolates. A subset of 56 HTCC isolates were identified by restriction fragment length polymorphism (RFLP) and rRNA gene sequencing methods. One hundred or 200 μl of culture was put through two cycles of freezing and thawing to promote cell lysis and concentrated in a 10,000-molecular-weight Vivaspin concentrator (Vivasience, Stonehouse, United Kingdom). Some samples were also treated with 150 μl of GES lysis buffer (5 M guanidine thiocyanate, 100 mM EDTA, 0.5% Sarkosyl) while in the concentrator. The lysates were then rinsed three times with 200 μl of Ultrapure water (Speciality Media, Phillipsburg, N.J.) to remove medium salts and lysis buffer. The final volumes of the concentrated samples ranged from 10 to 30 μl. Two to three negative controls (the same procedure with no added culture) were run with each set of concentrated samples. 16S rRNA genes were amplified by nested PCR. Two to 5 μl of each concentrated sample was added to the first PCR, which had a 20-μl reaction volume, and 2 to 5 μl of the first PCR was added to the second PCR, which had a 100-μl reaction volume. Twenty-five to 33 cycles were used for each PCR, for a total of 50 to 66 cycles of amplification. The PCR cocktail for both reactions contained 0.025 U of Taq per μl (Promega, Madison, Wis., or MBI Fermentas, Hanover, Md.), 5% acetamide, 1.5 mM MgCl₂, 200 nM each primer, 220 μM deoxynucleoside triphosphates (dNTP), and 1× PCR buffer (Promega or MBI Fermentas). The PCR cocktail was treated with UV irradiation to reduce the contamination levels present in the reagents (6, 24). The length of UV treatment needed was empirically determined by amplifying a set of negative and positive controls. The amplification conditions for both PCR reactions were 94°C denaturation for 30 s, 50 to 55°C (depending on primers used) annealing for 1 min, and 72°C extension for 2 min. The second PCR primer set had at least one primer that amplified from a position internal to the set of primers used in the first PCR. The primers used were 8F (5′-AGG GTT TGA TCT CCM CCG CGC-3′), 1492R (5′-GCT GGC CTA TAC GGG AGC ACC-3′), 1395R (5′-GCG GGC TCC TGT TCA GGG TTG-3′), 1522R (5′-GTC TAC TAC CTT GTT AGC ACT T-3′), and 1542R (5′-AAG GAG GTG ATC CAN CCR CA-3′), which are variations of commonly used primers that target bacteria or prokaryotes (21). The nested set of primers most frequently used was made up of 519F/1492R and 519F/1395R, but other variations of the listed primers were also used. Three negative controls and

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positive controls with \(10^6, 2 \times 10^6, 200, \) and 20 copies of the 16S rRNA gene from the clone SAR242 were run in each PCR set. All primers used have no mismatches to the SAR242 sequence, except for 1492R, which does not match the first and third bases on the 5’ end (nonpriming end). The concentration of the positive control DNA was measured in a Shimadzu UV160U spectrophotometer (Shimadzu Co., Kyoto, Japan). The 20-copy-positive control could be routinely amplified with a total of 50 to 60 cycles of nested PCR.

RFLP of the PCR product was done with the restriction enzymes MboI and HaeIII (MBI Fermentas) (38). HTCC isolates were determined to be a mix of more than one species if RFLP bands from each digest added up to two or more times the length of the expected PCR product. The cultures with fragments that added up to the expected PCR product length were grouped based on matching RFLP patterns, and at least one culture from each RFLP group was sequenced and phylogenetically analyzed.

Before sequencing, the PCR products were purified with the Qiagen PCR purification kit (Qiagen, Valencia, Calif.). The concentration of the purified product was measured in a Shimadzu UV160U spectrophotometer (Shimadzu Co., Kyoto, Japan). The purified PCR product was then sequenced by an ABI 373A or 377 automated sequencer (Applied Biosystems, Foster City, Calif.).

**Phylogenetic analysis.** HTCC sequences were aligned and masked in ARB (32). Phylogenetic analyses were performed with ARB and PAUP* (35). Phylogenetic trees were inferred by neighbor joining with the Jukes and Cantor model to estimate evolutionary distances. Bootstrap values were obtained in PAUP* from a consensus of 1,000 neighbor-joining trees. Short sequences of HTCC to estimate evolutionary distances. Bootstrap values were obtained in PAUP* (32). Phylogenetic analyses were performed with ARB and PAUP*

**Detection of growth and cell densities.** The probability of recovering a single inoculated cell in each well was tested using positive controls with \(10^6, 2 \times 10^6, 200, \) and 20 copies of the 16S rRNA gene from the clone SAR242. Culturability was measured by spotting MA2216 and R2A agar plates with the cell suspension. The average culturability for the six sample locations was 0.4 to 14.3% was calculated for the different sample collections (Table 1). The average culturability for the six sample collections collected between late May and mid-July was 8.8%, and the average culturability for the five samples collected between early October and early April was 1.2%. Comparisons of culturability were made between the HTC method and traditional plating on nutrient-rich agar media; the culturability ranged from 1.4 to 120 times higher by HTC methods (Table 1). In addition, MA2216 and R2A agar plates were spotted with the first 143 cultures grown from water collected during the summer of 1998 to determine if they had the ability to grow on these media. Only three grew on MA2216, and a fourth grew on R2A; none of these four cultures grew on both agar media (data not shown).

**Detection of growth and cell densities.** The cell densities of the HTC cultures ranged from \(1.3 \times 10^6\) to \(1.6 \times 10^6\) cells per ml.

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**RESULTS**

**HTC.** Our general approach to HTC is outlined (Fig. 1). This method, which allows a large number of culture attempts to be efficiently screened for growth and identified, was successful in bringing four major uncultured or undescribed groups of bacterioplankton into culture. These four groups include SAR11 (\(\alpha\) subclass) (16), OM43 (\(\beta\) subclass) (27), SAR92 (\(\gamma\) subclass) (8), and OM60/OM241 (\(\gamma\) subclass) (27).

**Culturability statistics.** Two hundred fifty-three extinction culture wells were scored positive for growth out of 2,484 wells screened for 3 years and 11 sample collections. A culturability range of 0.4 to 14.3% was calculated for the different sample collections (Table 1). The average culturability for the six sample collections collected between late May and mid-July was 8.8%, and the average culturability for the five samples collected between early October and early April was 1.2%. Comparisons of culturability were made between the HTC method and traditional plating on nutrient-rich agar media; the culturability ranged from 1.4 to 120 times higher by HTC methods (Table 1). In addition, MA2216 and R2A agar plates were spotted with the first 143 cultures grown from water collected during the summer of 1998 to determine if they had the ability to grow on these media. Only three grew on MA2216, and a fourth grew on R2A; none of these four cultures grew on both agar media (data not shown).

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ml, with a mean of $1.1 \times 10^5$ cells per ml and a median of $3.0 \times 10^3$ cells per ml. The minimum density for a culture to be detectable was $1.3 \times 10^3$ cells per ml. This range of cell densities is the result of as few as 10.0 to as many as 23.3 doublings during the 3-week incubation period, assuming only one cell emerges as a result of seasonal variation in bacterioplankton abundance. Forty-seven of the 56 cultures were identified; of the 9 cultures that were not identified, 7 were found to be unknown mixtures of several cell types based on RFLP analysis, and 2 did not amplify under the conditions used.

Imaging of the DAPI-stained isolates revealed unicellular organisms that were generally of small size. The SAR11 clade isolate HTCC150 was a small, curved rod (ca. 1 to 0.8 μm by 0.3 to 0.2 μm). The OM43 clade isolates HTCC163 and HTCC175 were short rods (ca. 0.8 to 0.5 μm by 0.5 μm). The SAR92 clade isolates HTCC148, HTCC151, and HTCC154 were short rods (ca. 1 to 0.7 μm by 0.7 to 0.5 μm). OM60/OM241 clade isolate HTCC160 was an irregularly shaped coccus that occasionally formed doublets and more rarely chains of three (ca. 0.7 by 0.7 μm). These measurements are subject to sizeable error, since these small cells are at or approach the resolution of visible light microscopes. The cells have been stained with a DNA staining dye and have been fixed with formaldehyde. The images shown are from the original extinction dilutions that yielded the four previously uncultured and undescribed groups (Fig. 2).

**Phylogenetic analysis and culture identification.** Uncultured or undescribed groups SAR11, OM43, SAR92, and OM60/OM241 accounted for the majority of cultures that were identified out of a subset of 56 cultures (Table 3). All cultured cells from 13 48-well plates (56 cultures) were chosen to represent 5 different sampling months to minimize biases that might emerge as a result of seasonal variation in bacterioplankton abundance. Forty-seven of the 56 cultures were identified; of the 9 cultures that were not identified, 7 were found to be unknown mixtures of several cell types based on RFLP analysis, and 2 did not amplify under the conditions used. There were a total of eight mixed cultures; HTCC149 was found to be a mix of cells from the SAR11 clade and unknown cells. The failure of two cultures to amplify is probably attributable to problems with the DNA extractions and/or low cell densities in the cultures. A considerable effort was made to ensure that these lineages did not fail to amplify because of mismatches to amplification primers. The theoretical statistical estimation for the number of pure cultures versus mixed cultures that should be acquired was consistent with the RFLP analysis (Table 3).

Of the 47 identified cultures, 4 were α-Proteobacteria (Fig. 3C). Two belonged to the SAR11 clade, and one each was from the genus *Maricoccus* and the *Roseobacter* clade. Eighteen isolates were identified as β-Proteobacteria (Fig. 3A). These included members of two clades, 16 isolates from the OM43 clade, and two related to the genus *Variovorax*. Nineteen cultures were γ-Proteobacteria (Fig. 3B). These included three subgroups: the SAR92 clade (15 isolates), the OM60/OM241 clade (3 isolates), and one group from the genus *Pseudomonas*. Six isolates were members of the phylum *Bacteroidetes*.

The 16S rRNA sequence for the SAR92 clone (M63811) was

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**TABLE 3. Phylogenetic identification and pure culture statistics for 56 cultures**

<table>
<thead>
<tr>
<th>Inoculation date (mo-day-yr)</th>
<th>No. of wells screened</th>
<th>No. of cultures detected</th>
<th>Theoretical no. of pure cultures</th>
<th>No. with culture identification</th>
<th>Mixed culture</th>
<th>Not identified</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SAR11</td>
<td>OM43</td>
<td>SAR92</td>
</tr>
<tr>
<td>5-21-98</td>
<td>96</td>
<td>7</td>
<td>6.7 (2.8, 12.8)</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>6-17-98</td>
<td>96</td>
<td>11</td>
<td>10.3 (5.5, 16.8)</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>10-29-99</td>
<td>96</td>
<td>10</td>
<td>9.5 (4.8, 15.9)</td>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1-26-00</td>
<td>192</td>
<td>11</td>
<td>10.7 (5.5, 18.2)</td>
<td>7</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>7-12-00</td>
<td>144</td>
<td>17</td>
<td>16.0 (9.8, 23.7)</td>
<td>3</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>624</td>
<td>56</td>
<td>53.4 (41.2, 67.4)</td>
<td>2</td>
<td>16</td>
<td>15</td>
</tr>
</tbody>
</table>

*a* Statistical estimation of the theoretical number of pure cultures acquired with 95% confidence interval. The total 53.4 was determined independently with 624 wells and 56 cultures in the pure culture equation.

*b* One SAR11 culture was mixed with an unknown cell type (RFLP analysis) and is also included under the heading “Mixed culture.”

*c* “Other” indicates cultures that fall into previously cultured groups.
found to be a chimera. From sequence positions 1 to 944, SAR92 is a member of the \(\gamma\)-Proteobacteria; from positions 1120 to 1354, it is a member of the \(\alpha\)-Proteobacteria. The identity of the sequence from 945 to 1119 is ambiguous. The \(\gamma\) portion of the SAR92 clone sequence represents a previously uncultured phylogenetic clade, we have termed the SAR92 clade.

Percent similarities of the sequenced HTCC cultures from the four previously uncultured or undescribed phylogenetic clades were determined, in which several of the sequences were close matches to clones in GenBank (Table 4) (2, 5, 33). Sequences of oligotrophic isolates from the OM43 and OM60/OM241 clades were recently deposited into GenBank as strain POCPN-5 (AB022337) and KI89C (AB022713), respectively, by N. Katanozaka and I. Yoshinaga (unpublished data). HTCC isolates from the four distinct phylogenetic clades SAR11, OM43, SAR92, and OM60/OM241 are more similar to cloned sequences from these clades than to those from previously cultured species, with the exception of HTCC168, which is 99.8% similar to the isolate POCPN-5.

### DISCUSSION

**Culturability statistics and detection of growth.** The goal of this study was to evaluate a culturing format for the high-throughput isolation of uncultured strains of bacterioplankton that are commonly found in gene clone libraries from marine environments. The use of microtiter dishes and a novel technique for making cell arrays enabled us to achieve a higher throughput rate, shorten incubation times, and raise sensitivity for the detection of cells with low growth rates relative to those in previous studies that employed the concept of extinction culturing in natural media.

The percentage of cells that could be cultured by the HTC approach was several orders of magnitude higher than that obtained by culturing on agar plates. Ferguson and colleagues found that the percentage of microbial cells in seawater that could be cultured on a rich nutrient agar medium (MA2216) increased from \(<0.1\%\) to \(13\%\) after 16 h and to \(41\%\) after 32 h of confinement in a 4-liter bottle at ambient sample collection temperature (14). Our results cannot easily be explained by this “bottle effect,” because (i) the cells were diluted into the 48-well plates between 1 and 4 h after collection from the jetty and within 9 h after collection from the boat; (ii) readily culturable genera, such as *Pseudomonas* and *Vibrio*, were rarely detected in our cultures; and (iii) four previously undescribed lineages were grown by our culture method.

Culturability was observed to be higher in the summer months (8.8%) than in the winter months (1.2%). There are at least two plausible explanations for this observation. First, bacterioplankton cells may be in a dormant state during the winter and either fail to grow or need longer incubation times for growth to be detected. Alternatively, the predominant strains or species of cells present in the winter could be organisms that are unable to grow under the laboratory conditions we provided, which were more similar to summer environmental conditions. The seawater medium used for these experiments was collected during the spring and summer months, and our incubation temperature of 16°C is closer to the summer temperature range of 10.0 to 14.7°C versus the winter range of 9.5 to 10.7°C for the 11 samples collected. Also, the summer months off the coast of Oregon are dominated by upwelling events that bring cool nutrient-rich water to the surface, which subsequently induces large algal blooms. During the winter, the water off the coast is diluted by the Columbia River water plume, mixed by frequent storm events, and not subject to algal blooms. The bacterioplankton that predominate during the summer may be better adapted to the higher nutrient levels and/or nutrient types provided and therefore more amenable to cultivation by the methods we used.

Based on RFLP analysis, the majority of the cultures identified were pure cultures. Theoretical estimates of the number of pure cultures expected were consistent with the number and proportion of pure cultures observed by RFLP analysis; 8 of 54 cultures studied in this manner were mixed cultures. This would indicate that most cultures were the result of only one of the inoculated cells growing in the well. However, RFLP analysis would miss mixed cultures with differential cell lysis or where the primers used for PCR amplification fail to amplify all cell types in a culture. In addition, a dominant cell type may preferentially amplify and thus appears as a pure culture in an RFLP analysis.

**Phylogenetic analysis and culture identification.** Phylogenetic identification of the isolates provided striking evidence that extinction culturing in microtiter dishes, with natural seawater and low thresholds of detection, results in the cultivation of microbial groups that appear in environmental clone libraries, but have not been previously detected in culture. The SAR11 and SAR92 clades, which were isolated in this study (transiently, in the case of SAR11) have previously been detected only by environmental rRNA gene cloning. rRNA gene sequences from isolates of other previously uncultivated clades, OM43 and OM60/OM241 (strains POCPN-5 and KI89C, respectively), were recently deposited in GenBank by other investigators.

Some of the isolates that were cultured belong to phylogenetic clades that are highly abundant in marine clone libraries. Clones in the SAR11 clade are abundant in clone libraries made from surface marine waters around the world (17). The
OM43 clade is a sister clade to a group of marine methylotrophs that includes *Methylophilus* and *Methylobacillus* and is commonly found in clone libraries from coastal sites, but not the open ocean (28). *Methylophilus* and *Methylobacillus* are classified as type I methylotrophs, which use the ribulose monophosphate (RuMP) pathway for carbon assimilation. The OM60/OM241 clades are frequently found in coastal marine clone libraries, and the SAR92 clade is found in open ocean as well as coastal clone libraries. In subsequent work (unpublished results), several strains obtained by these procedures were scaled up to 20-liter volumes for further study.

Several other major uncultured groups that are thought to be abundant in surface seawater, such as the SAR86 and SAR116 clusters, did not appear among the HTCC isolates. Further innovations in the HTCC approach will be needed to close the gap between culture collections and the microbial species dominating marine bacterioplankton communities. The approach we describe can be used to target specific bacterial groups for cultivation by screening cultures for the particular species dominating marine bacterioplankton communities. This approach can be used to target specific bacterial groups for cultivation by screening cultures for the particular species dominating marine bacterioplankton communities.

**ACKNOWLEDGMENTS**

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