PASSIVE ACOUSTIC MEASUREMENT OF DIVE VOCAL BEHAVIOR AND GROUP SIZE OF BLAINVILLE'S BEAKED WHALE (*MESOPLODON DENSIROSTRIS)* IN THE TONGUE OF THE OCEAN (TOTO)

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ABSTRACT

The vocal behavior of Blainville's beaked whale (*Mesoplodon densirostris)* was measured using the bottom-mounted hydrophones of the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas. The statistics for the vocal durations and gaps within these vocal periods were measured over multiple deep foraging dives. The sizes of foraging groups of *M densirostris* were estimated from the dive vocalization durations by applying click rate and detection ratio statistics derived from Woods Hole Oceanographic Institution (WHOI) Digital recording Tags (DTags) to visually verified data collected on the AUTEC range.

SOMMAIRE

Le comportement vocal de la baleine à bec de Blainville (*Mesoplodon densirostris)* a été mesuré à l'aide d'hydrophones installés sur le fond marin, au Centre d'évaluation et de tests sous-marins de l'Atlantique (AUTEC, de l'anglais Atlantic Undersea Test and Evaluation Center) des Bahamas. Les statistiques relatives à la durée des signaux acoustiques et les périodes qui s'écoulent entre les périodes de « chant » ont été mesurées pour des plongées multiples en profondeur (en comportement de recherche de nourriture). La taille des groupes de *M. densirostris* en recherche de nourriture ont été estimés d'après la durée des périodes de chant en plongée, en appliquant le taux de « clics » et des statistiques sur le rapport de détection dérivés des enregistrements numériques du DTags de la WHOI (*Woods Hole Oceanographic Institution*), afin de visualiser les données recueillies au centre AUTEC.

1. INTRODUCTION

Tests of a marine mammal passive acoustic monitoring, detection, and localization system have been carried out at the U.S. Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) training range in conjunction with the Bahamas Marine Mammal Research Organization (BMMRO) and the Woods Hole Oceanographic Institution (WHOI). BMMRO trained observers were directed to vocalizing animals on the range based on passive acoustic detections and localizations. They visually verified species and group size, and obtained photo-IDs of animals. WHOI placed DTags on 7 Blainville's beaked whales (*Mesoplodon densirostris*). The DTag records pitch, roll, heading, and depth, and records acoustic signals using stereo hydrophones. The tag provides detailed data on the tagged animal's movements and vocalizations.

The AUTEC range is located in a deep ocean canyon known as the Tongue of the Ocean (TOTO) off Andros Island in the Bahamas. The range consists of 82 bottom-mounted hydrophones that are deployed up to depths of 2000 meters. Sixty-eight of the hydrophones are arranged in offset rows on approximately 4 km baselines. The bandwidth of these hydrophones is 50 Hz to approximately 45 kHz. Fourteen additional hydrophones are arranged into two 7-hydrophone hexagonal arrays with a center hydrophone. These hydrophones are separated by a baseline of about 1.2 km and have a bandwidth from 8 to 50 kHz [6, 7].

Since 2004 *M. densirostris* has been the focus of this research, as it is the species generally sighted by observers at AUTEC, and is frequently detected acoustically on the range. This species has been associated with mass strandings linked to Navy sonar.

In a study from 1997-2002 in the Northern Bahamas, D. Claridge found the mean group size of *M densirostris* to be 4.1, with group sizes ranging from 1 to 11 animals [2]. Pairs of both *M. densirostris* and *Z. cavirostris* tagged simultaneously with DTags have been reported to dive and subsequently approach the surface in close proximity [5, 10]. Visual observations of *M. densirostris* at AUTEC by BMMRO observers on the water and passive acoustic monitoring on-shore also indicate that these animals dive as a group and vocalize at depth. Personnel acoustically monitoring the AUTEC range hydrophones detect groups of *M. densirostris* across the range throughout the course of any given day. This species is known to dive to depths in excess of 1200 meters [1, 8]. These dives are separated on

average by about 2 hours and the dive duration may exceed 60 minutes [1]. Vocalizations are produced only at depth during foraging. Vocalizations generally occur below 200 m [3].

M. densirostris produce short (~250 μs) frequency-modulated upsweeps from approximately 25 to 55 kHz, with an inter-click interval (ICI) of 0.2 to 0.4 s [3, 4]. The beam pattern of another beaked whale species, Cuvier's beaked whale (*Ziphius cavirostris*), has been shown to be highly directional [10]. The same *M. densirostris* clicks are often detected concurrently on only 1 or 2 hydrophones, depending on the animal's bearing and direction of movement, making localization difficult. However, as individuals in the group move during foraging, the group's clicks are detected on a number of surrounding range hydrophones, with click detections often shifting back and forth between adjacent hydrophones. When a group of *M. densirostris* starts vocalizing, a few intermittent clicks are often heard before they start clicking fairly consistently on the surrounding hydrophones. Similarly, as foraging comes to an end, a few intermittent clicks can still be detected after consistent clicking has ceased.

Clicks are detected using a multi-stage FFT-based energy detector [7]. The sample rate for the data is 96 kHz. A 2048-point FFT with 50% overlap is used. It provides a 46.875 Hz frequency resolution and a 10.67 ms time resolution. An adaptive threshold is run in each bin of the FFT. If energy above threshold is detected, the bin is set to a "1" and a detection report is generated. *M. densirostris* clicks are then isolated based on the frequency distribution of the detected signal [6].

Raw acoustic, click detection, and localization data have been collected at the AUTEC range during these tests. For this study dive vocalization durations of *M. densirostris* were measured from the click detection data, and a method was developed to estimate *M. densirostris* group size given this dive vocalization duration.

Groups of vocalizing beaked whales were isolated and the durations of the vocal periods during the dives for the groups were measured. Gaps in the vocalizations during these vocal periods were also measured.

To estimate group size, a normalized detection ratio and mean click rate was derived from DTag dive data. The normalized detection ratio is the ratio of total number of clicks detected on the array to the product of the total number emitted by the tagged animal multiplied by known group size and the number of hydrophones in the array. These data were used to predict the number of animals in another group based on the total number of clicks detected for this group during its dive vocal period on a hydrophone array.

In October of 2006, a WHOI DTag was attached to a Blainville's beaked whale at the AUTEC range in the Bahamas. The tag was recovered after 17 hours. Five deep foraging dives were recorded. Statistics from three of these dives were used as a predictor of group size using verified data collected at AUTEC during an independent exercise conducted with BMMRO visual observers.

2. METHODS AND RESULTS

2.1 Vocal Behavior

Click detection data from a species verification test conducted at AUTEC in April, 2005 with BMMRO and from a test conducted with The Technical Cooperation Program (TTCP) at AUTEC in February, 2007 were analyzed to quantify the vocalization periods for groups of diving *M. densirostris*. Groups were isolated and baseline dive vocalization durations were measured.

A program that recorded the start and stop time of beaked whale detections on each hydrophone was run on archived detection data. The program recorded a start time when a beaked whale click was detected on a hydrophone. A 60-second timer was then initialized for this hydrophone. If a detection did not occur within the 60-second window, the timer was stopped, and the time of the last detected click marked as the stop time. Each time a new click was detected, the timer was reinitialized. The program output the start time, stop time, and total click count for each hydrophone that had detections. The total click count is the number of clicks detected between a single start and stop time on a single hydrophone.

To isolate animal groups and measure dive vocalization durations, the start and stop data from groups of adjacent hydrophones were overlaid on a single plot. Generally, 7-phone arrays centered on the presumed group location were examined. AUTEC hydrophones are laid in offset rows with a baseline of ~4 km to form hexagonal arrays with a center phone. Based on tag analysis, beaked whale vocalizations are detected up to a range of 6.5 km. In order to help isolate vocalizing groups, total click counts of less than 5 clicks were discarded. The vocalization duration was derived by measuring the start and stop time of detections on the set of hydrophones believed to represent a single beaked whale group. Durations for the April, 2005 dataset were measured from the onset of consistent clicking on the analysis hydrophone array to the cessation of this consistent clicking. Durations for the February, 2007 dataset were measured from the first to the last detected click. A characteristic plot of detection start and stop time versus total click count for 3 hydrophones over 3 dives is given in ***Figure 1***. In the figure, the vocalization durations range from 20 to 21 minutes. Dives with vocalizations detected only on hydrophones on the edge of the range were not considered as part of the analysis. Vocalization periods longer than 52 minutes, twice the mean dive vocal phase of 26 minutes measured for *M densirostris* from DTag data [9], were also not considered. Difficulty in measuring dive vocal periods from the range hydrophones arises when two or more groups in close vicinity ensonify common sensors.

Sixty-four dives from April, 2005 and thirty-three dives from February, 2007 believed to be associated with single beaked whale groups were isolated and the vocalization durations measured. Dive vocalization statistics are shown in Table 1 and Figure 2.

Gap statistics were measured from the February, 2007 dataset. Gaps in the vocalizations refer to periods of time when fewer than five clicks from the group were detected

simultaneously on *any* given hydrophone associated with the group.

These gap statistics provided baseline data for typical beaked whale detections on the AUTEC range for the 2007 Behavioral Response Study (BRS). During this test a tagged Blainville's beaked whale was exposed to anthropogenic sound during a deep foraging dive. The animal's vocalizations were monitored using the AUTEC sensors during the exposure. Changes in typical vocal behavior were used as a real-time cue to the test conductor to secure the source.

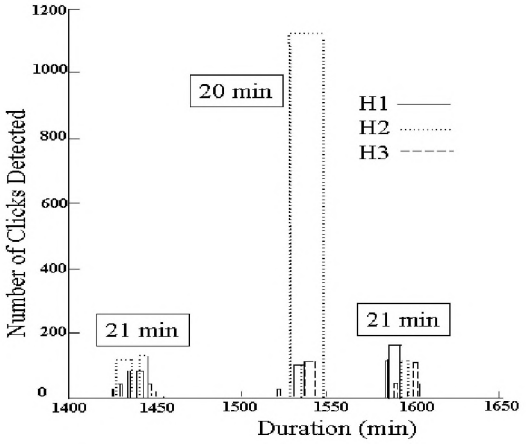

Figure 1: M. densirostris vocalization start and stop times vs. total number of clicks detected within the period for 3 dives on 3 hydrophones.

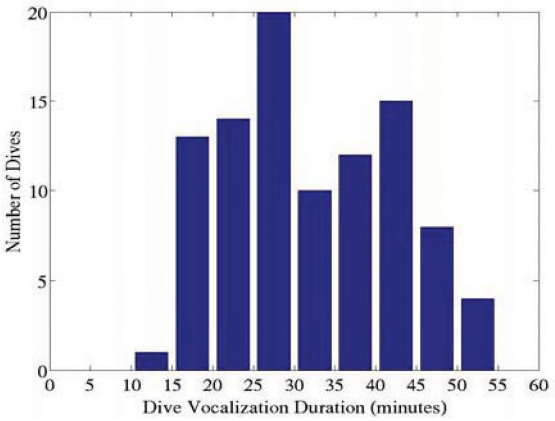

Figure 2: Vocalization duration vs. number of groups for 97 dives from the two datasets analyzed.

	April, 2005	February, 2007	Combined
# Dives	64	33	97
Mean	31.4	31.8	31.5
Median	28.5	32.6	30.3
Mode	26.0	37.0	26.0
Std Dev	9.9	10.5	10.6
Min	15.0	14.9	14.9
Max	51.0	50.4	51.0

Table 1 Dive vocalization statistics

Thirty-three dives were examined from 01/30/07-02/04/07, twelve of which had no gaps. A total of 63 gaps were measured; of these only five were more than 6 min long. 10% of the gaps started between 40 and 60% of the way through the corresponding dive vocalization duration. The gap statistics are indicated in Table 2.

	Mean	Median	Mode	Std Dev	Min	Max
# Gaps	1.9	1.0	0.0	2.3	0.0	8.0
Gap (min)	2.5	1.3	1.3	2.3	0.0	12.7

Table 2: Gap statistics

2.2 Click Counting

A method of click counting for the range hydrophones was developed to estimate the number of *M. densirostris* present in a group. This method uses the dive vocalization duration for each group, the total number of clicks detected on surrounding range hydrophones, and statistics (mean click rate and normalized detection ratio) derived from DTag data to estimate group size. DTag data were used in conjunction with nearby range hydrophones to estimate the mean click rate for an individual and the *normalized detection ratio* of the hydrophone sub-array of interest. The click rate is the number of clicks emitted by an individual per second during the vocal periods within deep foraging dives. The normalized detection ratio is the ratio of total number of clicks detected on the array to the product of the total number emitted by the tagged animal multiplied by known group size and the number of hydrophones in the array. The mean click rate and normalized detection ratio were then applied to three separate dives to estimate group size. These dives were randomly chosen from visually verified *M. densirostris* sightings with known group size. The goal of the analysis was to estimate the number of animals in the group from clicks detected on the hydrophone array in the vicinity of the sighted animals.

DTag Statistics

To estimate a mean beaked whale click rate, three dives were examined from a DTag deployed on an *M. densirostris* on 23 October 2006 by WHOI at the AUTEC range in the Bahamas. For each dive the total number of clicks detected on the tag from the tagged whale was divided by the tagged whale's vocalization period during the dive to estimate the click rate. These three click rates were then averaged to produce the mean click rate (CR) of 2.75 clicks/sec used for this analysis (***Table 3***).

Dive	Click Rate (CR)
1	2.66
2	2.87
3	2.72
Mean	**2.75**

Table 3: Mean click rate calculated from DTag tagged whale vocalizations.

To determine a normalized detection ratio (NDR) for the range hydrophones, a hydrophone sub-array of 7 to 10 hydrophones was first defined in the vicinity of the tagged animal. Detection data from range hydrophones surrounding the tagged animal were examined for the dive vocalization period. The hydrophone with the maximum number of clicks detected during this period was chosen as the center hydrophone for the sub-array. At the time of the analysis the exact position of the tagged animal was not known and the phone with the most detections was chosen as a first order approximation. A circle with a radius of 4.8 km was drawn around this center phone, and all hydrophones falling within the circle defined the hydrophone sub-array used in the analysis. An example of the sub-array designation is shown ***Figure 3***. The 4.8 km radius circle was chosen to be consistent with the *M. densirostris* group localization density estimation method presented in [6].

The total number of clicks (C_{ha}) detected on all hydrophones in the sub-array during the dive vocalization period was summed. The total number of clicks produced by the tagged animal during its dive vocalization period and recorded on the DTag was defined as C_t. The tagged animal was sighted in a group of four (two mother-juvenile pairs), though two other animals were sighted at a distance from the group. Using a group size of four, the normalized detection ratio (NDR) for each dive was defined as the total number of clicks detected on the hydrophone sub-array during the tagged animal's dive vocalization period (C_{ha}) divided by the total number of clicks emitted by the tagged animal during this period (C_t) multiplied by the group size (GS) and the number of hydrophones in the sub-array (H_{ha}):

$$NDR = C_{ha} / (C_t * GS * H_{ha})$$

The normalized detection ratios for the three dives were then averaged to produce the mean normalized detection ratio of 0.031 used in this analysis (***Table 4***).

Dive	H_{ha}	C_{ha}	C_t	*NDR*
1	*7*	*4626*	*4903*	*0.034*
2	*10*	*5528*	*4556*	*0.030*
3	*10*	*8639*	*7564*	*0.029*
	Mean NDR			*0.031*

Table 4: Detection ratio calculated from the DTAG.

Application

To test the efficacy of this click-counting approach for estimating the number of animals in a group, the mean click rate, CR, and normalized detection ratio, NDR, were then applied to data from three separate verified *M. densirostris* sightings. These verified data were collected during focal follows at AUTEC with trained surface observers from the Bahamas Marine Mammal Research Organization (BMMRO). *M. densirostris* groups were detected acoustically on the range. BMMRO observers were directed to a group's location and notified when vocalizations ceased. Within about 20 to 25 minutes the BMMRO observers visually sighted and counted the number of animals in the group. When the animals went on a terminal dive the observers notified the personnel monitoring the acoustics on-shore, and the group's vocalizations were again detected acoustically within about 5 minutes. The sightings occurred on September 27, 2005 in three different parts of the range, and at different times during the day (***Table 5***, ***Figure 3***).

The predicted number of animals and the predicted number of clicks detected on the hydrophone array were then compared to the number of animals sighted and the actual number of clicks detected on the array.

Closest Hyd	Date	Local Time	Group Size
H72	9/27/2005	10:30	2
H76	9/27/2005	11:06	5
H57	9/27/2005	15:25	4

Table 5: BMMRO verified sightings of M. densirostris groups at AUTEC on 09/27/2005.

For each sighting, click detection reports from the nearby hydrophones were examined to determine the dive vocalization duration (DVD) for the group, and the hydrophone with the maximum number of clicks detected during this period. This hydrophone was used as the center hydrophone, and a hydrophone array was again defined as all hydrophones that fell within a 4.8 km-radius circle centered on this hydrophone. The total number of clicks, C_{ha}, detected on the array during the dive vocalization period was determined. The number of animals predicted to be in the group, NA_p, was then calculated as the total number of clicks detected on the array divided by the product of the normalized detection ratio (NDR), the mean click rate (CR), the dive vocalization duration (DVD), and the number of hydrophones in the array (H_{ha}):

$$NA_p = C_{ha} / (NDR * CR * DVD * H_{ha})$$

For a known number of animals, NA, the predicted number of clicks detected on the array (C_{hap}) is given by:

$$C_{hap} = NA * NDR * CR * DVD * H_{ha}$$

Table 6 and Table 7 show the hydrophone arrays used and the associated group dive vocalization durations for the three verified *M. densirostris* sightings. For the sighting at hydrophone 72, the 4.8 km circle defined around 72 only included five hydrophones, since hydrophone 72 is located on the edge of the range. In addition, it appeared that another group was simultaneously vocalizing just north of this array, producing clicks detected by hydrophone 64. To avoid conflict with an adjacent group, hydrophone 64 was removed from the analysis.

The results for the predicted number of animals versus the actual number of animals sighted, and the predicted number of clicks detected on the hydrophone array versus the actual number detected, are shown in Table 8.

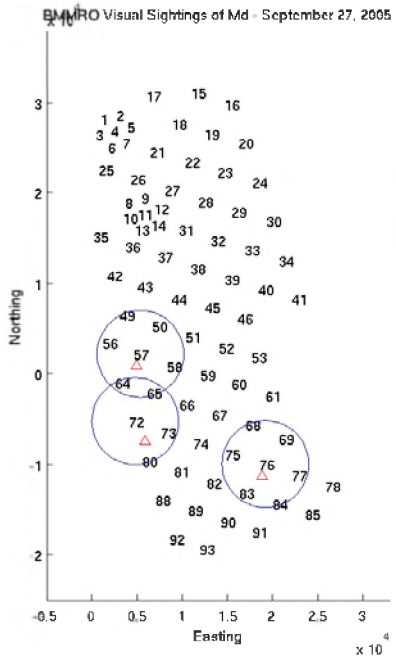

Figure 3: Three visual sightings by BMMRO of M. densirostris groups on 09/27/2005 are indicated by triangles. The corresponding 4.8km-radius circles used for the click counting are shown.

Closest Phone	Phones Used	Center Phone	H_{ha}	C_{ha}
H72	65, 72, 73, 80	H72	4	1343
H76	68, 69, 75, 76, 77, 83, 84	H76	7	5439
H57	49, 50, 56, 57, 58, 64, 65	H57	7	4884

Table 6: Analysis hydrophones used for the 3 verified M. densirostris sightings, with center hydrophone and total number of clicks detected on the array.

Sighting	Start Time	End Time	DVD (h:m:s)
H72	9:34:40	10:09:30	0:34:50
H76	10:14:51	10:46:15	0:31:24
H57	14:27:19	15:01:20	0:34:01

Table 7: Local start time, end time and dive vocalization durations in hours:minutes:seconds for the 3 verified M. densirostris sightings.

	Sighting Hydrophone Location		
	H76	H72	H57
NA_p	4.86	1.89	4.03
NA	5	2	4
C_{hap}	5593.28	1418.25	4847.51
C_{ha}	5439	1343	4884

Table 8: Predicted number of animals and clicks detected versus the actual number sighted and detected for the 3 verified M. densirostris sightings.

3. DISCUSSION

Vocalizing groups of *M. densirostris* in the TOTO were isolated by measuring and comparing the start and stop times of vocalizations on adjacent, widely distributed (4-km baseline) bottom-mounted hydrophones. The dive vocalization durations for multiple groups of animals were measured. These vocalization periods occur during deep foraging dives [3, 4]. The mean vocalization periods for two separate datasets and gaps in vocal periods for the second dataset were measured.

A generalized method for estimating the number of animals vocalizing in an *M. densirostris* group during deep foraging dives was developed using baseline tag data as follows:

1. Isolate a vocalizing *M. densirostris* group.
2. Estimate the group's dive vocalization duration (DVD) and the hydrophones ensonified by the group.
3. Assign the hydrophone with the most clicks during the DVD as the center phone of the analysis hydrophone sub-array. This sub-array is defined as all hydrophones that fall within 4.8 km of the center phone.
4. Adjust the DVD if necessary using the hydrophones in this analysis sub-array.
5. Sum all the clicks detected during the DVD on the hydrophones in the analysis sub-array.
6. Divide the total number of *M. densirostris* clicks detected on the sub-array during the DVD by the product of the DVD multiplied by the normalized detection ratio, the mean click rate, and the number of hydrophones in the sub-array to estimate the number of animals in the group.
7. Compare the results to the actual number of animals sighted.

This method makes 4 major assumptions:

1. *M densirostris* vocalizes at a constant rate.
2. The detection ratio is constant.
3. The distribution of hydrophones used to derive the estimating parameters is the same as for the test cases.
4. All detected vocalizations used for the estimate are produced by a single group.

The mean click rate and normalized detection ratio were obtained from one animal tagged on the AUTEC range. These estimates must be verified with data from additional tagged animals, and their variability quantified. Six tags were successfully placed on *M densirostris* during the Behavioral Response Study at AUTEC 13 August – 27 September, 2007. These tag data will be analyzed and compared to those presented here. The calculation of variance within these data will allow an associated estimate of group size uncertainty. In addition, data from other locations must be quantified and compared, as click rate and normalized detection ratio may be site dependent.

The calculated detection ratio depends directly on the click probability of detection, which depends on environmental conditions. The detection performance is a

function of the receiver performance and the input Signal to Noise Ratio (SNR). The SNR at the receiver is inversely proportional to the sea-state. As the sea-state rises, ocean noise increases, and the SNR at the receiver decreases, which in turn decreases the probability of detection.

M. densirostris spend little time at the surface and are inconspicuous while at the surface [2]. Consequently, sighting these animals is difficult in anything but low sea-states. The estimating parameters (normalized detection ratio and mean click rate) were derived from DTag data. Both the tag data and the verified sighting data were collected in low sea-state (0-1) conditions. To generalize this methodology across varied environmental conditions, the effect of SNR on the detection ratio must be quantified for higher sea-states.

The normalized detection ratio was calculated by totaling the number of clicks detected on hydrophones within a measured area. The number of clicks detected is a function of both the number of hydrophones and their distribution within this area. Thus the detection ratio is dependent upon the given hydrophone distribution, and must be recalculated for new hydrophone configurations.

Vocalizations associated with a group of beaked whales are detected on a set of hydrophones. It is assumed that the detected vocalizations used for this analysis were produced by single groups. However, there are cases in which adjacent groups may ensonify common hydrophones. In one case presented in this paper, detections from a hydrophone were rejected as they were attributed to two adjacent groups. This required manual data analysis. Improved methods for isolating groups should be investigated.

4. CONCLUSIONS

The vocal periods of foraging dives, or dive vocalization durations, for beaked whale groups were measured using passive acoustic detections from the AUTEC range hydrophones. Gaps in the vocal periods were also quantified.

The group size estimation method presented was applied to three dives from visually verified groups of animals with good results. In each case, the method successfully predicted the number of animals in the vocalizing group. The mean error over the three examples was 3%. However, the estimating parameters were derived from a tagged animal in the TOTO, and the method was applied to animals in the same location under similar environmental conditions. Extension of the method must incorporate additional measurement parameters as discussed above.

A passive acoustic density estimation method for *M densirostris* called group localization was presented in [6]. This method identifies groups of *M. densirostris* on the AUTEC range and uses a mean group size to estimate density. Click counting will be used in place of a mean group size in the group localization method to improve the estimate of *M. densirostris* on the AUTEC range.

It may be possible to estimate animal density directly from click counts using cue-counting methods similar to those used in traditional distance sampling. These methods are currently under investigation.

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