Original articles

Field validation of Tasmania's aquaculture industry bounce-diving schedules using Doppler analysis of decompression stress

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Abstract

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Introduction: Tasmania's aquaculture industry produces over 40,000 tonnes of fish annually, valued at over AUD500M. Aquaculture divers perform repetitive, short-duration bounce dives in fish pens to depths up to 21 metres' sea water (msw). Past high levels of decompression illness (DCI) may have resulted from these 'yo-yo' dives. This study aimed to assess working divers, using Doppler ultrasonic bubble detection, to determine if yo-yo diving was a risk factor for DCI, determine dive profiles with acceptable risk and investigate productivity improvement.

Methods: Field data were collected from working divers during bounce diving at marine farms near Hobart, Australia. Ascent rates were less than 18 $m \cdot min^{-1}$, with routine safety stops (3 min at 3 msw) during the final ascent. The Kisman-Masurel method was used to grade bubbling post dive as a means of assessing decompression stress. In accordance with Defence Research and Development Canada Toronto practice, dives were rejected as excessive risk if more than 50% of scores were over Grade 2.

Results: From 2002 to 2008, Doppler data were collected from 150 bounce-dive series (55 divers, 1,110 bounces). Three series of bounce profiles, characterized by in-water times, were validated: 13–15 msw, 10 bounces inside 75 min; 16–18 msw, six bounces inside 50 min; and 19–21 msw, four bounces inside 35 min. All had median bubble grades of 0. Further evaluation validated two successive series of bounces. Bubble grades were consistent with low-stress dive profiles. Bubble grades did not correlate with the number of bounces, but did correlate with ascent rate and in-water time.

Conclusions: These data suggest bounce diving was not a major factor causing DCI in Tasmanian aquaculture divers. Analysis of field data has improved industry productivity by increasing the permissible number of bounces, compared to earlier empirically-derived tables, without compromising safety. The recommended Tasmanian Bounce Diving Tables provide guidance for bounce diving to a depth of 21 msw, and two successive bounce dive series in a day's diving.

Key words

Occupational diving, repetitive diving, surface supply breathing apparatus (SSBA), Doppler, decompression tables, diving tables, decompression sickness, diving research

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Introduction

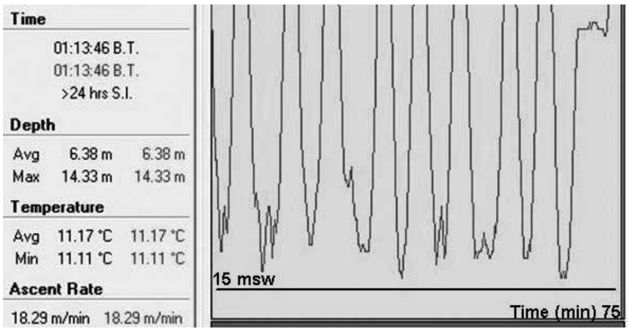
Tasmania's salmonid aquaculture industry commenced in 1986 and now employs over 900 people. The industry is Australia's highest value fishery, producing 43,989 tonnes of salmon (22% of total Australian fisheries production in 2011–12) with an export value of AUD513 million.[1] Marine aquaculture is diving intensive, and divers have made a significant contribution to product quality. There are currently over 100 divers employed in the Tasmanian industry. Aquaculture divers breathe surface-supplied air, and perform repetitive short-duration dives in fish pens, to depths of up to 21 metres' sea water (msw), in water temperatures as low as 8°C. They move from pen to pen in the course of their normal duties (Figures 1 and 2), and undertake multiple decompressions as they transit between pens (Figure 3 shows a typical dive profile). This makes 'bounce' or 'yo-yo' diving potentially more risky than traditional 'square-profile' diving (a single descent followed by a single ascent) with increased potential for bubble formation.[2] Initially, there were high levels of decompression illness (DCI) in the industry.[3,4] All currently available decompression tables are based on square dive profiles. Hence, prior to this study, there were no validated dive tables to guide the type of diving undertaken by aquaculture divers.

The Defence and Civil Institute of Environmental Medicine (DCIEM, now Defence Research and Development Canada, Toronto, DRDC Toronto) has had extensive experience in the development and validation of decompression tables using Doppler bubble detection, culminating in the production of the DCIEM air diving tables for single descent-ascent (square) and limited-repetitive dive profiles based on decompression stress.[5–9] Empirically derived dive tables based on the DCIEM no-stop times were implemented in the early 1990s for the Tasmanian aquaculture industry on the advice of diving medical specialists at the Royal Hobart Hospital (RHH).[3–5] In response to the high initial DCI rates in the fledgling aquaculture industry, these empirical diving tables were made more conservative than the usual DCIEM

Figure 1
Aquaculture diver about to enter a salmon pen

Figure 2
Aerial view of a salmon farm lease

Figure 3
Dive data picture from Sensus Pro dive data recorder



no-stop table limits, and it became common practice to add an extra decompression stop as a risk-reduction measure. From 1988 to 1998, after implementation of the new bounce-diving decompression schedules, there was a 98% reduction in the incidence of DCI, theoretically preventing up to 44 divers per annum from contracting this illness (and up to 200 recompression treatments). The incidence of DCI fell from 26.19 to 0.57 cases per 10,000 dives, from 11.0 to 0.62 cases per 100 divers per year, and from 17.46 to 0.06 cases per 1,000 tonnes of annual fish production (all P values < 0.0001).[4] The observed reduction in risk came at a cost of reduced diver productivity. It was posited that the empirically derived tables were too conservative.

There was reason to suspect that the decompression stress associated with bounce diving would be greater than for the more traditional dive profiles because of a (theoretical) increased risk of bubble formation produced by multiple decompressions.[2] Bubble nuclei formed during any given decompression to the surface may not necessarily resolve completely during the next descent, and may, therefore, be available to act as a focus for gas coming out of solution during subsequent decompressions.

The best way to investigate this was to undertake field studies of the working divers using Doppler bubble detection. The technology and capability to undertake this validation became available at the RHH Department of Diving and Hyperbaric Medicine (DDHM) when one of the authors (CVdB) undertook training in Doppler monitoring of divers at DRDC Toronto, Canada in 2001.

HYPOTHESES

a. Bounce diving is an independent risk factor for decompression stress.
b. Provided divers maintain in-water dive times that are less than DCIEM no-stop time limits according to the tables, and ascent rates obey DCIEM recommendations of 18 ± 3 msw·min^{-1}, bounce diving will not result in an unacceptable risk of DCI occurrence.

AIMS

- To investigate decompression stress produced from bounce diving using Doppler ultrasonic bubble detection;
- To undertake field assessment and validation of the empirically-derived tables used by Tasmania's aquaculture industry;
- To determine whether bounce diving is an independent risk factor for DCI;
- To investigate methods for improving productivity in the industry, guided by the results of this study.

Methods

DCIEM TABLES: DEFINITIONS AND TERMINOLOGY

Except for (c) and (d) below, the definitions used in the text are consistent with those in the DCIEM dive manual.[5] The following are provided for reference:

a. *Ascent rate – the rate of travel as a diver moves from*

depth to the surface: the recommended rate for the DCIEM tables is 18 m ± 3 m·min^{-1}.
b. *Bounce-dive series*: a series of two or more descents and ascents from a dive, which are separated by less than 15 min surface interval. An example of a bounce-dive series is depicted in Figure 3. If a surface interval (SI) between dives exceeded 15 min, the next dive becomes a repetitive dive, and requires calculation of repetitive groups using the DCIEM tables to ascertain time and depth limits of the subsequent dives.
c. *Bottom time*: the total elapsed time from when the diver first leaves the surface to the time (next whole min) that the diver commences the last ascent (measured in min). For a bounce-dive series, bottom time includes SIs between bounces, provided they are less than 15 min.
d. *In-water time*: this differs from bottom time and is the total time the diver spends in the water, minus the time spent at the surface during surface intervals. It includes the time of the last ascent and the decompression stop.
e. *Repetitive factor*: a numerical figure, used for repetitive diving, determined by the Repetitive Group and the length of a SI after a dive. A value of 1.0 reflects no residual nitrogen in the diver. Values ranging from 1.1 up to 2.0 reflect increasing amounts of residual nitrogen.
f. *Repetitive group*: a letter of the alphabet which relates directly to the amount of residual nitrogen in a diver's body immediately on surfacing from a dive. Letter "A" is lowest.
g. *Repetitive dive*: any dive that has a DCIEM repetitive factor greater than 1.0. This includes any series of more than one dive, where dives are separated by SIs of greater than 15 min, unless the SI was of sufficient duration that the diver's repetitive factor returned to 1.0.
h. *Surface interval*: The time which a diver has spent on the surface following a dive; beginning as soon as the diver surfaces and ending as soon as the diver starts the descent for the next dive.

A prospective, observational, cohort study was conducted over six years using Doppler ultrasound to assess sub-clinical decompression stress. This project was approved by the Institutional Research Ethics Committees at both the RHH and DRDC Toronto (RHH Ethics reference number H6455). All divers provided informed consent for data collection and participation in the study.

Commencing May 2002, field data were collected by one or more of the authors during routine diving activities at marine farms near Hobart, Tasmania. Farm visits were timed to coincide with maximum diving activity, and with dives that were consistent with the most common profiles used in the industry. At the commencement of the study the most common profiles were 12 msw and 15 msw. As the study progressed, there were changes in farming techniques and technology requiring extension of the data collection to deeper profiles. There were no ethical issues arising from this because the farms implemented the technology and diving processes independently of this study.

FIELD DATA COLLECTION

Field data were collected primarily by one of the authors (CVdB), with regular visits by DS to monitor diver health. A questionnaire was completed at the time of Doppler scanning, prior to diving. This collected information about the diver's preceding 24 hours including: exercise prior to diving, medications, alcohol consumption, tobacco usage, sleep, fatigue, food and fluid intake, colds or other infections, diving activity and any physical complaints. All of these factors were considered to be potential confounders that have been reported to increase bubble formation. Anticipated altitude exposures (by air or car) post diving were also documented. Divers also completed a post-dive health questionnaire and were required to report symptoms or signs of DCI in the 24 hours after diving.

Divers undertook their usual, working bounce-dive series breathing surface-supplied air from a pod of high-pressure cylinders. Air utilisation was recorded, providing an indication of the workload of the dive. A routine decompression stop for 3 min at 3 msw was performed at the end of each diver's last bounce dive. Each diver's depth and time underwater were monitored and recorded continuously using a submersible dive data logger (*Sensus Pro*, Reefnet Incorporated, Mississauga, ON, Canada, Figure 3), from which the data could be downloaded into a laptop PC upon completion of the dive. Maximum depth, bottom times, number of bounces, ascent rates and water temperature were recorded. The diver was blind to the data collected.

Data handling, analysis and reporting took place at the DDHM (DS, DC), with expert input from the DRDC Toronto. DRDC scientists (RN, DE) independently validated assigned bubble-grade classifications in a randomly selected 10% of readings, and assisted with statistical analysis.

DOPPLER MONITORING

Doppler sampling was undertaken according to the techniques described by Eatock and Nishi.[10–13] One author (CVdB) received training in Doppler monitoring at DRDC Toronto, and subsequently on several occasions over the course of the study, to maintain his skills. All measurements were performed by this individual, or under his direct supervision. Recordings were undertaken using a 2.5 MHz continuous-wave Doppler ultrasound device (TSI DBM 9008, Techno Scientific Inc., Ontario, Canada) with a Doppler array probe (TSI-DPA7). Doppler recordings were taken over the precordium and both subclavian veins at 20-min intervals for at least 2 hours post dive (or until bubbles were no longer detectable for three successive readings) and recorded onto magnetic audio cassettes. The first recording was performed immediately after the diver exited the water. Each recording at 20 min intervals included the following:

- precordium, at rest – 60 seconds;
- precordium, 3 squats – 30 seconds after each;

- subclavian veins, at rest – 30 seconds;
- subclavian veins, 3 hand clenches – 15 seconds after each.

DOPPLER DATA ANALYSIS

Doppler recordings were aurally graded according to the standard Kisman-Masurel (KM) Code.[9,14] Detected bubbles were subjected to a three-fold classification that analysed (i) frequency, (ii) either percentage of cardiac cycles affected (at rest) or duration (following movement), and (iii) signal amplitude of detected bubbles, to yield a single bubble grade (0 to 4).[14]

It was known from a large series of DCIEM air divers (1,726 subjects) that, based on the maximum recorded bubble grades from all monitoring sites and conditions (rest/movement), grades 2 or less (low stress) were associated with clinical symptoms of DCI in 1.1% of cases, and bubbles of grade 3 have been quoted as having a DCI incidence ranging up to 6.3%. Grade 4 bubbles had a DCI rate of 9.7% at the time DCIEM collected its original data.[9] Grade 4 bubbles may produce a much higher risk of DCI when detected after exceptional or extreme exposure dives.

Bounce tables were defined *a priori* as 'low risk' if the bubble scores complied with DCIEM/DRDC-defined limits of acceptability (grade 2 or fewer bubbles in 50% or more of the subjects). DRDC Toronto defined dive profiles producing Doppler bubble grades 3 or 4 in 50% or more of the subjects as of 'high risk' and were to be rejected for use. This study followed the DCIEM table recommendations and definitions.

DATA CONSISTENCY

Aural scoring is known to be observer-dependent; therefore, all Doppler recordings were graded by a single author (CVdB). A random sample of 10% of all recordings were scored and validated independently by DRDC Toronto to ensure data consistency.

STATISTICS

All data were entered into a Microsoft Access® (Microsoft Corporation – Redmond, Washington, USA) database and analysed using Graph Pad Instat® version 3.0 for Windows and Graph Pad Prism® version 4.03 for Windows (Graph Pad Software, San Diego, California, USA, 2003 and 2005). Bubble grades were treated as categorical data for statistical analysis. The highest KM bubble grade following each dive was tabulated for statistical comparison.

Bubble grades were dichotomized into 'acceptable' (grades 0–2) versus 'unacceptable' (grades 3–4) to facilitate subsequent statistical analysis. The resulting 2 x 2 contingency tables were subjected to Fisher's exact test. All tests were 2-tailed and $P < 0.05$ was considered statistically significant. The bubble grades were also correlated with any symptoms divers noted in the 24 hours following diving. When bubble grades were compared to continuous variables such as numbers of bounces or percentage of DCIEM time limits, Pearson's or Spearman's rank correlation coefficient was calculated and tested for significance of association, depending on whether data were continuous or categorical. Two-way analysis of variance was used to assess the relative contributions of independent variables to the dependent variable, Doppler bubble grade. It was planned to undertake multiple regression analysis to assess factors identified in the pre-dive questionnaire and also dive-related factors that affected bubble grades in this population of divers, if sufficient divers recorded unacceptable bubble grades.

It was predicted that more than 90% of divers would produce KM bubble grades of 2 or less, consistent with low-risk profiles, based on data from chamber attendants diving a 14 msw table at Royal Hobart Hospital.[15] If more than 50% of divers experienced bubble grades 3 or 4, then the profile would be rejected and the industry would be advised to modify their decompression table for that series of bounce dives. If less than 50% of divers had bubble grades 3 or 4, then profiles would be recorded as acceptable risk. Using sample size of 20 dives at each depth, this study had 80% power to detect an absolute 40% difference between the proportion of divers expected to have bubble grades 2 or less, and the point at which we rejected a given dive profile (using $\alpha = 0.05$). Being a field study in a workforce environment, it was recognised that there may be some deviation from the ideal, due to issues beyond our control.

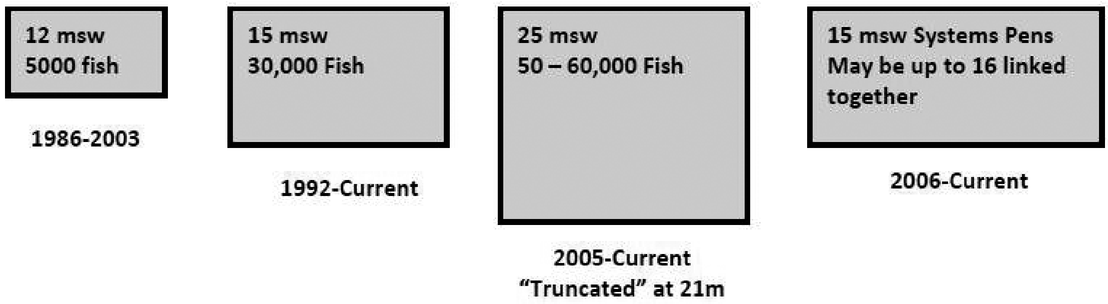
Hence, we aimed for a cohort sample of over 100 bounce-dive series, and a minimum of 20–25 bounce-dive series for each individual depth range. This would allow data collection consistent with DCIEM methods across the four most frequently dived profiles: 10–12 msw, 13–15 msw, 16–18 msw and 19–21 msw. The expected incidence of decompression illness over 100 dives was zero. The 95% confidence limits for 100 samples are 0–3.6 % risk of DCI, and for 20 samples are 0–16.8% risk of DCI, using the binomial distribution. There are recognised statistical limitations to proving dives are acceptable risk by defining DCI as a binary outcome (yes or no), given these wide confidence limits.[16,17] This is further limited if the index event (DCI) has a low incidence. The 1999 study observed only 0.57 cases of clinical DCI per 10,000 dives over the 1996–98 study period.[4]

Results

IMPACT OF EXTERNAL FACTORS ON DATA COLLECTION

This study required some adjustment to keep up with concurrent evolution of technology and dive practices occurring within the industry. At the commencement of the study, only two salmon pen sizes existed: 80 m circumference, 12 msw depth and 120 m circumference,

Figure 4
Evolution of salmon pens by depth and size during the course of the study



15–16 msw depth. The 12-msw pens were superseded in early 2003, preventing sufficient data collection of dive times close to DCIEM no-stop limits for 12 msw (150 min). The evolution of salmon pens is shown in Figure 4. Because of logistical issues, 25-msw pens were 'truncated' with a false bottom at 21 msw.

In addition, some farms expanded significantly, which increased the travel time between pens, and caused many dives to become repetitive dives because surface intervals exceeded 15 min. This reduced the numbers of bounce-dive series that were available for analysis. Unpredictable local events also had a negative impact on data collection. On more than 10 occasions, authors arrived at the salmon farm, ready for data collection, only to discover that work priorities had shifted that day to fix an emergency (e.g., seal strike on a pen – see journal cover image, mooring or other issues), and the bounces for that day had been cancelled. After a full day's expedition, with 80–100 km travel in either direction, no data were collected. This prolonged data collection to 6 years (May 2002 to March 2008).

Complete field data were collected from 55 different divers undertaking 150 bounce-dive series totalling 1,110 bounces (mean 7.4 bounces per series, SD 3.1). The 55 male divers (mean age 27.6 (SD 5.1) years, height 179.0 cm, weight 84.0 kg, BMI 25.7 kg·m^{-2}) were all professionally trained to minimum of AS/NZS 2815.2 (aquaculture-restricted).[18] All divers had not dived for more than 18 hours prior to commencing their bounce-dive series. The average water temperature during data collection was 12.3°C (range: 8–15°C). Four bounce-dive series were excluded from the analysis (total 16 bounces), three because the dive series extended too deep (22 msw – bubble grades 0, 1 and 2) and one because the diver suffered sinus barotrauma.

Figure 3 shows a sample recording from a bounce-dive series of nine individual bounces, to a maximum depth of 14.33 msw and surface-to-surface duration 73 min 46 seconds. The diver undertook a 5-min decompression stop spent at 3 msw in accordance with protocol, during the last ascent. The maximum recorded ascent rate was 18.3 msw·min^{-1}. Note the in-water time for the above dive was 55 min, and bottom time was 65 min.

BUBBLE GRADES AND BOUNCES FOR VARIOUS OPERATIONAL DEPTHS

Table 1 summarises mean in-water times, bottom times and median number of bounces for each depth. Apart from the 12-msw series, all depths had mean in-water durations that exceeded 80% of DCIEM table limits, and bottom times (adding all surface intervals between bounces and in-water times) that exceeded DCIEM limits.

Table 2 summarises the numbers of bounce-dive series and individual bounces undertaken by the divers and their bubble grades, stratified by dive depth. Twenty-two divers were evaluated after diving at different depths on different days; hence there were 77 subjects who contributed data across

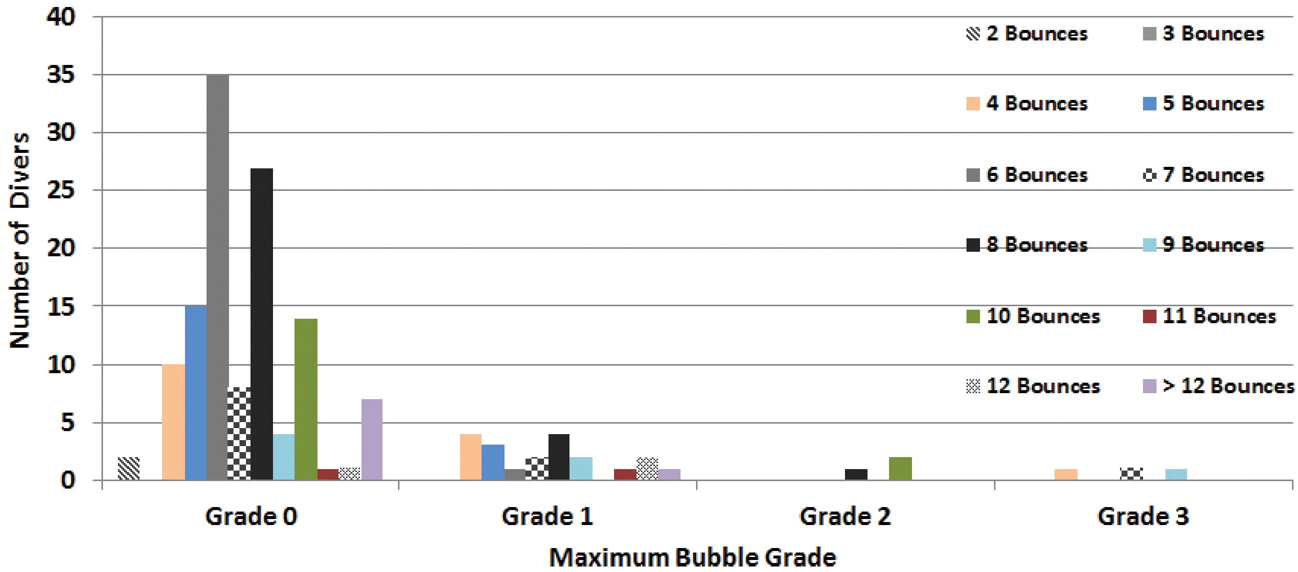
Table 1
Mean in-water times, bottom times and median number of bounces for each depth; Inter-quartile range – IQR

Depth (msw)	Mean in-water time (min)	DCIEM limit (min)	Mean bottom time (min)	Mean surface interval (min)	Median number of bounces (IQR)	Mean in-water time as % DCIEM no-stop limit	Mean bottom time as % DCIEM no-stop limit	Median bubble grade
≤–12	40	150	74	34	8 (8)	26	51	0
13–15	61	75	98	37	7 (6–10)	81	131	0
16–18	56	50	106	50	6 (5–9)	112	215	0
19–21	32	35	77	44	4 (4–6)	91	218	0

Table 2
Bounce dive series and individual bounces undertaken by the divers and their bubble grades, stratified by dive depth

Depth (msw)	Number of divers	Number of bounce dive series	Median number of bounces (range)	Bubble grades 0	1	2	3	Total bounces
≤ 12	10	24	8 (7–12)	22	2	0	0	194
13–15	41	82	7 (4–21)	63	14	3	2	651
16–18	18	32	6 (2–20)	24	7	0	1	207
19–21	8	12	4 (2–8)	8	3	1	0	58
Total	77	150	7 (2–21)	117	26	4	3	1,110

Figure 5
Bubble grades for all 150 dive series split by bounce numbers



the four depth ranges in Table 2.

Overall, 97% of bounce-dive series evaluated were low stress (Doppler grades less than 3), well within DCIEM tolerances. The median bubble grade for all 150 bounce-dive series was 0 (Figure 5). No divers experienced any symptoms suggestive of DCI post dive and none of the subjects required treatment for DCI during the study period.

From available bounce-series data, three dive depth ranges had sufficient data for evaluation of DRDC tolerances (because the in-water times were greater than 80% of DRDC limits) to test hypothesis (a). Data were incomplete for the bounce-dive series conducted up to 12-msw depth, owing to the industry adopting deeper salmon pens early in the study.

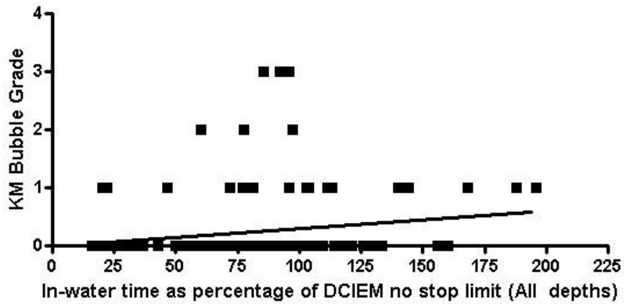
EFFECT OF IN-WATER TIMES

At 13–15 msw, the mean in-water time (61 min) was 81% of the DCIEM no-stop limit, and bounce-dive series up to 10 bounces resulted in a median bubble grade of 0. Twenty per cent of the bounce dive series in this depth range exceeded the DCIEM limit of 75 min; these data were regarded as valid for the reasons outlined in the discussion. The 16 bounce-dives series which exceeded DCIEM limits were evaluated in more detail. In-water times ranged from 76 to 126 min, mean 86.3 min. The mean cumulative SI between bounces was 36 min, and the median number of bounces was 10 (range 6–21). Twelve of these longer-duration bounce-dive series produced grade 0 bubbles and four produced grade 1 bubbles. Divers undertaking bounce-dive series with in-water times less than 75 min had lower median numbers of bounces (six per dive series), and less time on the surface (21.5 min).

At 16–18 msw, divers had a mean in-water time of 56 min, which exceeded DCIEM no-stop limits. All 24 bounce-dive series with six or fewer bounces resulted in a median bubble grade of 0, provided bottom time did not exceed 50 min.

Eighteen of 32 bounce-dive series exceeded DCIEM table limits of in-water times for this bounce-series depth range, so were evaluated in more detail. In-water times ranged from 52 to 98 min, mean 66.0 min. These dives had an average of 67

Figure 6
Graph comparing in-water dive duration (as percentage of DCIEM air table no-stop limit) and bubble grade showing positive correlation trend line



min cumulative SI, and the median number of bounces was six (range 2–20). Twelve of these longer-duration bounce dive series produced grade 0 bubbles and six produced grade 1 bubbles. Divers undertaking bounce dive series with in-water times less than 50 min had median numbers of 5.5 bounces, and less time on the surface (31.2 min).

At 19–21 msw, the mean in-water time (32 min) for the 12 bounce-dive series was 91% of the DCIEM no-stop limits. Ten of the dive series undertook up to six bounces with median bubble grades of 0. Four of the 10 bounce-dive series exceeded the DCIEM no-stop limits in this group, but because of small numbers and only four diver series having six or more bounces, the data are less robust.

There were insufficient data from the less than 12-msw range for evaluation because the average in-water time was only 26% of the DCIEM limit (mean in-water time 40 min, range 24–75 min; mean bottom time 74 min, range 53–139 min). Even allowing for this, it was apparent that a median of eight bounces did not result in significant decompression stress at 12 msw during these short-duration dives.

IMPACT OF BOUNCE DIVING ON DECOMPRESSION STRESS AS MEASURED BY BUBBLE GRADE

The correlation between the number of bounces and bubble grades for all 150 bounce-dive series was not statistically significant (Spearman $r = 0.07$, $P = 0.42$). When stratified by depth ranges, a trend towards significance was identified for the relationship between number of bounces and bubble grade in the 13–15 msw range. (Spearman $r = 0.21$, $P = 0.06$). No depth ranges had statistically significant relationships between numbers of bounces and bubble grades. Bubble grades of 0 were recorded in 78% of divers. There was no significant difference in the mean number of bounces performed by divers with 0 bubble grade (7.3, SD 3.1) compared to those with higher maximum bubble grades (7.4, SD 3.5); difference between the means -0.048 +/- 0.64, 95% CI -1.3 to 1.2, $P = 0.93$).

Figure 6 plots the relationship between in-water dive duration and bubble grade, which was statistically significant (Spearman $r = 0.23$, $P = 0.004$). This suggested that the possible trend observed for number of bounces and bubble grades may have been influenced by in-water dive duration. There was a highly significant relationship between number of bounces and in-water dive duration (Pearson $r = 0.28$, $P = 0.0006$). This was logical because, as divers undertook more bounces in the dive series, their dive duration increased.

The relationship between bubble grade and bottom time as a percentage of DCIEM limit, was statistically significant (Spearman $r = 0.17$, $P = 0.03$). Bottom time included (variable) time that divers spent on the surface during their bounce-dive series.

OTHER VARIABLES AFFECTING DECOMPRESSION STRESS

Pre-dive questionnaires identified that four divers experienced health issues prior to diving: one with gastroenteritis the day prior, one with a hand injury, one with epistaxis and one with a torn thigh muscle. None of these divers had bubble grades > 2. Intra- and post-dive factors included two divers being harassed by seals, and another undertook a very hot shower. Multiple sub-surface bouncing occurred in two bounce-dive series and four divers missed their scheduled decompression stops. None of these divers recorded a bubble grade > 1. The diver with sinus barotrauma was excluded from analysis as no Doppler readings were taken.

We also assessed whether or not recent diving influenced bubble grade. Although all divers commenced their bounce-dive series with a DCIEM repetitive factor of 1.0, some had dived the previous day(s) and some had not. When stratified as two groups – dived previous day versus not dived – there was no significant difference in bubble grades. We did not collect precise data on the time interval from the previous dive if it was greater than 24 hours.

The mean ascent rate for all divers was 18.8 (range 9–40) $msw \cdot min^{-1}$. Recommended DCIEM ascent rates were exceeded on 12 dive series (8% of total). None of the divers with rapid ascents had higher than grade 2 bubble, but the relationship between ascent rate and bubble grade was statistically significant (Pearson $r = 0.16$, $P = 0.046$).

The data were further analysed for sources of variance. In-water dive duration (per cent of DCIEM limit) accounted for 72.5% of the variance of bubble grades, and was highly significant ($P < 0.0001$). The ascent rate accounted for 13.8% of variance in bubble grade and was not significant ($P = 0.32$). Only 3.7% of variance was attributable to the number of bounces ($P = 0.47$). A multiple regression equation was calculated from available data, and the relationship between maximum bubble grade and the other three variables was significant in the model ($P = 0.04$):

Figure 7
DCI cases treated at Royal Hobart Hospital 1989–2010 showing trends for salmon farm divers

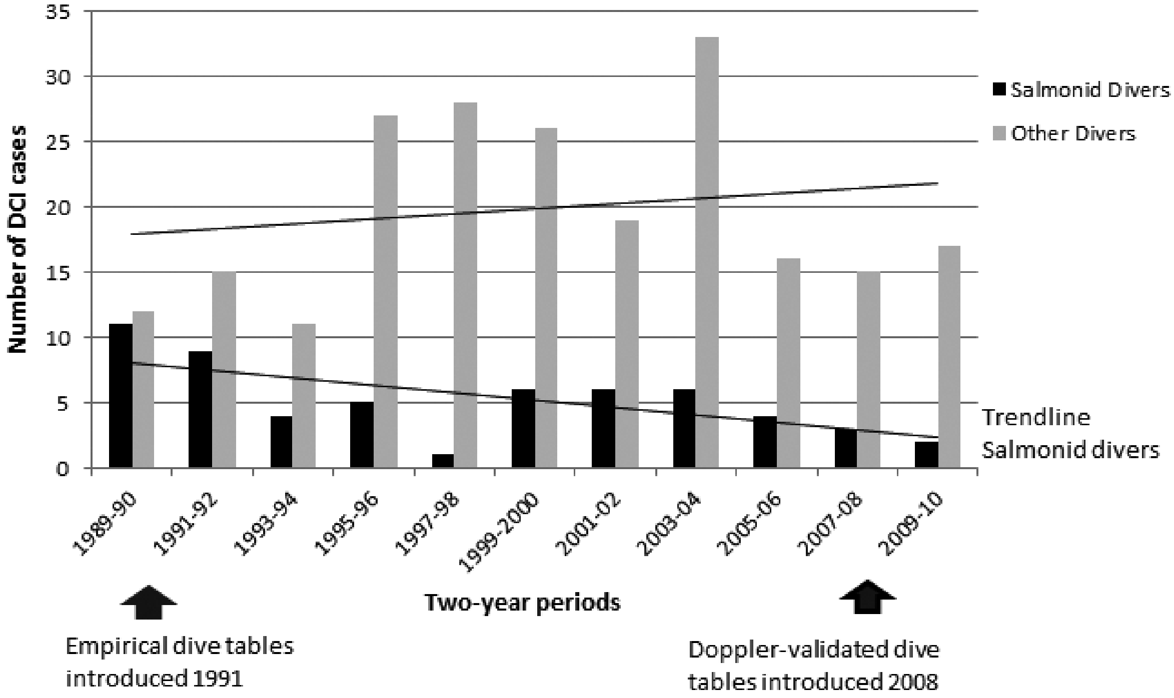


Table 3
DCI incidence compared to number of dives, number of divers and tonnage of fish

Period	Number of divers	Number of dives	Number of cases of DCI	Tonnes of fish	DCI rate per 10,000 dives	DCI rate per 100 diver years	DCI rate per 1,000 tones of fish
1989–1990	50	4,200	11	1,260	26.19	11	17.46
1993–1994	87	11,200	4	8,824	3.57	2.3	0.45
1997–1998	81	17,542	1	16,264	0.57	0.6	0.06
2003–2004	143	44,100	6	29,977	1.36	2.1	0.20
2008–2009	108	33,320	3	59,641	0.90	1.4	0.05

$$MBG = -0.42 - 0.0021 * N + 0.024 * A + 0.0029 * T \quad (1)$$

where MBG = maximum bubble grade for dive; N = number of bounces; A = maximum ascent rate; T = in-water time as percentage of DCIEM no-stop time.

DCI EPISODES FROM THE AQUACULTURE INDUSTRY

Over two decades of study, one of the authors (DS) has surveyed the aquaculture industry at 4–5-year intervals to determine the number of divers and number of dives undertaken. The last survey was undertaken in late 2008 at the end of study data collection. Table 3 demonstrates a fall in the incidence of DCI when measured per number of dives, number of dive years and tonnage of fish production. The DCI incidence for 2008–2009 was 1 per 11,106 dives.

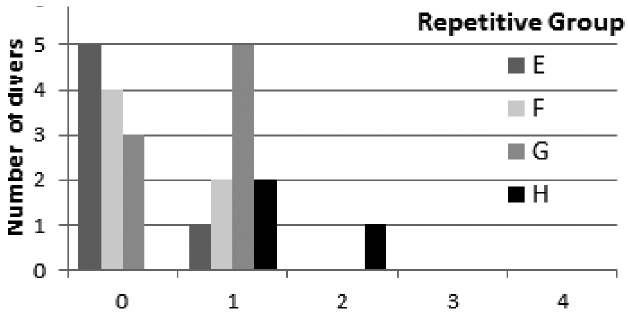
Figure 7 depicts all DCI cases treated at the DDHM from 1989 to 2010 in 2-yearly intervals. The population is split into two groups: salmonid divers and all other divers. All other DCI cases include other professional divers (e.g., abalone, inshore, offshore and scientific), recreational scuba and hookah divers. Since 1989, the numbers of cases from the aquaculture industry (salmonid divers) show a statistically significant falling trend (test for trend, $\chi^2 = 23.6$, $P = 0.008$), compared with all other DCI cases, which are increasing. The trend continued to 2010, beyond the end of the study period. The time points at which the empirical and Doppler-validated dive tables were introduced are marked below the X axis.

DOPPLER ANALYSIS OF TWO SETS OF BOUNCES

In response to an industry request, we undertook Doppler measurements on divers conducting two series of bounces in a day. This practice was already occurring at one company, and hence the measurements were observational of an existing (and unchecked) practice, rather than testing a new hypothesis. In response to the request, the authors advised that there should be strict guidelines governing the two sets of bounces, so that results would be reproducible and of practical use. The guidelines to allow two sets of bounces on the same day are outlined in Table 4.

The results of Doppler analysis of two consecutive bounce dive series using the above criteria were available from 23 divers. All first bounce-dive series were 16–18 msw. The depth range for the second bounce-dive series was 16–18 msw (mean 17.7 msw, mean duration 38 min, median number of bounces 4). Following the second set of bounces, the maximum bubble grade for any diver was 2, with a group median of grade 0 and the divers had DCIEM repetitive groups E to H (Figure 8), Bubble grades broadly followed the repetitive groups – as the repetitive group increased, so did the bubble grade.

Figure 8
Doppler grades and DCIEM air table repetitive groups after a second series of bounce dives



Discussion

This study took over six years to obtain sufficient field data in three depth ranges to confirm low risk from bounce diving. Many of the challenges are described in the results, and these demonstrate the difficulties of conducting field research on working divers. It was not logistically possible to evaluate every dive depth range with 100 samples. In addition, it was important that the assessed dives were sufficiently provocative: producing enough decompression stress to provide valid guidance in table development. In developing or testing tables and dive procedures, the number of dives that can actually be done is driven more by practical considerations than by trying to meet statistical criteria. Compromises have to be made and around 20 man-dives per profile without a DCI incident has been considered to be acceptable.[17] This was followed for our field study of aquaculture divers, but limiting depth ranges to those being dived operationally.

Ninety-seven per cent of dive profiles evaluated in this series were low stress (Doppler grades 2 or less), well within DRDC Toronto tolerances. Whilst this provided evidence of acceptable risk, it also led to difficulties with any multivariate analysis of causation of decompression stress, because very few dives were of sufficient stress, as defined by KM bubble grades. The only factors linked to higher decompression stress were the time spent in the water as a percentage of the DCIEM table limit and ascent rates.

A surprising result was the lack of correlation between number of bounces and Doppler bubble grades, and the overall low grades measured in the divers undertaking bounce diving. A number of factors may have influenced this result. Firstly, we may not have 'pushed' the divers into sufficient nitrogen uptake to create high decompression stress (i.e., dives may have been too conservative). In working divers, this conservative approach is justified. The divers were already using DCIEM tables to guide their practice; however, the study was observational so we did not seek to influence their dive practices whilst they were occurring. It was our aim to record a dataset that was close to table limits, and this was achieved for depths 13–15 msw, 16–18 msw and 19–21 msw. Our data support the use of DCIEM no-stop table limits as a guide to risk reduction when bounce diving. Only 8% of divers exceeded recommended ascent rates, and this also would have reduced risk. Even though the divers were blinded to the data recorder they were wearing, they may have been extra careful knowing their dive was being monitored as part of the study.

Some Doppler studies have used integrated scoring systems to evaluate progression of bubble grades over time, rather than peak values. A well known example is the Kisman Integrated Severity Score (KISS).[19,20] KISS provides a broader representation of bubble activity over time by estimating 'the area under the curve'. We did not calculate KISS in this study because we were interested in the maximum bubble grades at rest and with movement. As operational divers, the salmon farm population were active between dives, and this may have led to transient bubble release from activity (similar to the movement case), which is generally greater than the steady state at rest. As bubble grades of 0 were detected in 78% of divers in this study, KISS would have been zero for the majority of the divers. Although KISS provides a broader representation of bubble grades over time, it still does so only at fixed time points, 20 minutes apart. Given that 97% of the dives in this series were grade 2 or less, and there were no cases of DCI, we believe that the outcomes are consistent with acceptable levels of risk in the industry. Our original aims of the study were to investigate what was happening operationally and monitor working divers. There was no significant difference in the number of bounces performed by divers with bubble grade 0 compared to those with higher maximum bubble grades. This suggests that undertaking KISS calculations may not add further to the conclusions; however, we do

Table 4
Tasmanian Bounce Diving Tables
Criteria for two consecutive series of bounce dives

1. Divers are required to be DCIEM Repetitive Factor 1.0 at the commencement of the first bounce-dive series.
2. The maximum depth for the first bounce-dive series is no more than 18 metres.
3. The in-water time for the first bounce-dive series is calculated as the time from commencing first descent to the time of exiting the water, minus the sum of all time spent on surface intervals. The in-water time includes time spent in the water for the decompression stop.
4. The repetitive group for DCIEM tables is calculated from the first bounce-dive series in-water time, after surfacing.
5. A minimum surface interval of 2 hours must occur between the first and second bounce-dive series.
6. The repetitive group is then used to calculate the allowable bottom time for the second bounce-dive series.
7. The maximum depth of the second bounce-dive series shall be no deeper than the maximum depth of the first bounce dive series.
8. The number of allowable bounces in the second bounce dive series shall be restricted to half the number of the first bounce-dive series (maximum of 5 bounces), and with maximum bottom time as defined by the DCIEM repetitive group allowable bottom time.

Table 5
Tasmanian Bounce Diving Tables

Depth (metres)	Number of allowable bounces in dive series	In-water† dive time limit (min)
≤ 9	10*	300‡
10–12	10*	150‡
13–15	10	75
16–18	6	50
19–21	4	35
> 21	Use DCIEM repetitive dive tables	

1. Ascent rates shall be ≤ 18 metres per minute;
2. Surface intervals between bounces shall be < 15 minutes;
3. 3-minute decompression stop at 3 metres shall be performed during the last ascent;
4. A second bounce dive series is possible after a 2- hour surface interval, provided specific criteria are obeyed (Table 4).

Notes:
* Bounce numbers based on validated safety of 13 to 15-metre bounce-dive series;
† In-water time limit defined as: *the total time the diver spends in the water, minus the time spent at the surface during surface intervals. It does include the time of the last ascent and the decompression stop.*
‡ It is recommended bounce-series dive times are less than DCIEM table limits until fully validated.

plan to publish the calculations along with additional data, in a subsequent paper.

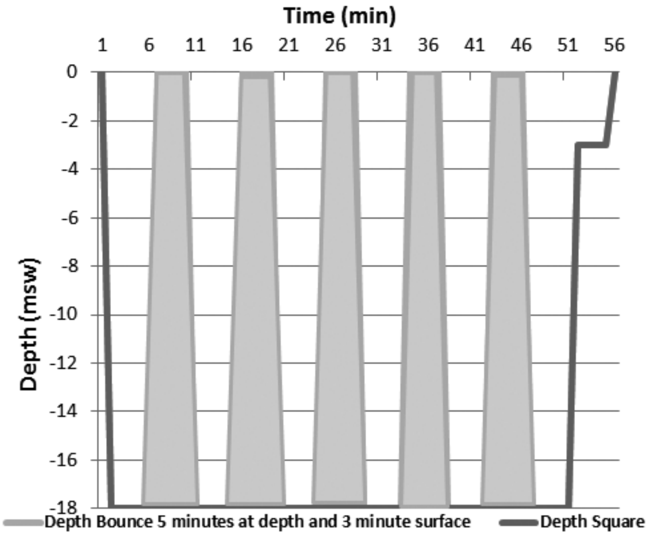
We also recognise the limitations of our method for calculating decompression stress using Doppler ultrasonic bubble detection. Recent use of 2-D echocardiography has demonstrated good intra- and inter-rater reliability, and may supersede aural grading systems in the future.[21] These systems are still recognised as semi-quantitative. Aural Doppler still has advantages for field research in that it is faster to undertake and divers can assist with accurate probe placement. Although scoring requires an experienced operator, the same is required for accurate images using 2-D echocardiography.

In this study, total in-water time did not take into account the surface interval between dives or that any off-gassing took place during this interval. It appears that there is sufficient off-gassing during the surface intervals, so that the 'effective' bottom time is less than or equal to the DCIEM limit even though the sum of the actual times spent on the bottom may exceed the DCIEM limit. This was illustrated by the data from the 16–18 msw depth range. Divers who exceeded DCIEM time limits for bottom times spent the same amount of time at the surface as they did in the water. There was time to off-gas between each individual bounce dive, which would have reduced nitrogen load in the body.

In addition, the criterion of restricting in-water time to less than the DCIEM limit added conservatism because this time includes all ascent times plus the 3-min decompression

Figure 9

Theoretical bounce-dive series showing five returns to the surface before completing the dive on the sixth ascent (the shaded areas reflect less nitrogen absorbed compared to a square dive profile)



stop on the last bounce. If there are seven bounces, then this reduced the time spent at depth by 10 min less than the DCIEM limit. With 12 bounces, the reduction was 15 min. Because bottom times included surface intervals, with a large number of bounces, the DCIEM limit for *bottom time* could be exceeded, but the *in-water time* could be less than the DCIEM limit. Hence less depth-time exposure may have offset the multiple decompressions. The decompression stop may have independently reduced risk of decompression stress, although this was not assessed in the study.

The above factors provide an explanation for the low decompression stress observed in our data. Bounce diving has reduced the 'area under the curve' compared with a square dive profile – hence, there would be less nitrogen uptake during the ascent, surface interval and descent phases of each surface bounce, compared to staying at depth (Figure 9). In Figure 9, the diver conducting bounce diving has five returns to the surface with a bottom time of 48 mins. Compared to the square dive profile, the bounce diver has less depth-time exposure by the equivalent of 20 min at 18 msw (i.e., the diver had 42% less depth-time exposure). An additional factor may have been that there was insufficient time for bubbles to grow until after the last ascent because divers were under pressure again quickly following their brief surface interval (akin to surface decompression diving). Finally, we cannot rule out other factors such as vibration from boat engines as divers travel between fish pens, which may have a protective effect.[22]

Our data are also consistent with mathematical modelling of yo-yo diving conducted by Flook who concluded: "*yo-yo diving of the type traditionally practised in fish farm diving can be very safe and that dividing the total bottom time into several shorter dives alternating with a surface interval is less of a risk than diving the envelope*."[23] Lower risk of DCI has been demonstrated in rats and pigs undertaking yo-yo diving with 2 or 3 ascents compared with single ascents.[24] Our data are the first to confirm that 'bounce' or 'yo-yo' dive profiles as part of routine occupational diving activities can be conducted with acceptable levels of risk.

A number of divers exceeded the defined DCIEM in-water time limits during this study: 16 of 82 at 13–15 msw, 18 of 32 at 16–18 msw, and 5 of 12 at 19–21 msw. These breaches of rules usually occurred accidentally, because divers were not aware of the exact depth of each salmon pen as they entered. For example, the centre of the pen may have been conical rather than flat, and the dead fish were situated 1–2 m deeper in the "*mort cone*" than the average depth of the bottom of the pen. The real-time dive data in Figure 3 demonstrates how brief some of the dips to maximum depth actually are. DCIEM limits apply only to the maximum depth in a given depth range. At the lower end of the depth range, the DCIEM limit would be considerably longer. For example, DCIEM modelling would allow an additional 10 min of diving at 17 msw compared to 18 msw. The divers' depths were clearly variable during all the bounces, and they were only at maximum depth for brief periods. Given these considerations and the inherent conservatism of the in-water definition, the inclusion of the data which exceeded DCIEM limits is supportable.

Bubble grades and dive duration as a percentage of the no-decompression DCIEM time limit demonstrated a significant positive correlation. This result was expected because previous research has demonstrated that as the diver approaches known decompression limits, their risk of bubbling increases.[6–14,16,17,25] Ascent rates also had a significant correlation with decompression stress. This emphasised the importance of maintaining ascent rates consistent with DCIEM recommendations and adding the routine decompression stop.

We have been able to demonstrate that it is possible to undertake bounce diving using DCIEM tables to guide depths and times. On the basis of these results we have been able to increase the permissible number of bounces at each depth compared with the earlier empirical restrictions. Our recommendations for dive times and numbers of bounces are summarised in Table 5 – *The Tasmanian Bounce Diving Tables*. These recommendations have the proviso that in-water dive times must not exceed DCIEM limits for a given depth, that ascent rates are kept at less than or equal to 18 msw min^{-1}, and that a 3-min decompression stop at 3 msw occurs during the last ascent.

We have been conservative in recommending a maximum of only four bounces in the 19–21 msw range, because our data for six or more bounces was based on only four divers. We also have less certainty regarding the 7–9 msw and 10–12 msw tables and this may be further investigated if industry technology changes in the future to using shallower pens. We recommend no more than 10 bounces in a series, and staying well inside DCIEM no-stop time limits for ≤ 12 msw, until further research has occurred. This recommendation may be overly conservative; however, it does allow some flexibility and a margin for untoward events.

Given that the majority of divers (126/150, 84%) contributing data had undertaken diving the previous day, or on multiple days prior to measurement day, we consider that our data are robust enough to be generalised, and may be applied to industries that require bounce diving as part of their operations on a day-to-day basis. We did not evaluate the possible risk factor for DCI resulting from a prolonged layoff (more than three days) before diving. Given that 97% of the dives in this series were grades 2 or less, and there were no cases of DCI, it is unlikely the study would have had the power to inform this question.

Following implementation of the Doppler-validated Tasmanian bounce diving tables in 2008, the industry benefitted from improvements in productivity, compared with the previous empirical bounce limits set in the early 1990s. The number of pens dived (or allowable bounces per dive series) increased by 25% from eight to 10 at 10–12 msw, by 50% from four to six at 16–18 msw, by 100% from two to four at 19–21 msw and by 150% from four to 10 at 13–15 msw. Dive times in the new tables are based on in-water times, whereas they were previously based on bottom times. There was additional productivity advantage from undertaking a second bounce-dive series in the same day and this was also validated by our research. We have demonstrated that, with strict criteria, it is possible to conduct a second series of bounces after an earlier first series. This will permit a diver to undertake up to 15 bounces in 15-msw-deep pens on the same day, provided the rules set out in Tables 4 and 5 are obeyed.

The improvements in productivity have occurred with continued downward trends in DCI episodes from the industry. This study demonstrated a fall in incidence of DCI when measured per number of dives, number of dive years and tonnage of fish production, over the last two decades. The reductions in DCI incidence have been maintained (Figure 7), despite relaxing the bounce limits as a result of this study. Other factors such as professional training of divers, appropriate use of dive tables, more effective diving procedures and substitution of tasks for some risky diving practices are likely to have contributed to this improvement in safety.[3] Had the industry incidence of DCI remained at 1990 levels, there would now be 44 cases of DCI treated at DDHM per annum based on incidence per 10,000 dives: or over 500 DCI cases per annum based on tonnage of fish. The industry has become more efficient regarding fish production and less diver-dependent for some tasks, such as net cleaning. The Tasmanian aquaculture industry is rapidly evolving, and with this evolution there are further changes in diving practices, and calls for greater flexibility. There have been requests to combine square dive profiles before or after bounce diving. We have received requests to assess deeper bounce-dive series, and also to complete the data collection on bounce diving in pens less than 9 msw. In addition the impact of nitrox diving, exercise post diving and ascents to altitude (very relevant in Tasmania) on decompression stress have yet to be tested.

Conclusions

This study has permitted significant improvements in productivity for the Tasmanian aquaculture industry between depths of 13 to 21 msw whilst maintaining a good safety record. Our data suggest that bounce diving was not a major factor causing DCI in Tasmania's aquaculture divers in the late 1980s and early 1990s. The industry is to be congratulated for embracing multiple improvements to diving procedures and improving diver training. In this research we have come full circle. A safety problem was detected and, with industry cooperation, controls were implemented, which were successful in reducing risk. Finally, we have been able to tailor some solutions to meet industry needs. It is a process of continual cooperation and evolution, and further study is ongoing.

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Disclosure

Associate Professor Smart receives income from occupational diver health assessments and treatment of divers with decompression illness.

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