



**QUEEN'S
UNIVERSITY
BELFAST**

Next generation planar waveguide detection of microcystins in freshwater and cyanobacterial extracts, utilising a novel lysis method for portable sample preparation and analysis

Devlin, S., Meneely, J. P., Greer, B., Greef, C., Lochhead, M. J., & Elliott, C. T. (2013). Next generation planar waveguide detection of microcystins in freshwater and cyanobacterial extracts, utilising a novel lysis method for portable sample preparation and analysis. *Analytica Chimica Acta*, 769, 108-113.
<https://doi.org/10.1016/j.aca.2013.01.033>

Published in:
Analytica Chimica Acta

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights

this is the author's version of a work that was accepted for publication in *Analytica Chimica Acta*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in *Analytica Chimica Acta*, [VOL 769, (2013)]

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Open Access

This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. – Share your feedback with us: <http://go.qub.ac.uk/oa-feedback>

Accepted Manuscript

Title: Next generation planar waveguide detection of microcystins in freshwater and cyanobacterial extracts, utilising a novel lysis method for portable sample preparation and analysis

Authors: Shauna Devlin, Julie P. Meneely, Brett Greer, Charles Greef, Michael J. Lochhead, Christopher T. Elliott



PII: S0003-2670(13)00181-5
DOI: doi:10.1016/j.aca.2013.01.033
Reference: ACA 232353

To appear in: *Analytica Chimica Acta*

Received date: 24-8-2012
Revised date: 3-12-2012
Accepted date: 14-1-2013

Please cite this article as: S. Devlin, J.P. Meneely, B. Greer, C. Greef, M.J. Lochhead, C.T. Elliott, Next generation planar waveguide detection of microcystins in freshwater and cyanobacterial extracts, utilising a novel lysis method for portable sample preparation and analysis, *Analytica Chimica Acta* (2010), doi:10.1016/j.aca.2013.01.033

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1 Next generation planar waveguide detection of
2 microcystins in freshwater and cyanobacterial
3 extracts, utilising a novel lysis method for portable
4 sample preparation and analysis

5
6 Shauna Devlin ^{a*}, Julie P Meneely ^a, Brett Greer ^a, Charles Greef ^b,

7 Michael J Lochhead ^b and Christopher T Elliott ^a

8 ^a *Institute of Agri-Food and Land Use (IAFLU), School of Biological Sciences, Queen's*
9 *University, Malone Road, Belfast, BT9 5BN, Northern Ireland*

10 ^b *MBio Diagnostics Inc, Boulder, Colorado, 80301, USA*

11

12 *Corresponding author: Institute of Agri-food and Land Use, School of Biological
13 Sciences, Queen's University, Malone Road, Belfast BT9 5BN, Northern Ireland

14 Tel: +44 (0) 2890974279

15 Fax: +44 (0) 2890976513

16 Email: sdevlin08@qub.ac.uk

17

18

18

19 Highlights

20 Sensitive assay for the detection of the most common and toxic microcystin variants

21 Detection of free and cell bound microcystin for a true reflection of toxin content

22 Novel, highly effective lysis method enabling fast and portable disruption of cells

23 Validated to measure microcystins below 1 and 0.1 ng ml⁻¹; free and intracellular

24 Next generation planar waveguide biosensor combining quantification and ease of use

25

26

27 Abstract

28 The study details the development of a fully validated, rapid and portable sensor based

29 method for the on-site analysis of microcystins in freshwater samples. The process

30 employs a novel lysis method for the mechanical lysis of cyanobacterial cells, with

31 glass beads and a handheld frother in only 10 min. The assay utilises an innovative

32 planar waveguide device that, via an evanescent wave excites fluorescent probes, for

33 amplification of signal in a competitive immunoassay, using an anti-microcystin

34 monoclonal with cross-reactivity against the most common, and toxic variants.

35 Validation of the assay showed the Limit of Detection (LOD) to be 0.78 ng ml⁻¹ and the36 CC β to be 1 ng ml⁻¹. Robustness of the assay was demonstrated by intra- and inter-

37 assay testing. Intra-assay analysis had % C.V.s between 8 and 26% and recoveries

38 between 73 and 101%, with inter-assay analysis demonstrating % C.V.s between 5 and

39 14% and recoveries between 78 and 91%. Comparison with LC-MS/MS showed a high

40 correlation ($R^2 = 0.9954$) between the calculated concentrations of 5 different41 *Microcystis aeruginosa* cultures for total microcystin content. Total microcystin

42 content was ascertained by the individual measurement of free and cell-bound

43 microcystins. Free microcystins can be measured to 1 ng ml⁻¹, and with a 10-fold

44 concentration step in the intracellular microcystin protocol (which brings the sample

45 within the range of the calibration curve), intracellular pools may be determined to 0.1

46 ng ml⁻¹. This allows the determination of microcystins at and below the World Health
47 Organisation (WHO) guideline value of 1 µg l⁻¹. This sensor represents a major
48 advancement in portable analysis capabilities and has the potential for numerous other
49 applications.

50

51 **Keywords:** Microcystin, planar waveguide, portable biosensor, novel lysis, blue-green
52 algae and cyanobacteria

53

54 1. Introduction

55

56 Cyanobacteria (Domain Bacteria) originate from the Precambrian era, 3.4 billion years
57 ago and were the first prokaryotes to use water in the fixation of carbon dioxide [1].
58 They are widespread throughout global waters, both marine and freshwater,
59 encompassing, not only hot tropical to temperate waters, but even the chilly waters of
60 the Antarctic ice shelves [2]. Of the many types of cyanobacteria, *Microcystis*
61 *aeruginosa* (predominantly freshwater) is the most common species, which produces
62 microcystins. In addition to *Microcystis*, microcystins are also produced by the
63 following genera: *Anabaena*, *Nostoc*, *Planktothrix*, *Anabaenopsis* and
64 *Hapalosiphon* [2]. Microcystins are cyclic heptapeptides with the structure; cyclo-(D-
65 Alanine-X-D-MeAsp-Y-Adda-D-Glutamate-Mdha), where X and Y are variable L-
66 amino acids, MeAsp and Mdha are Methylaspartic acid and Methyldehydroalanine,
67 respectively and Adda is (2S, 3S, 8S, 9S)-3-amino-9-methoxy-2,6,8-trimethyl-10-
68 phenyldeca-4(E),6(E)-dienoic acid [3]. There are over 90 variants of microcystins with
69 the most common being Microcystin-LR (MC-LR), which has Leucine at position 2

70 and Arginine at position 4 [4, 3]. They are hepatotoxic, due to their uptake via the bile
71 acid transport system delivering them into hepatocytes, where they inhibit
72 Serine/Threonine Proteases via Adda, causing over phosphorylation of proteins. Acute
73 toxicosis results in the disruption of the cytoskeleton, loss of cell structure and
74 adhesion, loss of tissue structure and the collapse of sinusoidal capillaries resulting in
75 hepatic haemorrhaging and ultimately death [5–8]. The deaths of 60 patients in a
76 dialysis unit in Brazil, in 1996, have been attributed to the use of contaminated water
77 during dialysis [9]. Lower levels of microcystins, although not acutely lethal, have
78 been shown to promote cancer (Group 2B carcinogen; possibly carcinogenic to
79 humans) and have immunotoxic and genotoxic effects [10–12]. The World Health
80 Organisation (WHO) have set the recommended limit at $1 \mu\text{g l}^{-1}$ for drinking water and
81 $20 \mu\text{g l}^{-1}$ for recreational waters [13–15]. Microcystins are small (MC-LR being 995.2
82 Da) and stable compounds, withstanding harsh conditions, such as high temperatures
83 and extreme pH. Removal is usually achieved by activated carbon filtration, ozonation
84 or chlorination; all being commonly utilised in water treatment [16–18].

85

86 The ability to detect microcystins is important and many tests exist. The vast majority
87 are laboratory based, with immunoassays enabling high throughput screening for total
88 microcystin concentrations and analytical methods (such as HPLC, Mass
89 Spectrometry[19–21]), although slower, allowing the quantification and identification
90 of individual variants within a sample [22, 3]. Recent attention has turned towards the
91 on-site detection of microcystins. Portable tests have long since focused on the lateral
92 flow format, a major drawback of which is that quantification usually relies on the
93 user's determination. However, the first lateral flow device (LFD) for microcystins,
94 devised by Kim et al (2003) [23], employed a custom made portable-laser fluorescence

95 scanner, eliminating the subjective nature of results interpretation. For this they used
96 Alexa Fluor 647®, a Cy5 labelled fluorescent probe, as the secondary, detection,
97 antibody, in a competitive assay, whereby a MC-LR conjugate was coated to the
98 surface and an anti-MC-LR monoclonal was used as the primary antibody. This assay
99 format works well for most biosensors, including planar waveguide, a technology, that
100 has been around for decades. Two portable assays, have been developed recently by
101 Long et al (2005) and Herranz et al (2012) [24, 25]. Both utilise modified versions of
102 the aforementioned assay format; Long et al use a Cy5 labelled monoclonal, and
103 Herranz coat the sensor surface with MC-LR as opposed to a MC-LR-conjugate. The
104 biosensors used are the Trace Organic Pollutant Analyser (TOPA) and a
105 commercialised version of the US Naval Research Laboratory (NRL) Array Biosensor
106 prototype, by Long et al and Herranz et al respectively. For the TOPA assay, one
107 analyte was measured at a time, with a cycle time of 20 min, 150 cycles per surface and
108 an LOD of 30 ng l⁻¹. The NRL Biosensor, can detect up to 6 analytes at a time, with
109 15 cycles per surface, a cycle time of 60 min and an LOD of 16 ng l⁻¹. The present
110 study utilises the next generation of evanescent wave/ planar waveguide detection. This
111 platform has all the advantages related to single use LFDs and portable biosensors yet
112 has the ability to perform the accurate quantification only associated with laboratory
113 based, methods. The unique MBio SnapEsi® LS sensor [26] employed in the present
114 study uses, a patented design, whereby the lens is integrated on a disposable cartridge; a
115 cartridge into which the sample and reagents are added and held. The cartridges are
116 custom made, spotted with (in-house prepared) toxin-protein conjugates, chosen and
117 optimised for the sensitive and selective binding of anti-microcystin monoclonal
118 antibody (also produced in-house). These cartridges eliminate the need for
119 cumbersome and expensive microfluidics often associated with advanced portable

120 sensors, thus there is no need for pumps, valves, tubing or buffer/waste reservoirs. In
121 the SnapEsi® LS assay there are no concerns about tubing becoming blocked; either by
122 lines drying out due to warm temperatures, air bubbles, or sample particulate blockages.
123 The cartridge can simply be used, read and disposed of. Thus a simple to use, low cost
124 and accurate means of detecting microcystins will be presented.

125

126 Further to this, we present a highly novel sample preparation method for the portable
127 lysis of cyanobacterial, *Microcystis aeruginosa*, cells, for the quantification of intra-
128 cellular microcystin levels. Microcystins are inherently endotoxins, therefore, the
129 measurement of freshwater only, fails to detect the majority of toxin present, as has
130 been highlighted by Codd et al (2005) [2] who state that guideline values “should
131 therefore apply to the sum of the intracellular and extracellular microcystin pools”; yet
132 the focus has remained on water testing only. This may be in part due to the difficulties
133 encountered in dealing with cyanobacterial samples in current analytical methods.
134 Cheap, quick and portable lysis usually relies on chemical disruption of cells, using
135 harsh reagents which may interfere with downstream assays, causing matrix
136 interference and thus skewing results. The best cellular disruption occurs via
137 mechanical lysis of the cells, such as that of glass bead beating, which has been
138 demonstrated to achieve full lysis of algal cells, in a quick time of only 10 min [27].
139 This laboratory based method required a paint shaker to mix the sample/glass bead
140 combination and a centrifuge to separate cells from freshwater samples. To overcome
141 this, centrifugation steps were switched to filtration and the paint shaker was substituted
142 for a, low cost, hand-held, battery operated frother. Other non mechanical methods
143 require filtration of the sample (glass fibre filters, GF/C) followed by slow toxin
144 extraction using solvents which are not compatible with immunoassays.

145

146 Presented here is an assay, proven to be capable of detecting microcystins in both free
147 and intracellular states, to a level of 1 ng ml^{-1} for free and 0.1 ng ml^{-1} for intracellular
148 microcystins. This rapid, semi-quantitative test, has an assay time of only 15 min for
149 free microcystins, and under 30 min for intracellular microcystins, inclusive of sample
150 preparation.

151

152

153

154

155 2. Materials and Methods

156

157 2.1. Reagents and Chemicals

158 Microcystin-LR was purchased from Enzo Life Sciences, through Alpha Technologies
159 Ltd, Larne Northern Ireland. Bovine Serum Albumin (BSA), Phosphate buffered saline
160 (PBS) tablets, Tween-20 and apo-Transferrin (bovine) were purchased from Sigma-
161 Aldrich, Gillingham, UK. Cyanobacterial cultures were obtained from the Culture
162 Collection of Algae and Protozoa (CCAP), Oban, Scotland and the Laboratory of
163 Ecotoxicology, Genomics and Evolution (LEGE) at the Centre of Marine and
164 Environmental Research (CIIMAR), Porto, Portugal. From CCAP *M. aeruginosa* strains
165 1450/3 (non-toxic) and 1450/6 (toxic) were purchased and from CIIMAR, strains
166 LEGE 91093, LEGE 91094, LEGE 91095 and LEGE 91096 were received. Jaworski's
167 and BG11 media were purchased from CCAP, Oban, Scotland. Alexa Fluor 647 goat
168 anti—rabbit IgG and Alexa Fluor 647 goat anti—mouse IgG antibodies were purchased

169 from Invitrogen Ltd, Paisley, Scotland. The anti-microcystin, 5C4, monoclonal was
170 prepared in-house and details will be published elsewhere.

171

172 2.2. Apparatus

173 For cell lysis a hand held frother was purchased from Argos Direct, Stafford, UK, while
174 the paint shaker, a Minimix standard shaker, was purchased from Merris Engineering,
175 Berkshire, UK. Swinnex, 25 mm filter holders, 25mm gaskets and 25 mm MF-
176 Millipore (mixed cellulose esters, hydrophilic, 0.45 μm and black gridded) membranes,
177 together with Millex-HA (0.45 μm , mixed cellulose) filters were purchased through
178 Premier Scientific Ltd, Belfast, Northern Ireland. The SnapEsi® LS System [28] was
179 supplied by MBio Diagnostics Inc, Boulder, Colorado, USA, as were the microarray
180 cartridges.

181

182 2.3. Preparation of Toxin Protein Conjugate (TPC);

183 MC-LR-Transferrin

184 MC-LR, 0.25 mg, was reconstituted in 50 μl Dimethyl sulfoxide (DMSO). To this was
185 added 50 μl *N*-Hydroxysuccinimide (NHS) (130 mM) and 100 μl *N*-(3-
186 Dimethylaminopropyl)-*N'*-ethylcarbodiimide hydrochloride (EDC) (39 mM), both
187 dissolved in 50 mM 2-(*N*-Morpholino) ethanesulfonic acid (MES), pH 4.7. This was
188 stirred for 30 min, protected from light, at room temperature. The active ester solution
189 was then added, dropwise to a vial containing 1 mg of Transferrin dissolved in 1 ml
190 PBS pH 7.4. This was stirred at room temperature, for 2 hours, again protected from
191 light. The TPC was dialysed against PBS pH 7.4 and tested by ELISA. The TPC was
192 sent to mBio Diagnostics for microarray printing, at 100 $\mu\text{g ml}^{-1}$.

193

194 **2.4. Microarray Printing**

195 Microarrays were printed using a Bio-Dot AD3200 robotic arrayer. Briefly, spots were
196 produced, with a diameter of 0.5 mm, using a Bio-Jet print head that dispensed 20 nl.
197 Four replicates of the TPC were printed onto a grid with 1 mm centres. Microarrays
198 were then blocked with a protein-based blocking agent (0.5% casein in PBS with
199 Proclin300 antimicrobial) prior to spin-drying. Microarrays were then assembled into
200 an injection moulded cartridge, which contained a 5 mm wide fluidic channel (max
201 volume 30 μ l) with a single inlet port for the addition of sample and reagents. Assays
202 were carried out on a rack, angled for optimum flow rate, enhancing passive fluid flow,
203 which is aided by capillarity due to the narrow fluidic channel.

204

205 **2.5. Culturing**

206 CCAP cultures were maintained in Jaworski's Medium, while CIIMAR LEGE cultures
207 were maintained in BG11 Medium. Culturing was done in glass Erlenmeyer flasks
208 (wide necked) with cotton wool plugs and foil lids and incubated at 20 °C with a light
209 intensity of 116 μ mol $m^{-2} s^{-1}$. All consumables were sterilised by autoclaving at 121 °C
210 for 15 min. Culturing work was carried out in a pre-sterilised (via 30 min UV
211 exposure) UV3 HEPA PCR cabinet. Cultures were maintained in log phase, with fresh
212 cultures being seeded from denser cultures (nearing stationary phase); 40 ml dense
213 culture added to 160 ml fresh media. Culture growth was monitored by cell counting
214 using Lugol's stain and a haemocytometer under x200 magnification.

215

216 2.6. Sample Lysis

217 A 25 mm swinnex filter (in a 25 mm Swinnex Filter Holder) was used to filter 50 ml of
218 sample/culture. The filter membrane was then transferred to a 7 ml bijou and the
219 captured cells resuspended with 5 ml PBS pH 7.4. To 5 ml of sample/culture, 1 g of
220 0.1 mm glass beads was added to a small glass beaker (15 ml), whose diameter was just
221 large enough to accommodate the frother whisk, whilst limiting the space for
222 beads/cells to accumulate in. The frother was then switched on and allowed to 'whisk'
223 the sample/bead mixture for 10 min. Once finished the sample was twice filtered (0.45
224 μm Millipore), to ensure complete removal of glass beads/fragments; once should be
225 enough, but a second filtration was included in case the first filter was perforated. A
226 negative toxin producer (CCAP 1450/3) was treated in the same way to produce the
227 matrix in which calibrants are prepared.

228

229 2.7. Assay

230 Reagent/Sample Preparation

231 Assay Buffer

232 The buffer was PBS pH 7.4 containing 0.05% Tween-20, 0.45 μm filtered.

233

234 Antibody Solutions

235 The monoclonal antibody, 5C4 was diluted (v/v), 1 in 100, from the stock solution of
236 approximately 0.88 mg ml^{-1} . The diluent was Assay Buffer containing 1% BSA, the
237 BSA acting as a stabiliser. The working stock was maintained at 4 °C and diluted
238 again, with Assay Buffer (without the added BSA) to a final concentration of 1 in
239 10000, for use in the assay. The 5C4 monoclonal antibody was shown to have cross-

240 reactivity for the most common microcystin variants, as follows: MC-RR, 108%; MC-
241 YR, 68%; MC-LA, 69%; MC-LW, 71%; MC-LF, 68%; and Nodularin, 94%.

242

243 The detection antibody, Alexa Fluor 647 goat anti-mouse IgG, was used to prepare a
244 detection antibody working stock solution, also stored at 4 °C (without added BSA),
245 protected from light. The stock solution was prepared by adding 100 µl of each
246 antibody to 2 ml of Assay Buffer. For use in assay conditions, a further 1 in 10 dilution
247 (with Assay Buffer) was required to get to the final 10 µg ml⁻¹ working solution.

248

249 Calibrants

250 Calibrants were prepared from a 1 µg ml⁻¹ solution of MC-LR, to yield concentrations
251 of 200, 50, 20 and 0 ng ml⁻¹, with dilutions made using Assay Buffer. These were then
252 used to spike 950 µl of matrix, using 50 µl per spike, to get final solutions with the
253 following concentrations: 10, 2.5, 1 and 0 ng ml⁻¹.

254

255 Assay Conditions

256 Equal volumes of 5C4 antibody and sample/calibrant were mixed and 150 µl
257 immediately applied to the cartridge. After 7 ½ min, 150 µl of detection antibody was
258 added. After 7 ½ min (15 min total time) the cartridge was read using the SnapEsi
259 reader.

260

261 2.8.Liquid Chromatography Tandem- Mass Spectrometry
262 (LC-MS/MS) Validation

263 Freeze-drying and solid phase extraction (SPE) were used to prepare and extract
264 microcystins from *Microcystis aeruginosa* samples for LC-MS/MS detection, as
265 reported elsewhere; using modified methods from Kim et al. (2009), Lawton et al.
266 (1994), Msagati et al. (2006) and Mooney et al. (2011) [29–31, 20]. Briefly, 50 ml
267 samples were freeze-dried and resuspended in, 5 ml, 75% methanol before enrichment
268 and purification with OASIS HLB cartridges, after the methanol content was diluted to
269 15%. Microcystins were eluted with 6 ml methanol, containing 0.1% Trifluoroacetic
270 acid, dried under nitrogen, resuspended in 80% methanol and analysed by LC-MS/MS;
271 using a Waters Acquity UPLC and a Quattro Premier XE Mass Spectrometer, run in
272 electrospray positive mode (ESI).

273

274 2.9. Surface Plasmon Resonance (SPR) Assay

275

276 CM5 research grade chips were used on a Biacore Q instrument. CM5 chips were
277 coated with MC-LR using the method devised by Vinogradova et al [32]. The flow rate
278 was 20 $\mu\text{l min}^{-1}$ for 4 min per cycle, with the 5C4 monoclonal antibody used at a 1 in
279 1000 dilution (v/v) using the 0.88 mg ml^{-1} stock solution. 5C4 was mixed with sample
280 prior to injections using a blend of 30% antibody and 70% sample. The calibration
281 curve consisted of six points; 10, 5, 2.5, 1, 0.5 and 0 ng ml^{-1} MC-LR. Calibrants were
282 prepared in matrix (*M. aeruginosa* CCAP 1450/3 lysate) to normalise for matrix
283 effects. Regeneration of the chip surface was achieved by injecting 75 mM Sodium
284 hydroxide and 10% Acetonitrile (in deionised water) for 1 min at 20 $\mu\text{l min}^{-1}$.

285

286 3. Results and Discussion

287 3.1. Milk Frother Validation

288 Validation of the frother required testing samples lysed by both the laboratory based
289 paint shaker [27] and portable frother by SPR. This was due to the observation that
290 disintegration of the glass beads occurred upon mixing, which resulted in the
291 appearance of small fragments, which could be mistaken for *M. aer* cells when viewed
292 microscopically, See Fig 1 for images. To overcome this, identical samples were tested
293 by SPR. For one sample, the paint shaker and 0.5 mm beads were employed and for
294 the other the frother and 0.1 mm beads were used. The ratio of 1 g per 2 ml of sample
295 was maintained, thus 2.5 g of 0.1 mm glass beads were added to the 5 ml sample. The
296 same mixing time was used for both, 10 min. The final samples were then tested by
297 SPR to determine the toxin concentrations present. The concentration as determined by
298 the paint shaker method was 9.0 ng ml^{-1} , while that of the frother method was 9.25 ng
299 ml^{-1} , resulting in a 103 % recovery of microcystin.. This confirmed that the lysis
300 procedure was as effective as that of the paint shaker.

301

302 3.2. Assay Format

303 The format of the assay was competitive inhibition, whereby the more microcystins that
304 were present in a sample/calibrant, the less anti-microcystin, 5C4, monoclonal there
305 was available to bind to the surface bound TPC. Thus the more microcystins present in
306 a given sample, the lower the signal would be. This is shown in Fig 2, showing the
307 fluorescence recorded for the four identical microcystin spots, on cartridges with
308 calibrants added.

309

310

311 3.3. Assay Validation

312 The limit of detection (LOD) was determined by taking the mean response for 20
313 negative (toxin free) samples and subtracting 3x standard deviations (S.D.) as is
314 standard for inhibition assays [33]. The response was then converted to concentration
315 via the calibration curve and derived as 0.78 ng ml^{-1} (see Table 1). This level was used
316 as a guide to estimate the detection capability ($CC\beta$), which was 1 ng ml^{-1} , equivalent
317 of the $1 \mu\text{g l}^{-1}$ WHO recommended level. Taking into consideration the 10-fold
318 concentration step in the sample preparation method for intra-cellular measurement,
319 this brings samples containing 0.1 ng ml^{-1} into the measurable range of the calibration
320 curve. No sample preparation method, other than filtration ($0.45 \mu\text{m}$) was included for
321 free microcystin measurement, as this would only serve to reduce the speed of analysis.
322 As can be seen from Fig 3, there was no overlap between the $20 \times 1 \text{ ng ml}^{-1}$ spiked
323 samples and the 20 negative samples from the LOD calculation (to $1 \times \text{S.D.}$).
324 Populations were also shown to be significantly different with a p value < 0.0001 ; 2-
325 tailed, unpaired t-test. The assay had a dynamic range (IC_{10} to IC_{90}) of 0.22 to 5.12 ng
326 ml^{-1} .

327

328 Repeatability and reproducibility (intra- and inter-run robustness) were demonstrated
329 by spiking at 3 different toxin levels, with 4 replicates per spiking level, across 2
330 batches of cartridges and repeating this over 3 days. The data was then analysed per
331 day to determine repeatability of the assay and then across the 3 days to determine the
332 reproducibility of the assay. The 3 spiking levels chosen were $CC\beta$, the midpoint (IC_{50})
333 and the level at which 75% inhibition of signal was achieved (IC_{75}), which were 1 , 1.27
334 and 2.78 ng ml^{-1} respectively. Inter-run analysis showed that spiking level recoveries
335 all lay between 78 and 91% with % C.V.s lower than 15% (see Table 2). For intra-run

336 analysis, recoveries were between 73 and 96 % with % C.V.s below 22% (see Table 2).
337 This demonstrated a high degree of repeatability for what is a semi-quantitative assay,
338 and providing values that could be expected with a fully quantitative, laboratory based
339 assay,
340
341 Final validation of the assay was performed by testing samples by the SnapEsi method
342 and comparing them to values determined by LC-MS/MS analysis. Table 3 shows the
343 calculated concentrations of the 5 *M aeruginosa* strains tested. The two microcystin
344 pools were combined to give a total microcystin content of each sample. These were
345 then compared to the concentrations derived by LC-MS/MS analysis and as can be seen
346 from the data in Table 4 the difference between the calculated concentrations is
347 between 0.8 to 1.3-fold, with an average of a 1.04-fold difference. Differing sample
348 preparation methods in addition to the differing detection methods generally result in
349 much greater variation in data generated. The R^2 value, when the calculated
350 concentrations were plotted against each other, Fig 4, was 0.9954, demonstrating the
351 reliability and accuracy of the method.

352

353 4. Conclusions

354 Due to the true and accurate level of microcystins in a water sample only being
355 ascertained if both free and cell-bound levels are quantified, a method has been
356 developed, and fully validated, to allow the calculation of the total microcystin content
357 of a sample. To allow for the development of a rapid and portable assay, a novel
358 method of cell lysis was also developed and validated, whereby a frother was used to
359 vigorously agitate a sample containing, 0.1 mm glass beads, mechanically lysing the

360 cyanobacterial cells, without the need for harsh chemicals, in just 10 min. The planar
361 waveguide assay, using a SnapEsi® LS sensor, is rapid, taking only 15 min and using
362 an anti-microcystin monoclonal antibody (5C4), that detects the more common, and
363 toxic, variants of microcystin; MC-LR, MC-RR, MC-YR, MC-LA, MC-LW and MC-
364 LF. The assay can detect free microcystins to 1 ng ml^{-1} and intracellular microcystins
365 to 0.1 ng ml^{-1} . The difference being due to a 10x concentration step that was included
366 in the intracellular sample preparation method; no sample preparation method was
367 required in the measurement of the free microcystin fraction. In addition to this, a
368 single, cheap, cartridge is used per sample that is simply discarded after reading, to give
369 an assay that is not only rapid and portable, but has quantitative capabilities that many
370 semi-quantitative laboratory based methods fail to reach.

371 Acknowledgements

372 The authors would like to thank the Department of Employment and Learning (DEL)
373 for funding the project, BEACONS (Biosafety for Environmental Contaminants using
374 Novel Sensors) (Reference, USI 001) via the US-Ireland Research Programme. The
375 authors also wish to thank Prof Vitor Vasconcelos of the University of Porto (CIIMAR)
376 for providing *Microcystis aeruginosa* cultures.. Thanks also to Dr Terry Fodey for his
377 invaluable help in preparing the conjugation chemistry protocols.

378

379 References

- 380 [1] R.E. Kopp, J.L. Kirschvink, I. a Hilburn, C.Z. Nash, Proceedings of the National
381 Academy of Sciences of the United States of America, 102 (2005) 11131–11136.
- 382 [2] G.A. Codd, L.F. Morrison, J.S. Metcalf, Toxicology and applied pharmacology, 203
383 (2005) 264–72.

- 384 [3] M.E. van Apeldoorn, H.P. van Egmond, G.J. a Speijers, G.J.I. Bakker, *Molecular*
385 *Nutrition & Food Research*, 51 (2007) 7–60.
- 386 [4] A. Chia, S. Oniye, Z. Ladan, Z. Lado, A. Pila, V. Inekwe, J. Mmerole, *African*
387 *Journal of Biotechnology*, 8 (2009) 6282–6289.
- 388 [5] U. Apte, P. Krishnamurthy, in: S. Monga (Ed.), *Molecular Pathology of Liver*
389 *Diseases*, Springer, 2010, 2010, pp. 147–163.
- 390 [6] W.J. Fischer, S. Altheimer, V. Cattori, P.J. Meier, D.R. Dietrich, B. Hagenbuch,
391 *Toxicology and Applied Pharmacology*, 203 (2005) 257–263.
- 392 [7] M.L. Wickstrom, S. a. Khan, W.M. Haschek, J.F. Wyman, J.E. Eriksson, D.J.
393 Schaeffer, V.R. Beasley, *Toxicologic Pathology*, 23 (1995) 326–337.
- 394 [8] L. Pearson, T. Mihali, M. Moffitt, R. Kellmann, B. Neilan, *Marine drugs*, 8 (2010)
395 1650–80.
- 396 [9] S. Pouria, a de Andrade, J. Barbosa, R. Cavalcanti, V. Barreto, C. Ward, W. Preiser,
397 G.K. Poon, G. Neild, G. Codd, *The Lancet*, 352 (1998) 21–26.
- 398 [10] *Iarc Monographs On The Evaluation Of Carcinogenic Risks To Humans*, 94
399 (2010).
- 400 [11] R. Nishiwaki-Matsushima, T. Ohta, S. Nishiwaki, M. Suganuma, K. Kohyama, T.
401 Ishikawa, W.W. Carmichael, H. Fujiki, *Journal of Cancer Research and Clinical*
402 *Oncology*, 118 (1992) 420–424.
- 403 [12] A. Sieroslawska, *Central-European Journal of Immunology*, 35 (2010) 105–110.
- 404 [13] WHO, (2008) 407–408.
- 405 [14] D. Campbell, L. Lawton, K. Beattie, G. Codd, *Environmental Toxicology and*
406 *Water Quality: An International Journal*, 9 (1994) 71–77.
- 407 [15] I. Chorus, J. Bartram, (1999).
- 408 [16] H.G. Gorchev, G. Ozolins, *WHO chronicle*, 38 (1984) 104–8.
- 409 [17] K. Tsuji, T. Watanuki, F. Kondo, M. Watanabe, H. Nakazawa, M. Suzuki, H.
410 Uchida, K. Harada, *Toxicon*, 35 (1997) 1033–1041.
- 411 [18] V.K. Sharma, T.M. Triantis, M.G. Antoniou, X. He, M. Pelaez, C. Han, W. Song,
412 K.E.O. Shea, A.A. De, T. Kaloudis, A. Hiskia, D.D. Dionysiou, *Separation and*
413 *Purification Technology*, 91 (2012) 3–17.
- 414 [19] L. Spooof, K. Karlsson, J. Meriluoto, *Journal of chromatography. A*, 909 (2001)
415 225–36.

- 416 [20] K.M. Mooney, J.T.G. Hamilton, S.D. Floyd, R.H. Foy, C.T. Elliott, *Environmental*
417 *Toxicology*, 26 (2011) 556–570.
- 418 [21] L. Lawton, C. Edwards, K. Beattie, S. Pleasanc, G. Dear, G. Codd, *Natural Toxins*,
419 3 (1995) 50–57.
- 420 [22] L.N. Sangolkar, S.S. Maske, T. Chakrabarti, *Water research*, 40 (2006) 3485–96.
- 421 [23] Y.M. Kim, S.W. Oh, S.Y. Jeong, D.J. Pyo, E.Y. Choi, *Environmental Science &*
422 *Technology*, 37 (2003) 1899–1904.
- 423 [24] F. Long, M. He, a N. Zhu, H.C. Shi, *Biosensors & Bioelectronics*, 24 (2009)
424 2346–2351.
- 425 [25] S. Herranz, M.D. Marazuela, *Biosensors and Bioelectronics*, 33 (2012) 50–55.
- 426 [26] J.P. Meneely, K. Campbell, C. Greef, M.J. Lochhead, C.T. Elliott, *Biosensors and*
427 *Bioelectronics*, (2012).
- 428 [27] R. Devlin, K. Campbell, K. Kawatsu, C.T. Elliott, *Harmful Algae*, 10 (2011) 542–
429 548.
- 430 [28] M.J. Lochhead, K. Todorof, M. Delaney, J.T. Ives, C. Greef, K. Moll, K. Rowley,
431 K. Vogel, C. Myatt, X. Zhang, C. Logan, C. Benson, S. Reed, R.T. Schooley, *Journal*
432 *of Clinical Microbiology*, 49 (2011) 3584–3590.
- 433 [29] I. Kim, G. Nguyen, S. Kim, J. Lee, H. Yu, *Environmental Engineering Research*,
434 14 (2009) 250–254.
- 435 [30] L. Lawton, C. Edwards, G. Codd, *The Analyst*, 119 (1994) 1525–30.
- 436 [31] T. a M. Msagati, B. a Siame, D.D. Shushu, *Aquatic toxicology (Amsterdam,*
437 *Netherlands)*, 78 (2006) 382–97.
- 438 [32] T. Vinogradova, M. Danaher, A. Baxter, M. Moloney, D. Victory, S. a. Haughey,
439 *Talanta*, (2011) 1–6.
- 440 [33] J.P. Meneely, M. Sulyok, S. Baumgartner, R. Krska, C.T. Elliott, *Talanta*, 81
441 (2010) 630–6.

442

443 List of Figures:

444 Fig 1. Image a (x 200 magnification) shows 0.1 mm glass beads after 10 min mixing
445 with the milk frother. The majority of beads disintegrate forming small fragments that
446 may be mistaken for cyanobacterial cells. Image b (x 200 magnification) shows CCAP

447 1450/6 *M. aeruginosa* cells; which would be difficult to distinguish amongst the bead
448 fragments in image a.

449 Fig 2. Images of microcystin spots as treated with calibrants: a, 10 ng ml⁻¹; b,
450 2.5 ng ml⁻¹; c, 1 ng ml⁻¹; and d, 0 ng ml⁻¹.

451 Fig 3. Determination of CCβ as 1 ng ml⁻¹, as shown by the 0 ng ml⁻¹ and 1 ng ml⁻¹
452 populations not overlapping (to 1 S.D.)

453 Fig 4. Comparison of mBio and LC-MS/MS results, showing a good correlation,
454 whereby R² = 0.9954.

455

456 List of Tables:

457 Table 1. Determination of LOD as 0.78 ng ml⁻¹

458 Table 2. Measured concentrations of spiked samples, along with S.D., % C.V.s and
459 mean recoveries, for repeatability and reproducibility analysis of assay.

460 Table 3. Microcystin content of *M. aeruginosa* cultures as calculated by mBio

461 SnapEsi.

462 Table 4. Comparison of mBio and mass spec concentrations for toxin producing *M.*

463 *aeruginosa* samples.

464

464

Response (Normalised Signal)					Calc Conc (ng ml⁻¹)
Mean	S.D.	%C.V.	3x[S.D.]	LOD	
1060.9	133.8	12.6	401.4	659.5	0.78

465

466

467

Accepted Manuscript

467

	Spiking Level (ng ml ⁻¹)	Measured Concentration (ng ml ⁻¹) ± S.D.	C.V. (%)	Mean Recovery (%)
Day 1	1	0.95 ± 0.13	14.0	95.1
	1.27	0.99 ± 0.28	21.9	78.2
	2.78	2.03 ± 0.39	19.3	73.1
Day 2	1	0.86 ± 0.13	15.5	85.9
	1.27	1.06 ± 0.28	26.3	83.3
	2.78	2.02 ± 0.36	17.6	72.6
Day 3	1	0.91 ± 0.10	10.5	90.9
	1.27	1.29 ± 0.11	8.4	101.3
	2.78	2.49 ± 0.44	17.8	89.4
Overall (Days 1 to 3)	1	0.91 ± 0.05	5.0	90.6
	1.27	1.11 ± 0.15	13.9	87.6
	2.78	2.18 ± 0.27	12.2	78.4

468

469

469

Culture	Cell bound Concentration (ng ml⁻¹)	Free Concentration (ng ml⁻¹)	Total Concentration (ng ml⁻¹)
1450/06	7.9	21.2	29.2
91093	63.6	16.5	80.1
91094	38.7	21.6	60.3
91095	128.2	461.5	589.7
91096	72.5	18.2	90.7

470

471

472

472

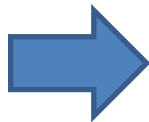
Culture	Calculated Concentration (ng/ml)		Difference (x-fold)
	mBio	Mass Spec	
1450/06	29.2	23.7	0.8
91093	80.1	108.1	1.3
91094	60.3	64.5	1.1
91095	589.7	536.2	0.9
91096	90.7	98.9	1.1

473

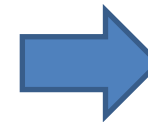
474

Accepted Manuscript

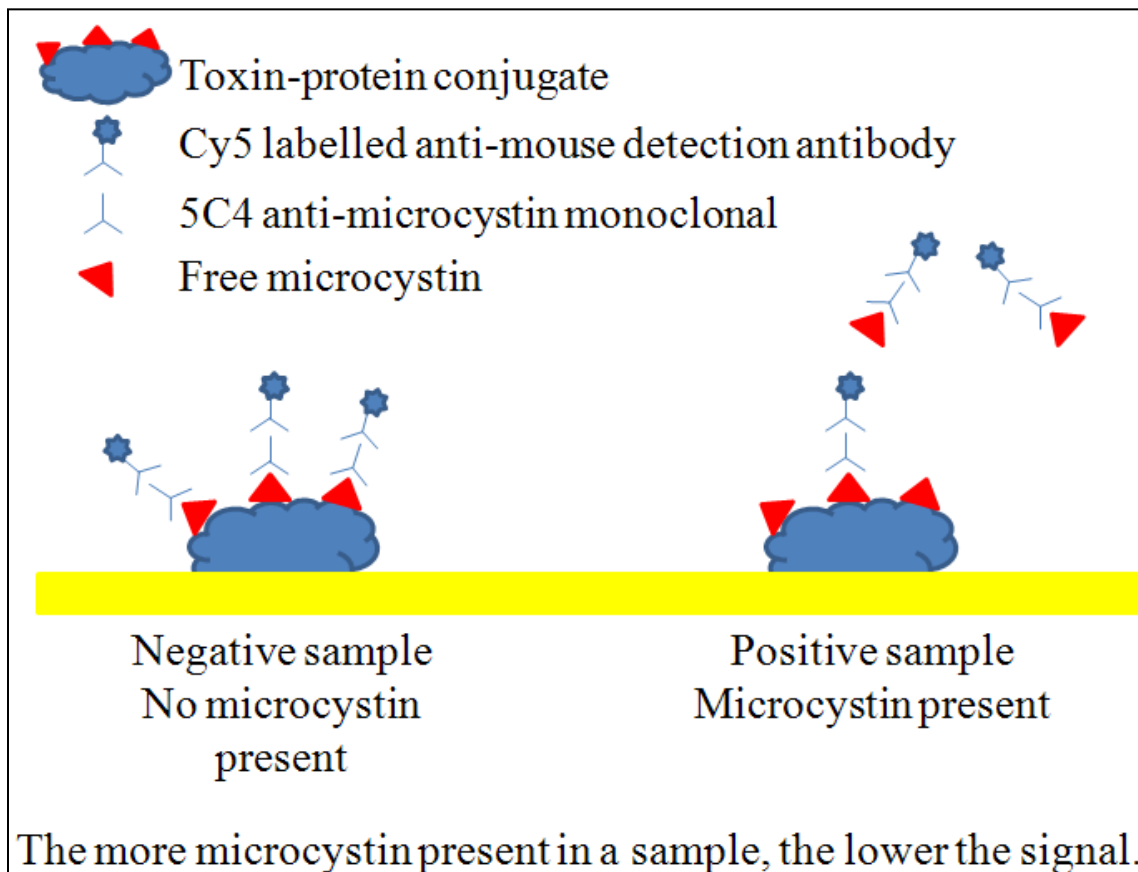
1. Sample Filtration



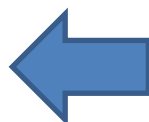
2. Resuspension of cells



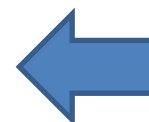
3. Sample Lysis



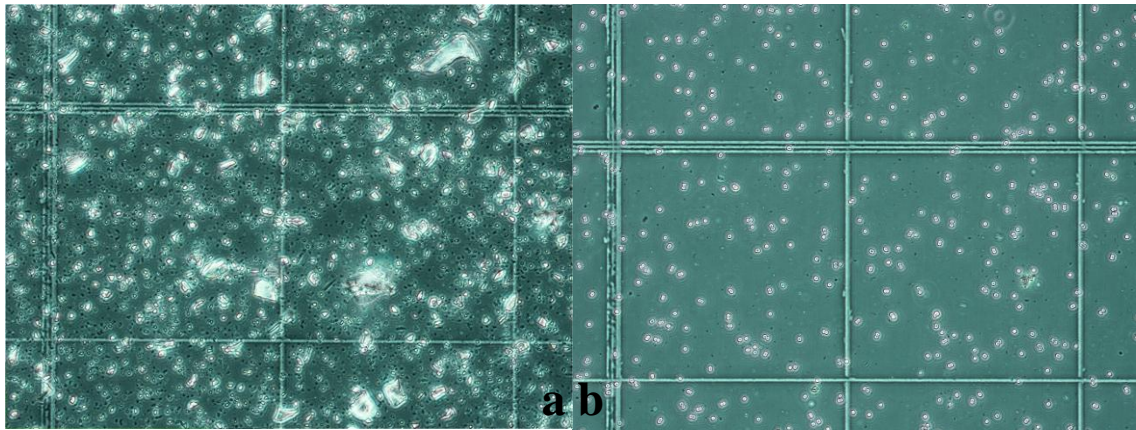
6. Read Signal



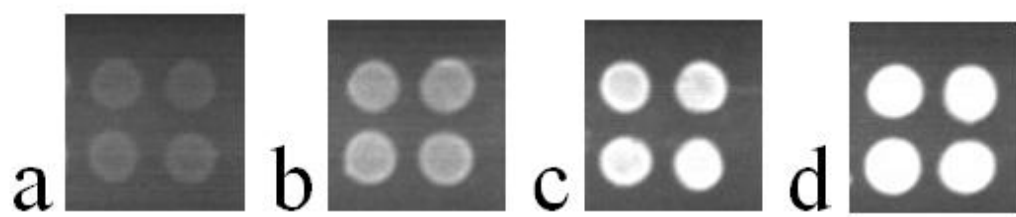
5. Application of sample



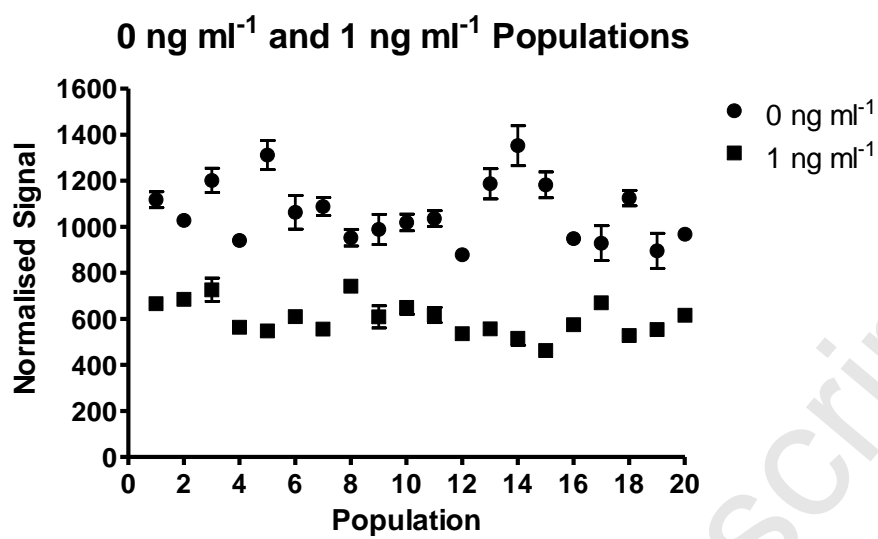
4. Sample filtration



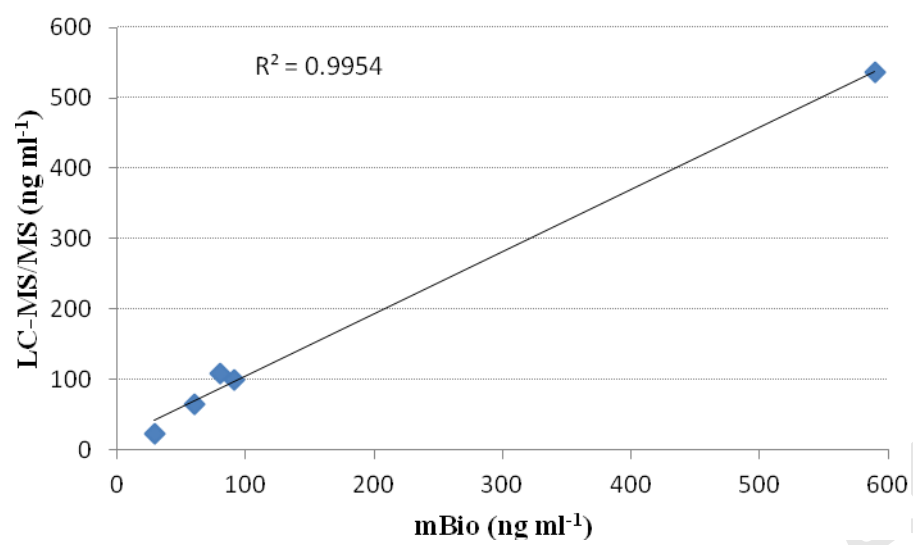
Accepted Manuscript



Accepted Manuscript



Accepted Manuscript



Accepted Manuscript