



Growth and survival of coral transplants with and without electrochemical deposition of CaCO_3

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Abstract

This study aims to investigate experimentally the effect of electrochemical deposition of CaCO_3 on linear and girth growth, survival and skeletal structure of *Porites cylindrica* Dana. Transplanted coral nubbins were subjected to up to 18 V and 4.16 A of direct current underwater to induce the precipitation of dissolved minerals. Naturally growing colonies showed a significant increase in percentage longitudinal growth over the treated and untreated corals. Survival followed a similar trend as the growth rate. Lowest survival rates were found in the untreated nubbins. Phenotypic alterations were observed in the treated nubbins where the basal corallites decreased in size with a concomitant increase in their number per unit area. This was probably due to increased mineral concentration (such as Ca^{2+} , Na^- , Mg^{2+} , CO_3^{2-} , Cl^- , OH^- and HCO_3^-) at the basal region of the nubbins. These alterations were accompanied by a significant increase in girth growth rates of the treated nubbins at their basal regions. The abundance of mineral ions at the basal region thus appeared to be utilized by the numerous small polyps for a lateral increase in size of the nubbins instead of a longitudinal increase. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: CaCO_3 ; Coral growth; Coral transplants; Electrochemical deposition; Mineral accretion technique

1. Introduction

Present-day coral reefs are facing rapid degradation due to both natural and anthropogenic factors. Efforts to rehabilitate or restore the ecological functions of coral reefs vary from the expensive deployment of artificial structures (Edwards and Clark, 1992; Clark and Edwards, 1994, 1995) to simple coral culturing activities (Franklin et al., 1998; Lindahl, 1998; Yap et al., 1998) depending upon the spatial scale. Most of these efforts

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involve reattachment of the fragments dislodged due to physical disturbances such as storms, ship groundings, blast fishing, or anchor damage in the hope that the system will be able to recover its natural state and function. Coral transplantation serves as a catalyst for recovery by increasing the live coral cover and topographic complexity on a reef. Other activities involve using sexual reproduction and larval recruitment to initiate recovery (Morse and Morse, 1996; Oren and Benayahu, 1997). This latter strategy takes time since it entails settling, metamorphosis and growth of the juvenile corals before they could contribute significantly to an increase in reef cover.

An important objective of reef rehabilitation is to ensure the survival of the donor coral (from which transplants are obtained) and attain a growth rate similar to that prior to the breakage event. A unique technology developed by a German architect named Wolfe H. Hilbertz in 1977 involves precipitation of ionic calcium and magnesium in seawater to form a carbonate substrate under the presence of low direct current underwater (Hilbertz, 1992). This substrate may serve as a natural platform for the transplanted corals and subsequent colonization of marine larvae.

The three hypotheses concerning growth enhancement mechanisms suggested by Hilbertz and Goreau (1996) are not fully explored experimentally. The first hypothesis is that the electric field that enables accretion may cause the precipitated carbonates to attach directly to the skeletons of coral transplants. The second is that the method induces CaCO_3 enrichment of water in the immediate vicinity of the coral, thereby enhancing natural calcification. The third one is that excess production and release of electrons due to the electrochemical processes occurring within the vicinity of the coral might affect the electron-transport chain for ATP production where the excess energy could be used for growth enhancement.

The mineral accretion technique has the potential to meet an important objective of coral reef rehabilitation. If the method enables growth enhancement, then the time required for a degraded habitat to recover may be reduced, because the coral cover will increase in a shorter period of time. It is assumed also that enhanced growth would imply improved survival due to better attachment, hence, lower losses.

This study aims to: (1) experimentally test the effect of electrochemical deposition of CaCO_3 on growth and survival of *Porites cylindrica* Dana; (2) determine if there are additional phenotypic alterations in the transplants induced by enhanced mineral accretion.

2. Materials and methods

2.1. Study site

The study was conducted at Quezon Island (16.22517°N, 120.04535°E) in the Hundred Islands National Park, northern Philippines (Fig. 1). The area has a narrow (20 m) reef flat, which slopes down to a sand bottom at a depth of 14 m. The experimental set-ups were deployed on the bare patches of the upper reef slope with depths ranging from 4 to 8 m. The area is dominated by monospecific stands of *P. cylindrica* followed by small patches of *Acropora echinata*. The substratum is composed mostly of sand and silt with some patches of consolidated rubble. The visibility in the area is relatively poor, especially during the

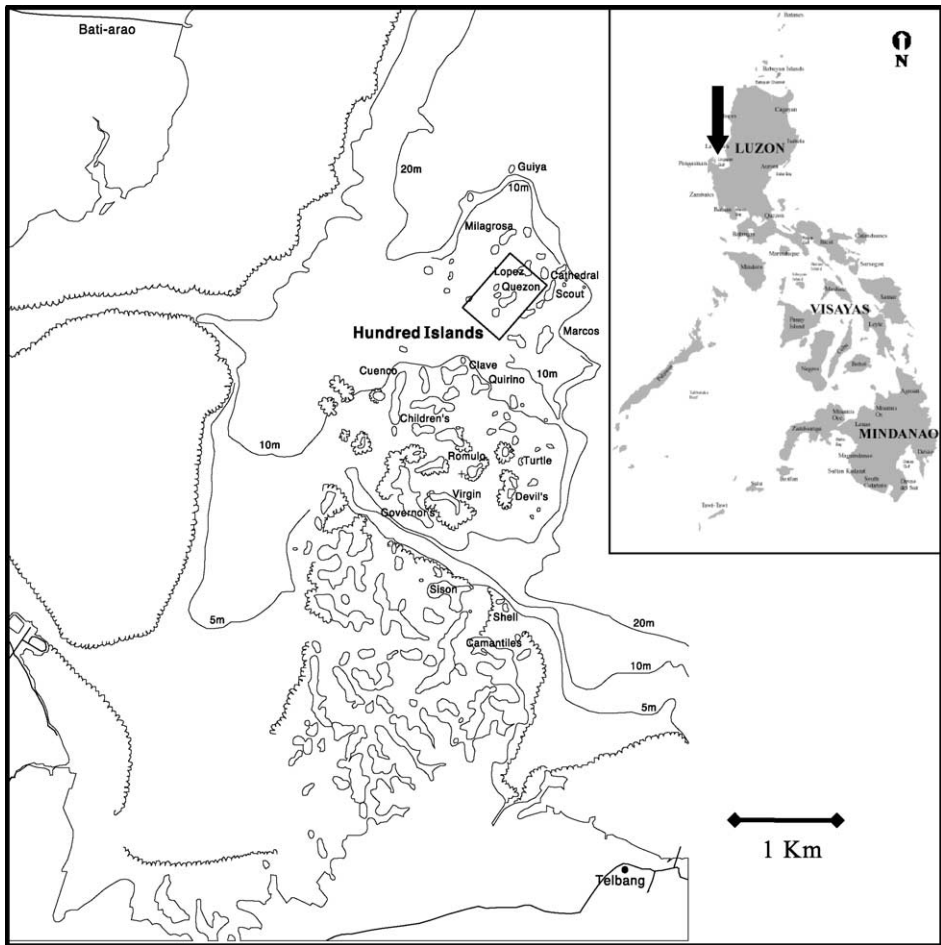


Fig. 1. Location of the Quezon Island study site (16.22517°N, 120.04535°E) at the Hundred Islands National Park, northern Philippines. See text for details on the specific study area.

northeast monsoon months (from October to February). The site also experiences disturbances such as siltation, anchor damage and occasional blast fishing. The experiments were conducted from December 1999 to January 2001 to cover both the northeast and southwest monsoons. In the present paper, only results from the period during which electricity was provided to the electrodes (from December 1999 to May 2000) are reported.

2.2. Experimental design

The experiment consisted of three treatments: corals with electrochemical deposition, those without, and natural colonies which served as the controls. Each of the treatments had three replicates (described below), each of which contained approximately 40 coral

nubbins. As for the controls, 40 branches were tagged at random in each colony to obtain the same sample size. All treatments were arranged in an interspersed fashion to minimize variations due to location on the reef slope.

An entire mineral accretion set-up was composed of an anode, a cathode, power source assembly and the structural platform.

The anode consisted of high-purity Ringsdorff™ graphite material. The graphite electrodes were fabricated into $5 \times 5 \times 70$ -cm blocks. A thick copper cable was inserted at one side of the block and the connection was sealed using a silicon sealant. This was the point of connection of the anode to the positive terminal of the power source.

The cathode was composed of a 1×1 -m galvanized steel mesh with a mesh size of 10 mm. The wire diameter was 0.7 mm. This served as the platform to which the corals were attached and where the accretion took place.

The power source was composed of 16 75-W AEG™ solar modules, six 6SM Superlite™ batteries, and three gauge 12×2 royal cables. Each solar module produced a maximum of 18 V during noon and a direct current of 4.16 A. The modules were connected in parallel to charge the batteries. The batteries were charged during daytime and supplied power to the set-up for 24 h. The battery output was 12 V and 2.5 A. The batteries were connected in parallel to maintain the low voltage and current levels.

All of the components were assembled into a single structure using a polyvinyl chloride (PVC) pipe framework. Each structure was composed of three graphite anodes (including the cable connections) suspended 20 cm above the cathode. The three anodes were spaced 28 cm away from each other and arranged in parallel. The plane of the anodes was also parallel with respect to the cathode. A polyethylene screen was placed beneath the cathode for additional support.

One month after the electricity was turned on, the batteries were no longer used due to corrosion and the mineral accretion set-ups were connected directly to the solar modules. This changed the voltage from 12 to 18 V and the direct current from 2.5 to 4.16 A. Since the electricity originated directly from the solar modules, the daily amperage followed a sinusoidal function (due to the shifting position of the sun) having a peak value of 4.16 A during noon.

The untreated set-up represented the coral nubbins that were not subjected to electro-chemical deposition and was included primarily to determine response to transplantation stress. It followed the same structural design as above except that no electricity was supplied. The graphite anodes were replaced with wooden blocks to account for any shading effect. The same galvanized mesh wire served as the substrate for the nubbins. It was reinforced beneath by a polyethylene screen to serve as a “secondary substrate” to hold the nubbins when the mesh fully corroded.

Three coral thickets within the vicinity were selected as controls. In each thicket, 40 thumb-sized branches were tagged using cable ties and labeled Dymo™ tapes. The tags were used as reference points for linear growth measurements.

2.3. Collection and preparation of coral transplants

Two hundred and sixty thumb-sized nubbins were collected from different thickets within the same reef site using wire-cutting pliers. They were maintained for 24 h on land

(in a seawater-filled bin) where temperature was maintained at 28 °C using seawater ice. The nubbins were then stained using 10 ppm Alizarin Red S dye for 48 h under direct sunlight with continuous aeration and temperature stabilization. The seawater was replaced every 24 h and fresh dye was added. The stained seawater was drained and was replaced by fresh seawater prior to transport. The stained nubbins were transferred to the study site (situated close by) and were again acclimatized for 24 h prior to transplantation.

2.4. Transplantation, growth and survival

The stained corals were wedged into the mesh and were distributed evenly across the area of each grid. Each of the nubbins was tagged at the base using cable ties and labeled Dymo™ tape. After tagging, the power supply was turned on to initiate accretion.

Linear growth was measured using a flexible tape accurate to 0.1 cm. Measurements were taken every other month from the tag to the tip of the nubbin. After 6 months, the corals were harvested for examination of phenotypic changes.

The number of surviving nubbins per bimonthly visit was counted and divided by the number at the previous visit. Transplants with 90% tissue necrosis were considered dead. Lost transplants due to wave action or removal by feeding fishes were considered mortalities.

The corallite sizes and their number per unit area in the individual nubbins were examined under a stereoscope using a micrometer eyepiece and a micrometer quadrat, respectively. The corallites were sampled at the apical, middle and basal regions of the coral nubbins. They were randomly selected for measurement and counting at different areas within each region.

A segment of each nubbin (1 cm in length from the tagged base) was then cross-sectioned using a high-speed rotating tile cutter to expose the alizarin stain. Girth growth was measured from the outer edge of the stain towards the edge of the skeleton using a vernier caliper accurate to 0.02 mm. Only the treated and untreated nubbins were analysed in this manner since the controls had not been stained.

2.5. Environmental parameters

The environmental parameters measured were temperature, salinity, turbidity, sedimentation rate and water movement. The purpose was to check whether the changes in growth rates were due to the experimental treatments or to changes in environmental conditions.

Temperature was measured using a mercury thermometer accurate to 0.5 °C (automatic temperature loggers could not be left at the site due to risks of theft). During each visit, measurements were taken at each set-up at 9:00 AM, 12:00 noon and 3:00 PM.

Salinity and turbidity of water samples taken to the laboratory were measured using a refractometer (accurate to 2‰) and a turbidimeter (accurate to 0.01 Nephelometric Turbidity Units), respectively. A total of 54 samples were obtained in the morning and another 54 during the afternoon sampling. The water samplings were carried out for two consecutive days per month to follow a complete tidal cycle.

Sedimentation rates were measured using sediment traps (English et al., 1994) each made of PVC with a mouth opening of 2-in. inner diameter. Three traps were tied together using a thick rubber sling and were deployed in two grids of each treatment (including the controls). Traps were deployed for 24 h and were replaced the following day for another 24-h sampling. The sediment samples were allowed to settle for 1 week then the excess water was decanted. The sediments were washed with fresh water to dissolve the salts. They were then filtered using preweighed filter paper and oven dried for 1 week at 60 °C until constant dry weight.

Water motion was measured using the clod card technique (Doty, 1971; Jokiel and Morrissey, 1993). The preweighed clod cards were deployed for 24 h and were replaced by another set to get the water motion of a complete tidal cycle. The final weights were taken after 2 weeks of air-drying.

2.6. Statistical analysis

To test if the environmental parameters had a significant effect on coral growth rates, the analysis of co-variance was employed (Zar, 1984) where the treatments were the main variables and the environmental parameters were the covariates. Multiple regression was used to verify the ANCOVA and determine which among the environmental parameters had an effect.

Percentage longitudinal growth rate of each nubbin for each treatment (and control) were computed as the final length (length at month 6) minus the initial length divided by the initial length and multiplied by 100. Values were tested for normality and homoscedasticity. Since the locations of the grids and control thickets were at different depths, the growth data were blocked according to their respective depth ranges. Hence, the term

Table 1
Monthly mean values \pm S.D. (n =sample size) of the environmental parameters measured over a year at the Quezon Island study site

	Temperature		Salinity		Turbidity		Sedimentation		Water motion	
	(°C)	(n)	(‰)	(n)	(NTU)	(n)	(mg cm^{-2} day^{-1})	(n)	(df)	(n)
December 1999	28.5 \pm 0.3	54	33 \pm 0.60	214	0.85 \pm 0.52	214			12.98 \pm 2.28	108
January 2000	28.5 \pm 0.3	54	33 \pm 0.63	214	0.34 \pm 0.22	212	0.24 \pm 0.17	36	5.79 \pm 1.79	108
February 2000	27.5 \pm 0.3	54	34 \pm 0.39	216	0.62 \pm 0.28	216	0.26 \pm 0.12	36	7.00 \pm 1.54	108
March 2000	29.5 \pm 0.2	54	34 \pm 0.00	216	0.29 \pm 0.19	215	0.12 \pm 0.07	36	3.36 \pm 1.81	108
April 2000	29.5 \pm 0.2	54	34 \pm 0.19	215	0.50 \pm 0.19	214	0.50 \pm 0.22	36	1.71 \pm 0.28	108
May 2000	29.5 \pm 0.0	54	34 \pm 0.00	216	0.26 \pm 0.15	216	1.37 \pm 0.46	36	1.10 \pm 0.24	108
June 2000	30 \pm 0.0	54	34 \pm 0.30	216	0.38 \pm 0.13	214	1.44 \pm 0.46	36	0.51 \pm 0.23	108
July 2000	29.5 \pm 0.0	54	34 \pm 0.30	216	0.21 \pm 0.14	216	0.16 \pm 0.09	36	0.31 \pm 0.11	108
August 2000	29.5 \pm 0.0	54	32 \pm 0.00	216	0.34 \pm 0.16	213	0.31 \pm 0.14	36	1.50 \pm 0.34	108
September 2000	29.5 \pm 0.0	54	32 \pm 0.41	216	0.27 \pm 0.14	213	2.44 \pm 6.14	36	1.13 \pm 0.31	108
October 2000	29.5 \pm 0.2	54	33 \pm 0.74	216	0.34 \pm 0.18	212	2.12 \pm 1.82	36	1.46 \pm 0.22	108
November 2000	29.5 \pm 0.0	54	33 \pm 0.30	216	0.39 \pm 0.24	215	1.44 \pm 0.68	36	1.47 \pm 0.29	108

Table 2

Analysis of covariance on the effect of the environmental parameters, treatments and blocks on the percentage growth of *P. cylindrica* (dependent variable: percentage growth)

Source	Type IV sum of squares	df	Mean square	F	Significance
Covariates					
Temperature	73.060	1	73.060	0.200	0.655
Sedimentation rate	1.745	1	1.745	0.005	0.945
Water motion	923.199	1	923.199	2.527	0.113
Salinity	36.536	1	36.536	0.100	0.752
Turbidity	1.598	1	1.598	0.004	0.947
Between subjects					
Block	1382.772	2	691.386	1.892	0.152
Treatment	5795.439	2	2897.720	7.932	0.000
Block*treatment	5788.072	4	1447.018	3.961	0.004
Error	110,332.771	302	365.340		
Total	634,756.261	316			
Corrected total	124,230.723	315			

Computed using $\alpha = 0.05$; $R^2 = 0.112$ (adjusted $R^2 = 0.074$).

“block” refers to a group consisting of two grids (=replicates) belonging to the two treatments and a coral thicket (control). There were three blocks situated at three different depths. Therefore, each treatment was replicated three times. The blocking was done to

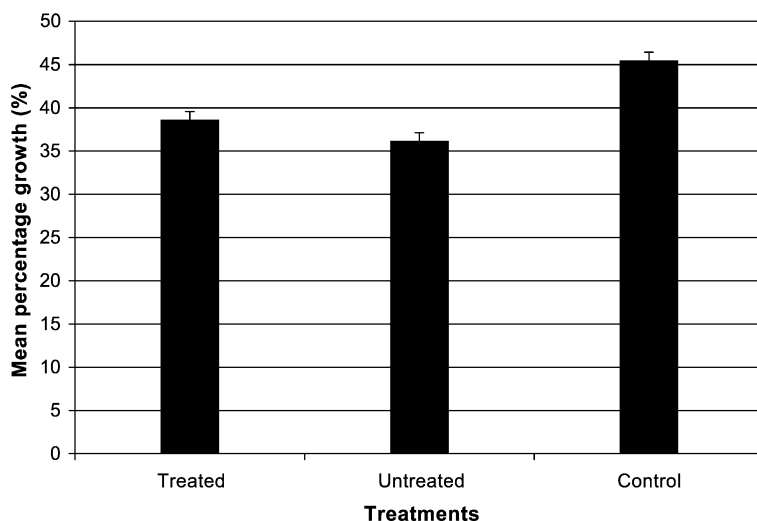


Fig. 2. Mean percentage growth rates of *P. cylindrica* for the whole 6-month duration of the study. Error bars are standard errors.

test if the effects of depth might have confounded the effects of the treatments. A univariate two-factor ANOVA was used to determine if there were significant differences between blocks and treatments (Zar, 1984). A Type IV Sum of Squares was used for the ANOVA since the data were unbalanced and had missing cells (Shaw and Mitchell-Olds, 1993). A regression analysis was used to explain the effect of depth on the treatment and blocking interaction. Initial lengths were not considered as covariates since growth rates are presented in percentages and the nubbins were randomly distributed among the grids. Where there were significant differences, multiple comparison tests were used to determine which treatments grouped together. The same procedure was used for the girth growth data, except that these were expressed as actual growth rates every 6 months instead of percentages.

A two-way nonparametric ANOVA was used for the data on corallite size and number since these remained heteroscedastic even after transformation (Zar, 1984). Nonparametric multiple comparisons were used to determine groupings if there were significant differences.

Table 3

Univariate two-factor ANOVA comparing percentage growth rates of the treated, untreated and control nubbins reared for 6 months (dependent variable: percentage growth)

Source	Type IV sum of squares	df	Mean square	F	Significance
Between subjects					
Blocking	908.568	2	454.284	1.258	0.286
Treatment	5430.133	2	2715.067	7.518	0.001
Blocking*treatment	6595.450	4	1648.863	4.566	0.001
Error	111,952.171	310	361.136		
Total	641,404.321	319			
Corrected total	124,411.581	318			

Multiple comparisons: Tukey HSD test

Treatments		Mean difference	S.E.	Significance
(I)	(J)	(I – J)		
Treated	untreated	2.450	2.655	0.626
	control	– 6.853	2.570	0.021
Untreated	treated	– 2.450	2.655	0.626
	control	– 9.303	2.604	0.001
Control	treated	6.853	2.570	0.021
	untreated	9.303	2.604	0.001

Homogenous subsets

Treatments	N	Subset	
		1	2
Untreated	100	36.127	
Treated	105	38.576	
Control	114		45.429

Significant differences in percentage growth rates are further tested for grouping using multiple comparisons.

The Kaplan–Meier product-limit method (Lee, 1992) was used to compare trends in survival of the corals among treatments over time. Distributions were compared using nonparametric tests. All statistical analyses were carried out using SPSS 9.0 for Windows.

3. Results

3.1. Environmental parameters

Monthly mean values of the different environmental parameters from December 1999 to November 2000 are given in Table 1.

None of the environmental parameters had a significant effect on growth (Table 2). Differences in percentage growth were due to the treatments (ANCOVA, $P=0.000$, $df=2$, $F=7.932$). This is confirmed by multiple regression ($P=0.582$, $df=4$, $F=0.716$).

3.2. Longitudinal growth

Fig. 2 shows the mean percentage longitudinal growth of corals with electrochemical deposition, those without, and the controls. The highest mean percentage growth was exhibited by the controls ($45 \pm 1.60\%$, $n=114$) followed by the treated corals ($38 \pm 1.70\%$, $n=105$) and the untreated corals ($36 \pm 2.37\%$, $n=100$).

The percentage increase in length of the control nubbins was significantly higher (Table 3; $P=0.001$, $df=2$, $F=7.518$) than the treated (Tukey: $P=0.021$) and untreated corals (Tukey: $P=0.001$). There were no significant differences between blocks, although there was a significant block by treatment interaction ($P=0.001$, $df=4$, $F=4.566$). However,

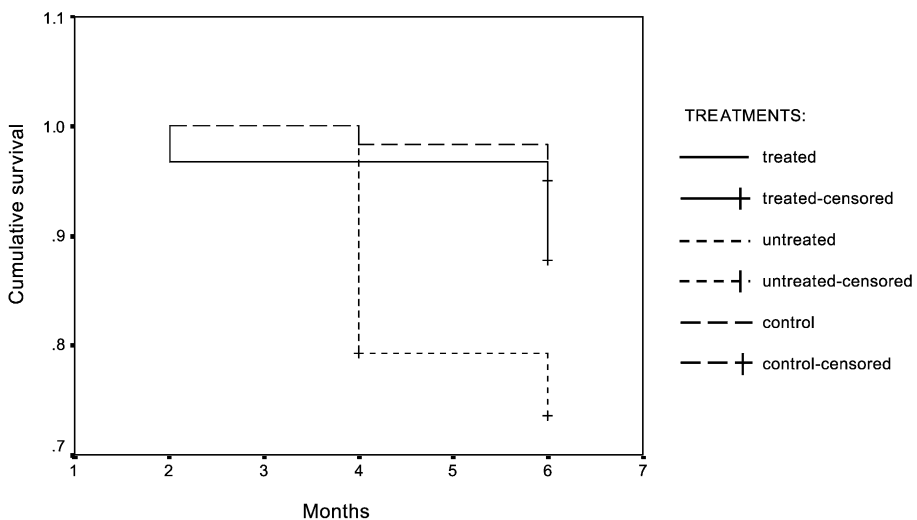


Fig. 3. Cumulative survival rates of *P. cylindrica* with electrochemical deposition (treated), without electrochemical deposition (untreated), and in natural control colonies over a 6-month observation period.

depth had only a marginal effect on the percentage growth rate ($P=0.05$, $df=1$, $F=3.864$, $R^2=0.012$) based on the regression analysis.

3.3. Survival

After 6 months, the controls showed the lowest mortality (5%) from an initial number of 120 to 114 nubbins followed by the treated nubbins (14%), from 120 to 103 (Fig. 3). The untreated nubbins exhibited the highest rate of mortality (30%) from 140 to 98 nubbins. Most of the mortalities were due to algal overgrowth.

Survival data analysis indicated significantly higher survival in the treated and control corals as compared to the untreated nubbins (Table 4).

3.4. Corallite size

In the natural colonies, the mean corallite diameters at the tip, midsection and base of a branch were 0.76, 0.85 and 0.93 mm, respectively (Fig. 4). The same trend was observed for the untreated nubbins where the average diameters were 0.74, 0.87 and 0.91 mm, respectively. In the case of the treated nubbins, there was a trend in increasing size from the tip to the mid region, but mean diameter decreased from the mid region to the base (Fig. 4). Average diameters from the tip to the base were 0.74, 0.87 and 0.78 mm.

Table 4

Comparison of the survival trends between the treated, untreated and control nubbins

(A) Mean and median survival time

Nubbins	Survival time (6 months)	
	Mean	S.E
Treated	5.87	0.07
Untreated	5.59	0.07
Control	5.97	0.03

* Cumulative survival curve did not cross 0.50 mark.

(B) Nonparametric comparisons

Treatment pair	Nonparametric comparisons						Verdict
	Log-rank		Breslow		Tarone-Ware		
	Statistic	Significance	Statistic	Significance	Statistic	Significance	
Treated* untreated	8.43	0.0037	9.34	0.0022	8.89	0.0029	treated > untreated
Treated* control	4.03	0.0448	4.05	0.0441	4.04	0.0444	control > treated
Untreated* control	21.81	0.0000	22.54	0.0000	22.20	0.0000	control >> untreated

Part A shows the mean survival time during 6 months of exposure. Part B shows the nonparametric comparisons between each treatment pair to determine the survival status of the nubbins in each treatment relative to other treatments.

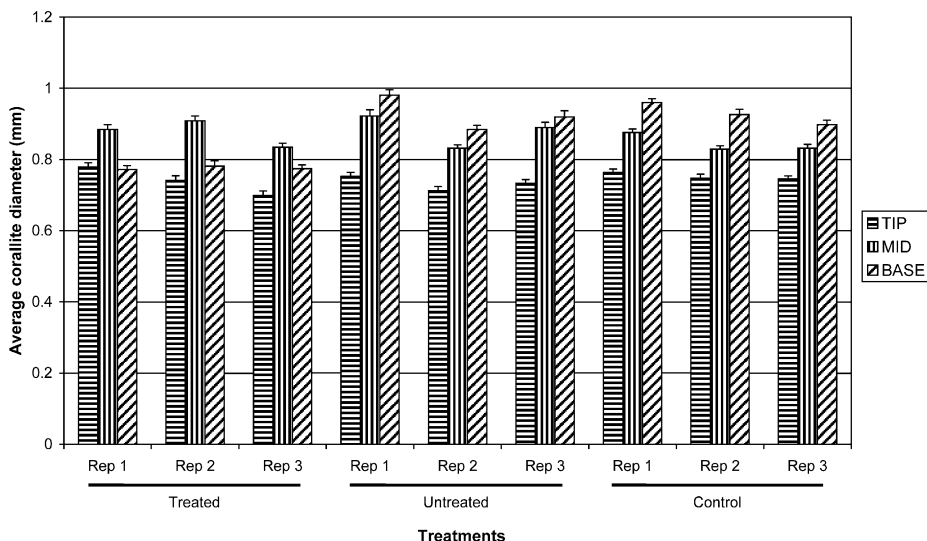


Fig. 4. Mean corallite diameter at the apical, middle and basal regions of the coral nubbins under the different treatment and control conditions. Error bars are standard errors.

There was a significant difference in corallite diameter between regions and between treatments with a significant treatment by region interaction (Table 5). Based on multiple comparisons, the corallite diameters of the treated nubbins were significantly different from the control and untreated ones. Corallite diameters among regions were also significantly different.

Table 5

Nonparametric two-factor ANOVA of the corallite diameters of the treated, untreated and control nubbins reared for 6 months

(A) Nonparametric two-factor ANOVA

Source	Sum of squares	df	H	$\chi_{0.05, v}^2$	Significance
Cells	72,710,056,335.00	8			
Treatment	13,440,830.13	2	53.475	5.991	$P \ll 0.05$
Region	114,291,447.80	2	454.716	5.991	$P \ll 0.05$
Treatment*region	72,582,324,057.00	4	288,773.365	9.488	$P \ll 0.05$

(B) Nonparametric multiple comparisons

Comparison	Difference	S.E.	q	$q_{0.05, inf}$	Conclusion
Control*treated	108,862	2360.225	46.1	3.314	control \gg treated
Control*untreated	523	2360.225	0.2	3.314	control = untreated
Untreated*treated	108,339	2360.225	45.9	3.314	untreated \gg treated
Base*tip	322,090	2360.225	136.5	3.314	base \neq tip
Base*mid	11,098	2360.225	4.7	3.314	base \neq mid
Mid*tip	310,992	2360.225	131.8	3.314	mid \neq tip

Part A shows the ANOVA results. Part B, the Tukey type nonparametric multiple comparisons of the corallite diameters among treatments and regions of the nubbins.

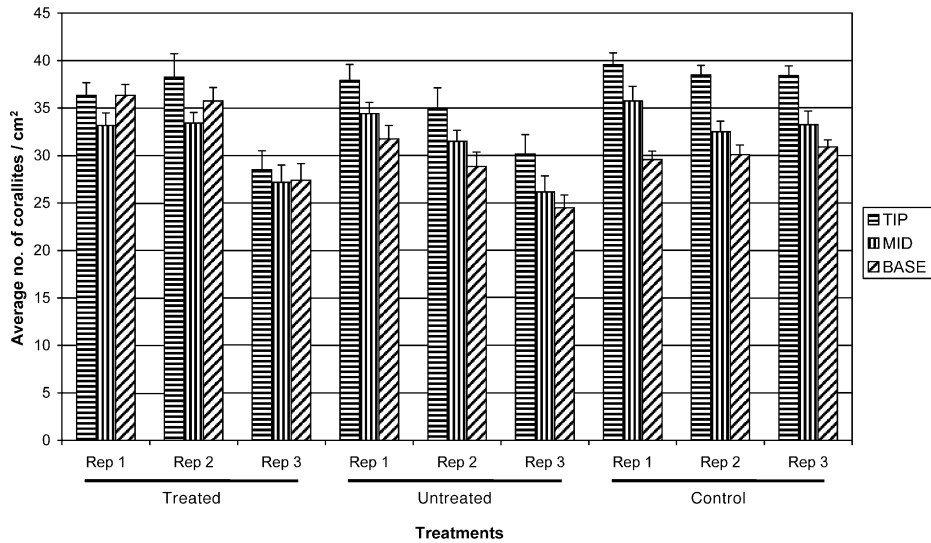


Fig. 5. Mean number of corallites per square centimeter at the apical, middle and basal regions of the coral nubbins under the different treatment and control conditions. Error bars are standard errors.

3.5. Number of corallites per unit area

As to be expected, there was an inverse relationship between corallite size and number per unit area (compare Figs. 4 and 5). There was a significant difference in corallite

Table 6

Nonparametric two-factor ANOVA of the number of corallites per unit area of the treated, untreated, and control nubbins reared for 6 months

(A) Nonparametric two-factor ANOVA						
Source	Sum of squares	df	H	$\chi^2_{0.05, v}$	Significance	
Cells	74,447,120.00	8				
Treatment	102,743.01	2	11.741	5.991	$P \ll 0.05$	
Region	384,825.26	2	43.976	5.991	$P \ll 0.05$	
Treatment*region	73,959,552.00	4	8451.725	9.488	$P \ll 0.05$	
(B) Nonparametric multiple comparisons						
Comparison	Difference	S.E.	q	$q_{0.05, inf}$	Conclusion	
Control*untreated	4666.50	187.93	24.83	3.314	control \approx untreated	
Control*treated	1774.50	187.93	9.44	3.314	treated > control	
Treated*untreated	2892.00	187.93	15.39	3.314	treated \gg untreated	
Tip*base	8869.50	187.93	47.20	3.314	tip \neq base	
Tip*mid	6262.50	187.93	33.32	3.314	tip \neq mid	
Mid*base	2607.00	187.93	13.87	3.314	mid \neq base	

Part A shows the ANOVA results. Part B, the Tukey type nonparametric multiple comparisons of the number of corallites among treatments and regions of the nubbins.

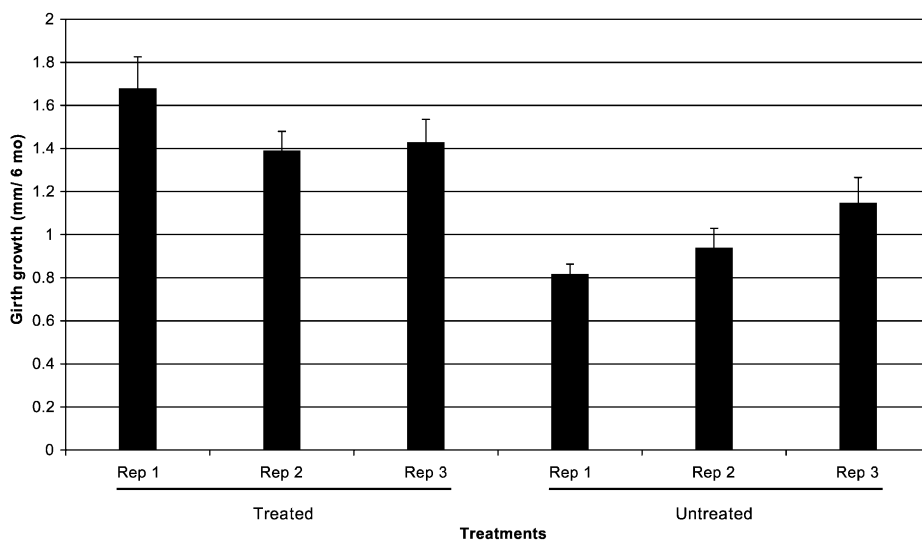


Fig. 6. Mean girth growth rates of *P. cylindrica* under treated and untreated conditions over a 6-month observation period. Error bars are standard errors.

number among treatments and regions (Fig. 5, Table 6). The number of corallites per unit area in the untreated and the control nubbins was significantly less than that of the treated corals.

3.6. Girth growth

The treated nubbins showed a consistently greater increase in girth growth in all replicates compared to the untreated nubbins (Fig. 6). The ANOVA test indicated significant differences between treatments (Table 7; $P=0.000$, $df=1$, $F=40.001$) but not between blocks. There was a significant block by treatment interaction ($P=0.048$, $df=2$, $F=3.134$).

Table 7

Univariate two factor ANOVA comparing girth growth rates of the treated and untreated nubbins reared for 6 months (dependent variable: girth growth)

Source	Type IV sum of squares	df	Mean square	F	Significance
Between subjects					
Blocking	0.043	2	0.021	0.873	0.421
Treatment	0.977	1	0.977	40.001	0.000
Blocking*treatment	0.153	2	0.077	3.134	0.048
Error	2.295	94	0.024		
Total	3.743	100			
Corrected total	3.498	99			

4. Discussion

The mineral accretion technology which involves the electrochemical deposition of minerals such as CaCO_3 , $\text{Mg}(\text{OH})_2$, CaSO_4 and NaCl (Meyer and Schuhmacher, 1993) enabled the formation of a natural substrate that reinforced the attachment of coral nubbins. Firm attachment of the coral transplants is known to enhance survival (Bowden-Kerby, 1997; Lindahl, 1998; Ammar et al., 2000). This is true for the control nubbins and nubbins exposed to electrochemical deposition. The untreated corals although fixed to the grids were still movable and as the metal mesh corroded, the nubbins were more vulnerable to removal. A firmly attached coral can allocate more energy to lesion recovery and subsequent growth.

The growth rate reported in our study reflects a particular level of voltage and current (18 V and 4.16 A at maximum). Growth rates may differ at lower electrical regimes. Previous studies that used this method had voltages varying from 1 to 24 V (van Treeck and Schuhmacher, 1997), 8 to 12 V (Schuhmacher and Schillak, 1994), and 6 to 12 V (Hilbertz and Goreau, 1996). Our voltage level still falls within the range found in the published literature. Lower voltage and current levels are favorable to ensure the accretion of aragonite rather than brucite (Hilbertz, 1992; Meyer and Schuhmacher, 1993). The probability of other chemical reactions occurring, aside from accretion, increases as the voltage level increases (Goreau, personal communication).

The orientation of the coral transplants with respect to the plane of the cathode also had an effect on growth rates. Since precipitation was observed to occur directly on the cathode, and not in the water column (Schuhmacher, personal communication), this resulted in a gradient in the concentration of mineral ions where highest levels occur near the cathode and decrease with distance. If a nubbin is oriented normal to the plane of the cathode, the basal polyps experience the highest concentration of mineral ions as compared to the apical polyps. The calcification rate is therefore potentially higher at the base. Data on corallite size and number show that the treated nubbins developed more polyps at the base. The relative abundance of mineral ions at the basal region appeared to enable the rechanneling of some energy from that used in active uptake (of the ions) for skeletal deposition to that used for reproduction by intra-tentacular budding. The increase in number of corallites and their close packing would also tend to increase the girth of the nubbins rather than their length. This was clearly shown in the data for both percentage longitudinal growth and girth growth. There was a significant increase in girth growth of the treated nubbins over the untreated ones, but only a slight (and statistically insignificant) increase in percentage longitudinal growth.

Both the treated and untreated nubbins experienced transplantation stress due to handling, staining, transport and reattachment. These resulted in lower percentage linear growth rates as compared to the controls (Buddemeier and Kinzie, 1976; Yap and Gomez, 1985; Yap et al., 1992). Growth rates tend to recover after the corals have acclimatized to their new conditions.

The presence of the gradient in ion concentration would limit the kind of coral to be used for transplantation if an important aim is to enhance growth. Since most of the mineral ions are concentrated a few millimeters above the cathode substrate, then it is

logical to use corals that grow more laterally rather than vertically. This way, the growing edges are maintained within the boundary of high CaCO_3 concentration.

The ability of the mineral accretion technology to enhance survival and growth (to a certain degree) provides the potential to be an effective rehabilitation tool. This reduces the unnecessary loss of corals due to mortality.

The basal regions of the treated nubbins are being further tested for skeletal micro-density, bulk density and porosity.

5. Conclusion

P. cylindrica transplants had a survival rate of 86% after 6 months of exposure to mineral accretion, which was higher than that of the untreated corals (70%). Percentage linear growth was significantly different between the controls and the other treatments. The latter experienced a decrease in growth rate probably due to transplantation stress. The presumed saturation of mineral ions at the basal region of the treated nubbins could have triggered the intra-tentacular budding of the basal polyps, as seen in the increase in the number of corallites and their concomitant decrease in size. This led to a significant increase in girth and skeletal density (unpublished data) in the basal region.

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