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Advancing Glioblastoma Imaging: Exploring the

2 Potential of Organic Fluorophore-based Red

3 Emissive Carbon Dots

- 4 Justin B. Domena^a, Braulio C.L.B. Ferreira^a, Emel K. Cilingir^a, Yiqun Zhou^a, Jiuyan Chen^a,
- 5 Qiaxian R. Johnson^c, Bhanu P.S. Chauhan^c, M. Bartoli^d, A. Tagliaferro^d, Steven Vanni^{b ef},
- 6 Regina M. Graham^{b g}, Roger M. Leblanc^{*a}

7 Author Address

- 8 ^a Department of Chemistry, University of Miami, Coral Gables, FL 33146, USA
- 9 ^b Department of Neurological Surgery, Miller School of Medicine, University of Miami, Miami,
- 10 FL 33136, United States
- ¹¹ ^c Department of Chemistry, William Paterson University of New Jersey, 300 Pompton Rd,
- 12 Wayne, NJ 07470, USA
- 13 ^d Department of Applied Science and Technology, Politecnico di Torino, Italy
- ^e HCA Florida University Hospital, 3476 S University Dr., Davie, FL, 33328
- ¹⁵ ^f Department of Medicine, Dr. Kiran C. Patel College of Allopathic Medicine, Davie, USA.
- 16 ^g Sylvester Comprehensive Cancer Center, University of Miami Miller School of Medicine,
- 17 1475 NW 12th Ave, Miami, FL, 33136, USA

18 * Corresponding author: rml@miami.edu

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21 Abstract

22 Over time, the interest in developing stable photosensitizers (PS) which both absorb and 23 emit light in the red region (650 and 950 nm) has gained noticeable interest. Recently, carbon 24 dots (CDs) have become the material of focus to act as a PS due to their high extinction 25 coefficient, low cytotoxicity, and both high photo and thermal stability. In this work, a Federal and Drug Association (FDA) approved Near Infra-Red (NIR) organic fluorophore used for 26 27 photo-imaging, indocyanine green (ICG), has been explored as a precursor to develop water-28 soluble red emissive CDs which possess red emission at 697 nm. Furthermore, our material was 29 found to yield favorable red-imaging capabilities of glioblastoma stem-like cells (GSCs) 30 meanwhile boasting low toxicity. Additionally with post modifications, our CDs have been 31 found to have selectivity towards tumors over healthy tissue as well as crossing the blood-brain 32 barrier (BBB) in zebrafish models.

33 **1. Introduction**

The utilization of red emission in the phototherapeutic window (650-950 nm) for bio-imaging and photo-therapeutics involves the exploitation of exciting chromophores located on the PS¹. A key feature of the far-red range of excitation stems from the fact that there is an increase of light penetration in tissues. Unfortunately, current commercial PS which use excitation wavelengths outside the phototherapeutic window have their light absorption dampened by light scattering or

reflection of light by the host's tissue²⁻⁴. To achieve optimal efficiency, PS used in theranostics 39 40 techniques require the utilization of light within the red region to (NIR-I) window ranging 41 between 650-950 nm, respectively⁵. A direct consequence of this requirement results in the degradation of the PS such as photobleaching or thermal degradation^{6,7}. Additionally, modern 42 43 PS have the disadvantage of low blood clearance from the host which limits biomedical applications⁸. Significantly, CDs have attracted increasing attention in various biomedical areas 44 45 of application such as *in vitro/in vivo* imaging, biosensor, drug delivery, photodynamic therapy, 46 and photothermal therapy^{9–17}. This interest is due to their characteristic of being free of metals, 47 having relatively low cytotoxicity in animal models, and boasting both high photo and thermal stability^{18,19,28,29,20–27}. Up to date, there has been a scarcity of literature that focuses on water-48 49 soluble, red emissive carbons dots past 650 nm suitable for biological studies. Xiong and coworkers have explored the synthesis of red emissive CDs through a bottom-up approach using 50 51 a hydrothermal one-pot synthesis of red emissive CDs using urea and p-phenylenediamine as 52 precursors in 50 mL of water at 160°C for 10 hrs³⁰. The CDs, when purified via silica column 53 chromatography resulted in products with a wide emission range from 440 to 625 nm. The 54 rationale behind this characteristic was attributed to the increase of oxygen species on the CD's 55 surface which effectively lowers the band gap of the CDs causing a bathochromic shift towards the lower red region at 625 nm. The data demonstrated that the surface chemistry of CDs plays a 56 57 pivotal role in elucidating red emission. Further works by Zheng et al. suggest that complex 58 surface modifications of produced CDs with cyanine-based dyes are of interest to unlock the 59 potential route to develop red emissive CDs³¹. Although promising, the previous work 60 mentioned fails to produce red emissive CDs which are also water-soluble. In our work, we 61 posit a variety of synthetic pathways for the formation of CDs derived from ICG, citric acid, and PEG which leads to an enhanced bathochromic shift to produce amphiphilic CDs with highly
valuable emission in the red region. Our materials are ideal candidates for study as a NIR PS in
systems both *in vivo* and *in vitro*.

Glioblastoma (GBM) is a grade IV astrocytoma and is the most common malignant brain 65 in adults. Accounting for 1.35% of all cancer incidents, GBM is responsible for 4% of cancer 66 related deaths yearly with a survival median of 15 months^{32–34}. Therapy can fail in treating GBM 67 68 due to various reasons. These include the difficulty of surgically removing the entire tumor, 69 limitations in the effectiveness of anti-cancer drugs in reaching the brain, and the presence of treatment-resistant GSCs. This subpopulation of GBM tumor cells exhibit early tumor 70 71 progression, aggressive invasion into the surrounding brain parenchyma, and chemo-resistance due in part to the overexpression of multidrug resistance pumps (P-glycoproteins), which leads to 72 increased efflux of drugs as well as imaging agents from the tumor cells³²⁻⁴⁰. It has been well-73 74 documented that the extent of tumor resection directly correlates with patient outcome⁴¹. To 75 optimize tumor resection and patient outcome, surgeons are exploring fluorescence guided 76 surgery in which the tumor cells are fluorescently labeled in order for the surgeon to visualize 77 tumor cells especially at the leading edge of the tumor. The use of 5-aminolevulinic acid (5-ALA) is increasing in the clinical area^{42,43}. 5-ALA is a non-fluorescent precursor to heme and is 78 79 converted to the fluorescent product protoporphyrin IX (PpIX) in tumor cells. However, PpIX 80 has its limitations as both photobleaching and variations of the concentration levels within the 81 tumor. The tumor core normally presents much brighter fluorescence when compared to the 82 leading edge as well as between patients with very low fluorescence observed in lower grade astrocytomas⁴⁴. Therefore, the development of novel photo-stable imaging agents that can target 83 84 both bulk tumor cells and GSCs is necessary to achieve the most efficient success rate^{45–47}. The ideal fluorescent agent would demonstrate high selectivity toward tumor cells, high sensitivity to
improve contrast between tumor and normal tissue and low toxicity.

In this work, an (FDA) approved hydrophilic cyanine-based dye, namely ICG, was explored as 87 a model precursor to develop red emissive CDs (R-CD). ICG was selected as the precursor of 88 89 choice due to the wide scope of clinically excellent properties such as low toxicity, efficient 90 binding to blood lipo-proteins, short lifetime in blood circulation, and usability in the tissue 91 optical window (NIR) region⁴⁸⁻⁵¹. Herein, we hypothesize that it is possible to develop 92 hydrophilic CDs from ICG. Furthermore, it is expected that the CDs will retain most of the 93 functionality of the precursor such as favorable optical behavior in the far-red region to 94 effectively image tumor cells. CDs have several advantages over other red-emissive organic 95 dyes. They demonstrate high resistance to photobleaching, strong absorption in the red/NIR 96 region and are biodegradable. In comparison, ICG, another red-emissive material, suffers from 97 poor chemical and optical stability, as well as mediocre photothermal properties. Recent studies 98 found that CDs derived from NIR dyes such as ICG exhibit significantly improved thermal stability and resistance to photobleaching compared to ICG⁵². Moreover, their photothermal 99 100 properties were greatly enhanced. The CDs showed a wider functional pH range, a 50% 101 improvement in photothermal conversion efficiency, and superior photothermal cyclability. 102 These findings indicate that CDs have the potential for more effective and stable applications in 103 various fields. In our work, R-CDs derived from ICG modulate BBB penetration and tumor 104 homing capabilities depending on peptide-surface functionalization. To our knowledge, this 105 work is the first account of far-red emissive CDs in purely water-based application.

107 **2. Experimental Section**

108 2.1 Materials

109 ICG (>99% purity) and polyethylene glycol 1000 (PEG1000, >99% purity) were procured from Sigma-Aldrich (St. Louis, MO). Anhydrous citric acid (BDH, 99.5% purity) was obtained 110 111 from VWR (West Chester, PA). Nine residue peptide LINTT1 (AKRGARSTA) 94.5% purity 112 was obtained from LifeTein (Somerset, NJ). Transferrin (>98% purity) from human blood plasma was obtained from Sigma-Aldrich (St. Louis, MO). Dialysis tubing with molecular 113 weight cutoff (MWCO) of 3500 was bought from Thermo Scientific (Rockford, IL). Deionized 114 115 (DI) water used was ultrapure (type I) water which was purified using a Millipore Direct-Q 3 116 water purification system acquired from EMD Millipore Corp. The purified water displayed a 117 surface tension of 72.6 mN m⁻¹, a resistivity of 18.2 M Ω cm and a pH value of 7.0 ± 0.3 at 20.0 ± 118 0.5 °C. All the chemicals were used as received. The human pediatric glioblastoma cell line (SJ-119 GBM2) was obtained from Children's Oncology Group (COG, Texas Tech University, Health 120 Science Center, TX, USA) and maintained in RPMI media supplemented with 10% Fetal bovine 121 serum (FBS) and 1% penicillin-streptomycin (P/S). Human mesenchymal stem cells (MSCs) 122 were maintained in MEM alpha supplemented with 20% FBS and 1% P/S. Glio3, Glio9 and 123 Glio38 are GSCs derived from patient's resected tumors following patient consent and Institutional Review Board (IRB) approval^{53–55}.GSCs were maintained in neural stem-cell media 124 125 consisting of DMEM/F12 3:1 supplemented with 20 ng/mL each of epidermal growth factor 126 (EGF) and fibroblast growth factor (FGF), 2% Gem21 and 1% P/S. All cell culture reagents were 127 obtained from ThermoFisher Scientific except for EGF, FGF and Gem21 which were obtained from Gemini Biosciences. All cell lines were routinely tested for mycoplasma using LookOut 128

129 mycoplasma PCR detection kit (Sigma Aldrich, St. Louis, MO, USA) according to the 130 manufacturer's instructions and maintained at 37 $^{\circ}$ C in a humidified 5% CO₂ incubator.

131 2.2 Synthesis of R-CDs

132 The R-CDs were obtained by means of microwave pyrolysis of citric acid (0.200 g), ICG (0.005 g), and PEG1000 (0.050 g). To preface, the precursors were dispersed in a beaker 133 134 containing 15 mL of DI water ultrapure (type I) and sonicated for 1 min to ensure a homogenous mixture which was observed to be a vivid light-green color. The solution of starting material 135 136 was then placed in the microwave and set for 150 s at a power setting of 700 W. Post pyrolysis, 137 it was observed that the solution remained with roughly 5 mL of water with a dispersion of dark 138 green colored solubilized product. The solution was then collected and centrifuged for 30 min at 139 10,000 RPM for three cycles to remove large, suspended particles. The remaining supernatant 140 was then placed within a 3500 MWCO Snakeskin dialysis for 72 hrs in deionized (DI) water 141 ultrapure (type I), with the water changed every 12 hrs. The purified solution of R-CDs was then 142 frozen at -40°C for 24 hrs and sequentially set for lyophilization for 72 hrs, producing a free-143 flowing dark green powder. These freeze-dried R-CDs were then used for study.

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146 2.3 *R*-CD-Ligand conjugations via carbodiimide (EDC/NHS) coupling

Both AKRGARSTA and transferrin (R-CD-AKRGARSTA and R-CD-Transferrin, R-CD-Tf) conjugates were synthesized by carbodiimide coupling which was feasible due to the abundance of carboxylic acids functional groups on the surface of the CD. This conjugation 150 involves the primary amine group of either the nine-residue sort peptide AKRGARSTA or 151 transferrin, which can form a stable amide bond. First, 50.0 mg of R-CD was solubilized in 10 152 mL of Phosphate-buffered saline (PBS, pH 7.4) and allowed to stir for 30 min. To proceed with 153 the activation of -COOH groups on the surface of R-CD, 63.9 mg of 1-ethyl-3-(3-154 dimethylaminopropyl) carbodiimide (EDC) was transferred into 5 mL of the same buffer within 155 a vial and mixed to ensure a homogeneous mixture. Additionally, 193.2 mg of N-hydroxy 156 succinimide (NHS) was also transferred into another vial containing 5 mL of the same buffer and 157 mixed. Sequentially, both EDC and NHS were aliquoted in 1 mL increments to the solution 158 containing the R-CDs and were allowed to stir for 30 min. To synthesize the conjugate of 159 interest (R-CD-AKRGARSTA or R-CD-Tf), either 7.2 mg of AKRGARSTA or 20 mg of 160 transferrin was solubilized in a separate vial containing 5 mL PBS buffer and was aliquoted in 1mL increments of the mixture of R-CD, EDC, and NHS. The resultant mixture was then 161 162 allowed to stir for 48 hrs while protected from light. This process allows the conjugation from 163 the -COOH group on the surface of the R-CD and the -NH₂ of the ligand of interest. The newly 164 formed CD conjugate was then purified by dialysis against ultra pure water for 72 hrs to allow 165 unreacted small molecules to exit from the dialysis membrane with 3500 Da MWCO. Finally, 166 the purified R-CD-AKRGARSTA was lyophilized to yield a dark green powdered product. Successful conjugation was confirmed by circular dichroism spectroscopy (CDS), zeta potential 167 168 (ZP), and mass spectrometry (MS) (Figure S1). Whereas the R-CD-Tf conjugate was 169 lyophilized to yield a turquoise powdered product with its conjugation confirmed by 170 photoluminescence (PL), transmission electron microscopy (TEM), Atomic force microscopy 171 AFM, MS and ZP (Figure S2-3).

174 2.4 Characterization

175 UV-vis spectra were obtained from an Agilent Cary 100 UV-vis spectrophotometer. PL 176 characterization was performed on a Fluorolog HORIBA Jobin Yvon fluorometer with a slit 177 width of 5 nm for excitation and emission. All optical characterization spectra were obtained 178 with quartz cells possessing an optical pathlength of 1 cm. Fourier-transform infrared (FTIR) 179 spectroscopy data were obtained with a PerkinElmer FTIR (Frontier) spectrometer (Waltham, 180 MA, USA) by using the attenuated total reflection (ATR) technique with air as background. 181 AFM images of CDs were obtained with an Agilent 5420 AFM (Santa Clara, CA, USA). To 182 perform AFM measurement, a drop of diluted CDs aqueous solution was applied on a clean 183 silica mica slide and air dried, which then was transferred to do the screening using tapping 184 mode. The tips used were silicon tips (length: 225 µm; thickness: 5 µm) manufactured from 185 Nanosensors with a force constant of 15 N/m. TEM was performed by using a JEOL 1200X 186 TEM (Peabody, MA, USA). For TEM measurements, a drop of the R-CDs solution was placed 187 on a carbon coated copper grid and air dried prior to examination. The ZP was recorded on a 188 The thermogravimetric analysis (TGA) and derivative Malvern Zetasizer nano-series. 189 thermogravimetric analysis (DTG) of R-CDs and some precursors were conducted using a 190 thermo-microbalance (TG 209 F3 Tarsus, Netzsch, USA) while heating under a flow of nitrogen 191 gas from 40 to 1000 °C at a rate of 10 °C/min. Raman spectra were recorded using a Renishaw 192 Inviah Spectrometer equipped with а 193 blue (457 nm), green (514.5 nm), and red (wavelength 785 nm) laser source and a 50x objective. 194 Applied power using green laser source was in the range of 10 to 100 μ W, with the red laser line from 50 to 500 μ W and for the blue laser line from 100 μ W to 1 mW. X-ray photoelectron 195

196 spectroscopy (XPS) spectra were recorded by using a PHI 50 0 0 Versaprobe (Physical 197 Electronics, Chanhassen, MN, USA) scanning X-ray photo electron spectrometer 198 (monochromatic Al K-alpha X-ray source with 1486.6 eV energy, 15 kV voltage, and 1 mA 199 anode current). The circular dichroism experiment was run under room temperature on the Jasco 200 (J-810) Circular Dichroism Spectropolarimeter. To obtain a good S/N ratio during the CDS 201 analyses, 100 µg/mL was used as the concentration of all samples (R-CD, RCD-AKRGARSTA, 202 and R-CD-Tf) in water as solvent; standard sensitivity; 100 nm/min scan speed; 1 nm band 203 width; 1 s response time; 0.5 nm data pinch and 5 accumulation scans.

204 2.5 Cell Viability

205 Cell viability was determined using the CellTiter 96® Aqueous One Solution Cell 206 Proliferation Assay (MTS) (Promega Madison, WI, USA). R-CDs were dispersed in phenol red-207 free DMEM cell culture media at a concentration of 10 mg/ml. SJ-GBM2 cells and MSCs were 208 plated at a density of $1 \ge 10^5$ and $0.5 \ge 10^5$ cells/ml, respectively. GSC cell lines were plated in 209 neural stem cell proliferation media supplemented with 5% FBS at a density of $1.5 \ge 10^5$ 210 cells/ml. The following day cells were treated with 1-500 ug/ml and viability determined 72 hrs 211 later. Data is presented as percent viability compared to non-treated controls.

212 2.6 Cell Imaging

To facilitate cell adhesion, Glio3, Glio9 and Glio38 cells were plated in a media supplemented with 5% FBS at a concentration of 1 x 10^6 cells/ml. At 24 hrs later, cells were exposed to increasing concentrations of R-CDs (50-1000 ug/ml) for 6 hrs. To determine the cellular location of R-CDs, Glio3 and Glio38 cells were treated with 500 ug/ml for 1 hour. Cells were washed with PBS and treated with 4% paraformaldehyde for 30 min, washed again in PBS 218 and cover slips mounted using Prolong Gold Antifade reagent with and without 4',6-diamidino-219 2-phenylindole (DAPI). Images were obtained using a Floid Cell Fluorescent Microscope 220 (Thermo Fisher Scientific, Waltham, MA). For R-CD washout experiment, Glio 3 and Glio 38 221 neurospheres were treated with 100 ug/ml R-CDs for 4 hrs. For R-CD washout, cell culture 222 media was removed and neurospheres washed with PBS to remove any remaining R-CDs and 223 incubated for an additional 48 hrs in fresh media. Alternatively, the neurospheres were washed 224 and fixed immediately following treatment (0 hrs). For R-CD peptide experiments, GSCs and 225 MSCs were treated with equimolar concentrations of R-CDs or R-CD- AKRGARSTA for 1 hour 226 and imaged following PBS washes and fixation as described above.

227 2.7 Image analysis

ImageJ was used to quantify the fluorescence intensities of to evaluate CD uptake according to literature⁵⁶. First, images of GSC and MSCs incubated with the respective CD were median filtered to calculate an overall background value of each image, respectively. The region of interests (ROIs) for each image was detected by binarizing the images using an adaptive threshold value determined by a fixed percentile value of fluorescence intensities. Then, a weighted-fluorescence intensity was calculated for each image as follows in **Eq.1**.

Mean fluorescence =
$$\frac{\sum_{i=1}^{N} [(FI_{ROI,i} - Bg)A_{ROI,i}]}{\sum_{i=1}^{N} A_{ROI,i}}$$
(Eq.1)

FI_{ROI} is the average fluorescence intensity from a given ROI, Bg is the background fluorescence intensity, A_{ROI} is the area of a given ROI. Mean fluorescence intensity was calculated for all control and treatment groups.

237 To further quantify the fluorescence to as an increase in fold, the corrected total cell 238 fluorescence (CTCF) was calculated. The CTCF was obtained by first outlining the cell of 239 interest and their respective background. These acquired measurements enable the generation of 240 values for both the selected area and integrated density for the cell as well as the mean intensity 241 for the background. To measure the amount of CD fluorescence within cells, the calculation of 242 the CTCF was performed by subtracting the product of the average fluorescence in the 243 background and the area outside the cell from the total amount of fluorescence inside the cell. 244 This method has been described in previous literature^{57–59}.

245 2.8 Statistical Analysis

Significance was determined using Student's t-tests for all pairwise comparisons of the different treatments that were tested. All the results are presented as the mean \pm standard error of the mean (SEM). Significance was set at p \leq 0.05.

249 2.9 Zebrafish injection and bioimaging

250 Wild-type zebrafish at 5 days post fertilization were obtained from the Zebrafish Core 251 Facility at University of Miami and anesthetized by 0.02% tricaine. Then, 20 mg/mL of CDs 252 aqueous solution were intravascularly injected into the heart of zebrafish. After 10 min, the 253 zebrafish were mounted with low-melting agar and observed under the Leica SP5 confocal 254 microscope under bright field and fluorescence at excitation of 405 nm. The animal care protocol 255 for all procedures used in this study was approved by the University of Miami Animal Care and 256 Use Committee and complies with the guidelines of the National Science Foundation. Zebrafish 257 studies were conducted under the procedures related to the IACUC 21-182 for the use of zebrafish and meets the criteria for review under Section IIIF in accordance with the *NIHGuidelines*

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263 **3. Results and Discussion**

264 3.1 Characterizations of R-CDs

The analysis of the UV-vis spectrum of R-CDs reveals typical absorption bands attributed to the π - π * transitions of the C=C bond and the n- π * transition of the C=O bond at 210 and 397 nm, respectively (**Figure 1**)⁶⁰. Further bands found at 770 and 890 nm are reminiscent of the bands usually observed from ICG at 710 and 790 nm, respectively. These bands are normally related to nitrogen-containing heterocyclic structures which the dye is composed of. The



Figure 1. UV-vis analysis R-CDs, (inset) UV-vis spectrum of ICG.

bathochromic shift of the absorbance of R-CDs is hypothesized to be attributed to the increase of
oxygenated groups as confirmed by FTIR due to the implementation of citric acid and PEG1000
during the synthetic process.

273 The PL of R-CDs was studied to assess the viability of the material in fluorescent imaging 274 techniques across a wide range of excitations. The expected result was to produce CDs that 275 retained optical properties similar to ICG which has notable emission peaks at 599 and 815 nm, 276 respectively. It was hypothesized that there may be degradation of the dye during the synthetic 277 process resulting in slight loss of conjugation, leading to an increase of the energy band gap producing a slight hypsochromic shift⁶¹. It is noteworthy that this behavior was observed in the 278 279 PL of the R-CDs when they were stimulated with light between 360 to 700 nm, at 20 nm 280 intervals (Figure 2A). R-CDs were found to possess red emission at 697 nm as well as a 599 nm 281 emissive peak similar to the ICG dye (Figure 2B). Interestingly, R-CDs were found to have a 282 clear isosbestic point at both 575 and 665 nm. These findings support a uniformity on the PL 283 profile across a long range of the visible spectrum. This discovery holds significant implications 284 as it suggests that the optical characteristics of the R-CDs will remain consistent across a specific 285 range of wavelengths owing to their uniformity. We hypothesize, during the synthesis of R-CD, 286 the electronic structure of the ICG molecule is partially preserved and is interconnected via PEG 287 chains. This results in the production of CDs that have similar excitation and emission properties 288 as the dye precursors.



Figure 2. Optical analysis of R-CDs. (A) R-CD PL spectrum, (B) ICG PL spectrum.

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290 FTIR is a suitable technique for revealing the surface functionality of CDs, which typically 291 consists of functional groups containing oxygen and nitrogen. Moreover, FTIR has the unique 292 ability to penetrate to a depth of 2 µm, making it a powerful tool for qualitative analysis of both 293 the surface and core of CDs. A comparative analysis of R-CDs and the starting material was 294 performed to reveal a glimpse into the surface of the CD (Figure 3). Stretching vibrations are 295 1700 cm⁻¹ are due to presence of C=O bonds on the surface of the CD. Upon deeper analysis of 296 R-CD, the intense peaks at 1335 and 1277 cm⁻¹ are due to the asymmetric S=O and C-N 297 stretching vibrations, respectively. This characteristic supports the presence of moieties from the 298 ICG dye, which have the same respective peaks. Between 3000 and 3100 cm⁻¹ one would expect 299 to observe the C-H stretching of the alkenes which make up the carbonized network of R-CDs, 300 though increased spectral broadening from the carbonized network diminishes an observable peak. Additionally, the broad peak in between 3300 and 3580 cm⁻¹ are attributed to stretching 301 vibrations of O-H groups present as well as the medium peak at 2850 cm⁻¹ indicative of C-H 302 303 stretching vibrations of alkane groups due to the PEG1000 present during the synthetic process,

304 confirming the availability of these groups on the surface of the R-CDs, respectively. The peaks 305 at 1085 and 1205 cm⁻¹ can be ascribed to -C-O- and C-OH groups on the surface of the R-CDs, 306 respectively. These results suggest that R-CD retains most functionality from ICG which 307 passivates the surface⁶². Additionally, through the implementation of PEG1000 during the 308 synthetic procedure, increased -OH functional groups are to be found on the surface of the CD. 309 It is hypothesized the abundance of these groups is responsible for the high solubility of R-CDs 310 in water⁶³.



Figure 3. FTIR spectral analysis of R-CD, PEG1000, Citric Acid, and ICG.

Functional moieties can be identified and quantified by TGA and DTG measurements by their different and discernible decomposition temperatures. TGA and DTG of citric acid were previously provided, so they are not shown in **Figure 4**⁶⁴. In general, the TGA of R-CDs and PEG (**Figure 4A**) show a similar thermal decomposition trend across different temperatures, which demonstrates a structural similarity between R-CDs and PEG, as a result of the use of PEG during the synthesis of R-CDs. Also, it is worth noting that an estimated 10% residue

remained after the decomposition of ICG. Considering the structure of ICG containing Na⁺ and -318 319 SO_3^- , the remnant is likely to be $Na_2SO_3(8\%)$ or $Na_2SO_4(9\%)$, which basically matches the 10% 320 residue mass percentage. Upon dialysis, the R-CDs no longer retained Na+ ions, resulting in the 321 absence of any residual signal in the TGA analysis of the R-CDs. In addition, the DTG results 322 display noticeable differences and similarities between R-CDs and their precursors (Figure 4B): 323 (1) ICG has five decomposition stages: 40-177, 177-268, 268-368, 368-544 and 544-828 °C; (2) PEG has three decomposition steps: 40-138, 138-419, and 419-514 °C; (3) the R-CDs possess 324 325 five decomposition periods: 40-172, 172-248, 248-403, 403-523 and 523-1000 °C; (4) the DTG 326 of PEG and R-CDs are somewhat similar; (5) the thermal stability of R-CDs is higher than ICG, 327 PEG and citric acid considering an enhanced highest decomposition temperature, which might 328 benefit from a higher carbonization degree that resulted from the hydrothermal treatment during 329 the CD synthesis; (6) with the DTG of a well-established CD species as a reference,⁶⁵ any peaks 330 between 40-122 °C indicate the loss of water molecules (moisture). The mass loss at 122-168 °C 331 suggests the loss of water molecules formed through intramolecular dehydration condensation reactions⁶⁶. The stage between 168-250 °C is ascribed by the decomposition of edge-plane 332 oxygen-containing functional groups such as epoxy, carboxyl and carbonyl groups⁶⁷. The stage 333 334 at 250-338 °C is due to the decomposition of some relatively stable oxygen-containing functional 335 groups and sublimation of small carbon frameworks. The stage at 338-448 °C indicates the 336 decomposition of amines^{68,69}. Eventually, the stage at 448-1000 °C indicates the decomposition of graphene-like structures^{70–72}; (7) thus, in the first stage, PEG (40-138 °C) showed a desorption 337 of moisture while ICG (40-177 °C) and R-CDs (40-172 °C) exhibited the loss of water molecules 338 339 from moisture and formed through intramolecular dehydration condensation reactions. However, 340 ICG doesn't contain hydroxyl groups so the mass loss for ICG is hypothesized to be primarily 341 moisture desorption; (8) the second decomposition stages of ICG (177-268 °C) and R-CDs (172-342 248 °C) are similar with a mass loss of 9 and 10%, respectively, due to the decomposition of 343 edge-plane oxygen-containing functional groups such as epoxy, carboxyl, and carbonyl groups. 344 Nevertheless, the only edge-plane oxygen-containing functional group in ICG is -SO₃, so this DTG peak is likely to indicate the loss of -SO₃, which can be confirmed by the mass percentage 345 346 (10%) of -SO₃ in ICG (*Note:* one -SO₃ will be left to form Na₂SO₃ or Na₂SO₄). Additionally, in 347 this temperature range, citric acid is transformed into aconitic acid, itaconic acid and anhydrous 348 itaconic acid while releasing CO₂ and water molecules, so it is hard to identify that the mass loss 349 of R-CDs is due to the release of CO_2 or SO_2 solely based on the DTG measurement. In 350 comparison, the second decomposition stage of PEG was extended to 419 °C. Given the simple 351 unit-repeated structure of PEG, the dramatic mass loss (97%) during the second stage of 138-419 352 °C shows the breakdown of the unit-repeated oxygen-containing backbone; (9) the 353 decompositions of relatively stable oxygen-containing functional groups and carbon frameworks 354 were observed in the third decomposition stage (248-403 °C) of R-CDs and the corresponding 355 mass percentage in R-CDs is 82%. On the contrary, due to the lack of oxygen-containing 356 functional groups in ICG, the mass loss (13%) at 268-368 °C was hypothesized to occur due to 357 the decompositions of short alkane and alkene chains. A similar mass loss at this stage between 358 R-CDs and PEG also suggests a similarity in the structure; (10) due to the presence of amines, 359 ICG (368-544 °C) and R-CDs (403-523 °C) possess a fourth decomposition stage with a mass 360 loss of 21 and 9%, respectively. However, since amines are incorporated in aromatic structures, 361 the highest decomposition temperatures of at least ICG were raised together with the mass loss 362 compared to the theoretical amine contents; (11) compared to PEG and citric acid, given the 363 aromatic rings in the structure of ICG, the dramatic decomposition of ICG occurred at the last stage of 544-828 °C with a mass loss of 39%. Meanwhile, R-CDs also showed a mass loss of 5% corresponding to the decomposition of graphene-like structures in the core; (12) according to the contents of oxygen-containing carbon frameworks (82%) and aromatic rings (5%) inherited from PEG (MW: 1000 Da) and ICG (MW: 775 Da), respectively, the structure of 1 mole R-CDs (MW: 966 Da) is hypothesized to be composed of 1 mole PEG (incomplete), 1 mole ICG (incomplete) and an unknown amount of citric acid (incomplete).



Figure 4. TGA (A) and DTG (B) of R-CDs and some precursors including ICG and PEG.

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371 Raman spectroscopy is a facile and non-destructive technique that can be used to characterize 372 the crystallinity and chemical functionality of graphitic materials, as well as to elucidate defects. 373 As a powerful tool for investigating the disorder and crystallinity of CDs, Raman spectroscopy 374 can help to determine the level of disorder present in CDs, which plays a crucial role in their 375 electronic and optical properties. By using Raman spectroscopy to understand the degree of disorder and crystallinity of CDs, researchers can optimize their performance for various 376 377 applications such as bioimaging. For our system, we are interested in both the position and intensity of two prevalent spectral bands (D band and the G band). The G-band denotes the 378

amount of graphitization (sp² hybridization) R-CDs has and the D-band represents the degree of 379 defects and functionalization of R-CDs such as sp³ hybridization^{73,74}. The Raman spectrum was 380 reported in the range from 600 to 2200 cm⁻¹ and fitted according to Tagliaferro et al.⁷⁵ as shown 381 in Figure 5. The spectrum of R-CDs reveals two distinct peaks at 1375 (D-band) and 1585 cm⁻¹ 382 (G-band), respectively⁷⁶⁻⁷⁸. Additionally, the baselined fitted Raman spectrum of R-CDs shows 383 384 the presence of highly disordered systems with a large D peak and broad 2D region. The 385 intensity ratio of the peak of the G band to the D band (I_D/I_G) was up to 2.9. In graphitic 386 material, a higher in I_D/I_G ratio indicates that the synthesized R-CDs have an increased amount sp^2 clusters in its structure^{79–81}. 387



Figure 5: Raman spectra R-CDs

389 The ZP of the R-CDs was obtained to further understand the surface and the surface charge. In 390 brief, ZP is an essential technique for characterizing the surface properties of CDs such as 391 surface charge, stability, and functionalization. By measuring the ZP, researchers can gain 392 valuable insights into the electrostatic interactions between the CDs and their surrounding 393 environment. This information is crucial for understanding the behavior of CDs in various applications such as drug delivery, imaging, and sensing. Furthermore for our system, this 394 395 technique is important to understand the colloidal stability of CDs in solution. Hence, a large 396 absolute value above 20 mV has been observed to result in CDs that participate in interparticle 397 repulsion leading to a well-dispersed colloidal solution^{82,83}. The R-CDs were found to have a 398 negative potential of -29.2 mV suggesting the presence of surface functional groups such as 399 carboxylic and amides possibly attributed to the functionality left by ICG (Figure S3). Furthermore, the ZP data supports CDs high dispersibility/solubility when in solution since TEM 400 401 and AFM measurements confirmed a lower percentage of agglomerations. The ZP of R-CD-402 AKRGARSTA was found to be -18.5 mV. This discovery is a good indication for aiding in the 403 confirmation of the conjugation taking place as we hypothesize that the peptide shields the 404 highly negative moieties on the surface of the R-CDs causing there to be a slightly less negative 405 charged CD. Additionally, the ZP of R-CD-Tf reinforces the same rationale as the ZP was 406 observed to be -18.2 mV.

TEM images were studied regarding R-CDs, R-CD-AKRGARSTA, and R-CD-Tf to understand the X–Y plane size distribution. The sample was sonicated for 15 min prior to measurements to breakdown any aggregate formation. R-CDs showed a narrow Poisson size distribution of 1.0-6.0 nm with a mean size of 2 nm (**Figure 6A**). The TEM of R-CD-AKRGARSTA had a Poisson size distribution of 1.0-6.0 nm with a slightly bigger mean size of 412 2.5 nm which is attributed to the peptide bound on the surface (**Figure 6B**). In following, the 413 TEM of R-CD-Tf was found to have had a Poisson size distribution of 1.0-7.5 nm with the 414 largest mean size of 3.0 nm (**Figure 6C**). We hypothesize this change is due to the bulky 415 transferrin which is bound to the surface of R-CD. Each histogram for all three types of CDs 416 comprises of a particle count of over 300 particles with a high degree of uniformity. AFM was 417 also performed on the R-CDs to understand the height profile of the CDs in the z-axis. The 418 AFM images display R-CD particles height within 2.0–2.8 nm, which is consistent with the previous TEM diameter distribution confirming the quasi-spherical structure of the R-CDs. The
AFM of R-CD-AKRGARSTA was found to have a particle height of 2.5-3.5 nm in agreement
with the TEM. Likewise, the AFM of R-CD-Tf revealed a particle height of 2.5-4.0 nm which
conforms with its TEM.

To further understand the surface chemistry, R-CDs were analyzed by using XPS (Figure S4)
and high-resolution spectra for each relevant element (Figure 7) are reported together with table
on the elemental composition (Table 1) and functionalities distribution (Table S1). As shown in



Figure 6. Morphology of R-CDs and R-CD conjugations. (A) R-**ED TEM** image with a scale bar of 200 nm, particle size histogram, AFM image and scale.; (B) R-CD-AK**ROARST**A TEM image with a scale bar of 200 nm, particle size histogram, AFM image and scale.; (C) R-CD-Tf TEM image with a scale bar of 10 nm, particle size histogram, AFM image and scale. 28.9 1.1 0.5

table 1, the preliminary results of elemental composition of R-CDs show a high amount of 426 427 oxygen up to 28.9 % a low content of both nitrogen (1.1 %) and sulfur (0.5 %). This was reasonably due to the massive presence of PEG chain fragments. In Figure 7A, R-CDs C1s 428 spectrum showed the presence of relevant components due to sp^3 hybridized carbon (283.5 eV) 429 430 and to sp² hybridized carbon (peaked at 284.7 eV) with an intensity of 30.1 and 52.0 %, respectively. Furthermore, C-X (X = N, O, S; 285.8 eV) is present with an intensity of up to 12.7 431 % while COOH (289.1 eV) reaches up to 5.1 %. O1s spectrum is significantly simple with a 432 433 major component due to C-O (531.3 eV) up to 90.2 % while sulphonate (532.2 eV) and COOH 434 (533.3 eV) represent only the 6.0 and the 3.5 % respectively (Figure 7B). This is in good 435 agreement with the model based on ICG fragments connected through PEG chains and residual 436 fragments of citric acid. N1's spectrum is considerably simple (Figure 7C), and it is composed by one signal due to N5 (399.9 eV) as the sp² one that is composed by only one component due 437 438 to sulphonates (166.6 eV, Figure7D).

Table 1: : Elemental composition of R-CDs as calculated from XPS survey spectra (average uncertainty of up $\pm 1\%$).



440

Figure 7: XPS spectra of relevant element for R-CDs.

441 3.2 Formation Mechanism of R-CDs

442 Preliminary consideration of the structure should be based on both TGA and FTIR data. As 443 shown by TGA data, the graphitic domains are limited to only 5 wt.% of the total amount of R-444 CDs and there is unneglectable similarity with neat PEG suggesting the persistence of polyether 445 chains into the final structure of R-CDs. Similarly, the FTIR spectrum of R-CDs suggests the 446 presence of alkyl chains together with the persistence of sulphonyl residues and the presence of 447 small amounts of aromatic and nitrogen containing aromatic systems. Additionally, Inductively 448 Coupled Plasma (ICP) analysis excludes the presence of sodium and Raman spectrum clearly 449 supports the presence of highly disorganized aromatic domains. Considering the characterization 450 data and the chemical formula of each reactant, we propose a mechanism for the formation of R-451 CDs that is composed by several pathways as shown in **Figure 8**.

452 Firstly, we can considered the hemolytic cleavage of 1 in the polyenes chain (C=C energy 453 bond up to 255 kcal/mol⁸⁴) producing unsaturated species 2-4. These species could undergo 454 through a Diels-Alder cycloaddition condensation forming chemical families like compound 5. 455 Another modification of 1 is the isomerization of polyunsaturated chain that connects its two 1H-456 benzo[g]indole units forming 6. This species represents an interesting platform diene able to self-457 condense forming species such 10 that could further condense producing small condensed 458 aromatic systems. Alternatively, 6 could undergo inter-molecular condensation with several 459 species such as 2-4 or unsaturated citric acid derivatives (7-8) formed under microwave 460 irradiation. Interestingly, cyclic anhydrides such as 13 could evolve into 4H-pyran derivatives 461 such as 14 and 15 accounted for the aromatic oxygen moieties detected by TGA analysis. 462 Similarly by TGA, the evolution of 8 could produce species with a naphtalenic (21) or biphenyl 463 (23) cores. The condensed ICG derivatives formed under microwave irradiation are highly 464 functionalized and hardly evolved to proper layered supramolecular structure as proved by the 465 residual functionalities detected by analytical by FTIR and MS. Additionally, 24 can degrade 466 under microwave irradiation forming low molecular weight species hydroxyl (25) or/and vinyl 467 (26) terminated species. Hydroxyl ended chains could easily react with acidic functions, both 468 carboxylic and sulphonyl, forming 27 while 26 could react with both dienes forming species
469 such as 28 and with acidic moieties forming 29.

The PEG linked condensed ICG fragments could be schematized with a structure such the one reported in **Figure 9**. The scattering and small size of aromatic domains is in good agreement with both Raman and TGA analysis suggesting a hybrid structured in between a polymeric and layered CDs. Accordingly, aromatic clusters are surrounded by a polyether environment bonded through ester and saturated carbon-carbon bond. This could boost their local interaction through $\pi - \pi$ stacking and could be accounted for the fluorescence emission at 697 as reported for similar systems by Wang et al⁸⁵.



Figure 8: R-CDs formation mechanism.



479 **Figure 9:** R-CDs structural model.

480 3.3 Cell Viability of R-CDs

481 GSCs have been shown to be resistant to current treatment modalities and are responsible for 482 tumor regrowth following surgery. Hence, it is important to develop an imaging material that 483 can readily undergo cellular uptake. Additionally, it is necessary that the material is non-toxic towards cells before using it for imaging applications. We anticipate that our R-CDs will have 484 485 high cell viability due to the abundance of PEG on the surface, which has been proven to have excellent biocompatibility with cells⁸⁶⁻⁸⁹. To determine the potential biocompatibility of R-486 487 CDs, the cell viability was determined using non-tumor, and tumor cell lines: normal MSCs, SJ-488 GBM2 and GSCs Glio3, Glio9, and Glio38, respectively. Cells were treated with increasing 489 concentrations (1-500 µg/mL) and cell viability was determined following 72 hrs of exposure. 490 The R-CDs were relatively non-toxic to all cell lines especially at concentrations of 100 µg/mL 491 or below. At drastically high concentrations of 500 µg/mL, the cell viability of MSC and SJ-GBM2 were 65 and 83% (p > 0.05), respectively (Figure 10A). This finding is important as the 492 upper limits of concentrations for cell viability are usually presented as 100 µM^{90–92}. Suggesting 493 494 that within normal standards, R-CDs are highly non-toxic which is a feature of PEGylated 495 nanoparticles⁹³. At the upper limit concentration, the cell viability for Glio3, Glio9 and Glio38 496 were 100, 85 and 108% (p > 0.05), respectively (**Figure 10B**). As expected, the R-CDs were 497 highly bio-compatible which further reinforced the need to apply these CDs for bioimaging.



Figure 10. SJ-GBM2 and MSCs (A) and GSC lines, Glio3, Glio9 and Glio38 (B) were exposed to R-CDs at concentrations shown and viability determined by MTS assay 72 hrs later. *p<0.05 compared to non-treated controls.

499 3.4 Red Fluorescent Imaging Capabilities of R-CDs

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Given the relatively low cytotoxicity observed, especially in the GBM cells, the fluorescent imaging capabilities of R-CDs were assessed. For these studies we chose to use GSCs. Cancer stem cells (CSCs) including GSCs express high levels of ATP-binding cassette (ABC) transporters which not only pump anti-cancer drugs out of the cell but many fluorescent dyes as well. In fact, CSCs are also referred to as the side population and can be isolated from tumors or 505 cancer cell lines by their ability to rapidly efflux fluorescent dyes such as Hoechst 33342. The 506 ability to fluorescently label the CSCs as well as the bulk tumor cells is necessary for maximal 507 tumor removal by fluorescence-guided tumor resection techniques. Therefore, we sought to 508 determine the potential of R-CDs to effectively label our GSC lines. Glio3, Glio9, and Glio38 509 were treated with increasing concentrations (50-1000 µg/mL) of R-CDs for 6 hrs and visualized 510 by fluorescent microscopy. Upon observation it is evident that the fluorescent intensity increases 511 in a concentration dependent manner. Figure 11A displays the comparison between the 512 fluorescence microscope bright field (Bf) and the red channel for non-fluorescent and fluorescent 513 cellular visualization. While no fluorescence was observed in the non-treated controls, 514 fluorescence was observed in all 3 cell lines at 100 μ g/mL. As the concentration is increased to 515 an upwards of 1000 µg/mL, the fluorescence is notably stronger. Furthermore, while R-CDs 516 dispersed throughout the cell, they appeared to be localizing mainly in the cytoplasm (Figure 517 11B) since DAPI staining normally targets and highlights only the cell nucleus. Based on these 518 results, R-CDs may be well-suited for cell/tumor imaging in the red region. Additionally, the 519 favorable cell viability and imaging serves as motivation to address the challenge presented by 520 GBM, which is increased drug efflux of theranostic materials.



В



Figure 11. (A) GSCs were exposed to R-CDs as concentrations shown for 6 hrs and imaged with Bf and using the red channel. Scale bar is 50 μ m. (B) GSCs were exposed to 500 μ g/mL for 1 h and the fluorescent intensity observed. DAPI was used to stain the cell nucleus. Arrows indicate reduced fluorescent intensity in cell nucleus. Scale bar is 25 μ m.

522 3.5 Drug Efflux Assessment of R-CDs in Glio3 and Glio38

523 The R-CDs were assessed for their ability to resist drug efflux by both Glio3 and Glio38 neurospheres (Figure 12A, 12B). The neurospheres were exposed to R-CDs for 4 hrs and 524 525 imaged immediately (0 hr) or at 48 hrs following the removal of the CDs from the cell culture medium. The neurospheres exhibited robust fluorescence both immediately following exposure 526 as well as 48 hrs later despite the removal of the R-CDs from the cell culture media. This 527 528 indicates that the R-CDs are not readily effluxed from the GBM neurosphere cells. Overall, these 529 favorable results make sense due to the presence of the PEG-linked network of R-CDs. 530 Literature confirms that PEG plays a key role in efflux pump inhibitions as well as PEGylated 531 compounds generally having a high cellular uptake^{94,95}. With these results in mind, we sought to develop tumor selective R-CDs which possess low drug efflux. 532



Figure 12. (A) Glio3 and (B) Glio38 neurospheres were treated with 100 ug/ml R-CDs for 4 hrs and imaged immediately (0 hr) for R-CDs removed, neurospheres washed 2 times in cell culture media and incubated an additional 48 hrs prior to

533

534 3.7 Cellular Uptake Enhancement by Homing Peptide Conjugation of AKRGARSTA and R-CD

- 535 To enhance the cellular uptake of R-CD, the conjugation between the CD and short homing
- 536 peptide AKRGARSTA was described in the **Experimental Section** with the scheme provided in

537 Figure 13. This particular peptide is known to provide higher cellular uptake towards GBM cell 538 lines since its mechanism of action relies on the interaction with key cell receptors. Based on our 539 PCR results (Figure S5-6), GBM cells overexpress neuropilin1 (NRP1) and p32 (C1QBP) which 540 normally interacts with AKRGASTA peptide for cellular intake. The rationale of why we are 541 interested in this specific homing peptide is due to the fact that there is a significantly higher 542 expression of both neuropilin1 (NRP1) and p32 (C1OBP) in GBM than in the normal brain as 543 provided in Figure S5-6. Furthermore, the justification of this reaction stems from 544 AKRGARSTA peptide's mode of action regarding GBM. The initial interaction of 545 AKRGARSTA begins at the p32 receptor of GBM tumor cells which are overexpressed on the 546 surface of vascular and malignant cells followed by proteolytic processing. This process then 547 exposes the C-end Rule (CendR) motif of the peptide (AKRGAR) to enable neuropilin-1 (NRP-1) binding⁹⁶. Thus, activating a specialized tumor penetration pathway. AKRGARSTA has been 548 549 established as a conjugate for nanoparticles to deliver targeted treatment of breast cancer and 550 glioblastoma^{97,98}. Therefore, we posit that through this conjugation, the R-CD conjugates will 551 effectively enhance cellular uptake as provided in Figure 14.



Figure 13. Schematic representation of the conjugation of AKRGARSTA to R-CD (R-CD-AKRGARSTA) using





Figure 14. Schematic representation of the R-CD-AKRGARSTA penetration pathway with



554 Regarding the characterization of the conjugate to ensure the success of the reaction, CDS 555 was implemented to detect the presence of the peptide on the purified product. CDS is one of the 556 main techniques used to determine the secondary structure of a protein or peptide, making it possible to obtain its ellipticity signal^{99,100}. A protein's structure mainly depends on the amino 557 558 acid sequence and its length. The longer the peptide chain, the more complex the structure can 559 be. Furthermore, the amino acid within the peptide tends to intramolecularly interact with one 560 another via dipole-dipole (H-bonding), π -related and hydrophobic interactions, alongside 561 covalent bond as disulfide bridges between cysteine residues^{101,102}. In addition to these 562 interactions, solvents also influence the final structure of the proteins which dictates their functionality according to their stabilization¹⁰³. Therefore, investigation of its architecture is a 563 564 must to understand how it interacts and behaves with other compounds. When proteins or peptides are studied using CDS, it is possible to obtain insights about their structure^{104,105}.Based 565 566 on the implementation of this methodology to our system, the data displayed on Figure 15A 567 indicates that the R-CDs do not present any significant signal on the CDS which concludes that 568 R-CDs are identified as non-chiral nanoparticles. In contrast, when the conjugated sample (R-CD-AKRGARSTA) was analyzed, the ellipticity signal within the range of 190 - 250 nm 569 570 suggests that the coupling reaction was successful. Due to the small number of amino acids 571 residues (9), the peptide cannot form a more complex structure than a random coil based on 572 comparisons with the literature. In addition, to further sustain the random coil as the structure of 573 this peptide, we utilized the Beta Structure Selection (BeStSel) algorithm on the CDS spectrum 574 which didn't present any predominant beta-sheet structure (80 % or higher) as shown in Figure $15B^{106-108}$. 575



Figure 15. (A) Circular Dichroism spectra of naked R-CD and R-CD conjugated to AKRGARSTA; (B) BeStSel estimated secondary structure based on the circular dichroism data. The analysis of the BeStSel was repeated three times for each CD with an experimental uncertainty of $\mp 0.10\%$.

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577 To assess the discreet differences of cellular uptake between cell lines, Glio3, Glio9, Glio38 578 and non-cancer MSCs were treated with 100 µM of either R-CD or R-CD peptide conjugate for 579 1 hr and evaluated by fluorescent microscopy (Figure 16). Non-treated (NT) cells were included as a control. Remarkedly, the images show a vast difference in fluorescence intensity between 580 581 both R-CD and R-CD-AKRGARSTA. Although the red channel imaging of R-CD is favorable, 582 clearly the conjugate boasts superiority in terms of imaging capabilities for Glio3, Glio9, and 583 Glio38. We can ascribe this result due to the enhanced selectivity of tumor cells over non-tumor 584 cells via the short homing peptide AKRGARSTA as described previously. This specificity is 585 evident when observing the red channel of the non-tumor MSC cell line as there are less 586 significant changes between the CDs and conjugate.



Figure 16. Effect of peptide targeting of R-CDs on cell cancer and non-cancer cells. A. GSC lines Glio3, Glio9, Glio38 and non-cancer MSCs were treated with 100 μ M of either R-CDs or R-CD- peptide conjugate (Conjugate) for 1 hr and evaluated by fluorescent microscopy. Non-treated (NT) cells were included as a control. Cell nuclei were stained with DAPI (blue channel) and CD fluorescence. Scale bar represents 67 microns and was visualized using the red channel. Merged red and blue channels are shown.

588 To elucidate the degree of fluorescent enhancement between the CD and its conjugate, both 589 mean fluorescence intensity and percent increase of corrected total cell fluorescence (CTCF) 590 were determined as described in Experimental Section. The observation of the mean 591 fluorescence in both GSC and MSCs are again noted to have noticeable differences which 592 correspond to nanoparticle uptake between the CD and CD conjugate (Figure 17A). With 593 regards to the results on R-CDs, whereas the mean fluorescence in MSC is 64, in Glio3, Glio9, 594 and Glio38 the values are 61, 39 and 66, respectively. Yet to our satisfaction, R-CD-595 AKRGARSTA yielded much higher mean fluorescence with Glio3, Glio9, and Glio38 having 596 values of 156, 87 and 186, respectively. This data not only corroborates the earlier suggestion 597 that the conjugate has an effective mechanism for cellular uptake, but also indicates that there 598 was minimal alteration in the material intake by MSC. The mean fluorescence of conjugated R-599 CDs in MSC provided a value of 77, which is only slightly higher than that of bare R-CDs. To 600 provide clearer insight into the increase of fluorescence due to the enhancement of cellular 601 uptake of the CDs, the CTCF values between R-CD and R-CD-AKRGARSTA were calculated 602 to determine the percent increase of fluorescence (Figure 17B). As expected, the data yielded 603 highly valuable information which supports the qualitative observation of the initial images. In 604 Glio3, Glio9, and Glio38, R-CD-AKRGARSTA has shown to increase the CTCF by 2.56, 2.23, and 2.82-fold, respectively. In MSC, the conjugate only resulted in a CTCF increase of 1.2-fold. 605 606 The specificity of R-CD-pep for the tumor cells can also be demonstrated in Figure S7 in which 607 Glio3, Glio9, Glio38 and MSCs were exposed to only 50 µM R-CD-Pep and imaged by 608 fluorescent microscopy. While the GBM stem cell lines, Glio3, Glio9 and Glio38 clearly 609 demonstrated pronounced fluorescence, the fluorescence of the non-tumorous MSCs is barely 610 visibly. These results support our hypothesis that the peptide bound onto the surface of R-CD611 has specificity to mainly target GBM tumor cells.



Figure 17. Fluorescence assessment of 100 μ M CDs incubated for 1 hr of CDs on GSC cell lines Glio3, Glio9, Glio38 and non-cancer MSC. (A) Mean fluorescence intensity. (B) Fold increase of CTCF from R-CD-AKRGARSTA when compared to R-CD.

613 *3.7 Crossing the BBB via R-CD-Tf Conjugate in zebrafish model*

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614 Given the nature of GBM, it is imperative to address the challenge to cross the BBB. To be 615 specific, the CNS comprises of both the brain and spinal cord which is protected by the intricate 616 mechanisms that are regulated within the BBB³⁴. Moreso, the BBB serves as a physiological 617 point of entry that has high specificity towards what molecules are permitted entry from the 618 blood circulation of the host into the CNS. This feature coupled with physical characteristics of 619 the BBB being composed of capillary endothelial cells that are interconnected by tight junctions leads to the difficult transport of materials such as drugs or CDs into the CNS¹⁰⁹. In fact, the vast 620 621 majority of both large molecules and nanoparticles are unable to pass the BBB without surface 622 modifications¹¹⁰. To remedy this limitation, our group has successfully conjugated R-CDs (R-623 CD-Tf) with the ligand transferrin with a scheme provided in Figure 18A. Transferrin was selected as the ligand of choice due to the BBB's brain capillary endothelial cells having a high
degree of expressed transferrin receptors. These transferrin receptors have been proven to permit
the entrance of transferrin-conjugated nanoparticles according to literature¹¹¹.

627 To investigate the prospect of transporting R-CD-Tf into the CNS the zebra model was due to 628 their physiological homology to humans. This complex vertebrae species possesses the ideal 629 hormones, receptors, and major neurotransmitters that allow researchers to develop therapeutic agents in vivo that can be extended to human disease¹¹². Furthermore, given their physical 630 631 attributes such as small size, transparent body, and conditions to breed, the zebrafish is a more facile model to both simulate and follow non-invasive imaging techniques in the CNS than that 632 633 of mice¹¹³. The larval zebra fish were used at 5 days post fertilization as studies conclude that 634 the maturation of the BBB of zebrafish is completed within 3 days comparable to mammals¹¹⁴. As indicated in Figure 18B, the CDs of choice were injected into the heart of the larval zebrafish 635 to allow the pumping of the material through the blood stream. We predict that, in comparison 636 637 to R-CD, R-CD-Tf will successfully be received by the transferrin receptor and transported 638 through the BBB and into the CNS.



Figure 18. (A) Schematic representation of the conjugation of transferrin to R-CD (R-CD-Tf). (B) Image of zebrafish with the highlighting of both the heart (injection site) and central canal (observation area).

The confocal images of the larval zebrafish were overlapped with the bright field images which yielded quite interesting results (**Figure 19**). As expected, due to the absence of transferrin on the surface, the R-CDs when visualized under 405 nm excitation did not appear to be in the central canal suggesting that the R-CDs did not penetrate the BBB. Although it is worthwhile to note that the R-CDs were able to be clearly observed throughout the image. Upon analysis of the overlapped images containing R-CD-Tf, red fluorescence of the central canal was observed

646 indicating crossing of the BBB by R-CD-Tf. In following, we hypothesize that the R-CD-Tf 647 were successfully transported into the CNS across the BBB as provided in Figure 20. The 648 finding of this result has strong impact in the field of imaging as this is the first time to our 649 knowledge to observe stable, water-soluble and far-red emitting CDs to cross the BBB 650 successfully.



Figure 19. Confocal image of R-CD-Tf versus R-CDs in the CNS of zebrafish under 405 nm excitation. The blue arrow indicates the central canal of spiral cord of zebrafish.



Figure 20. Graphic visualization of the transit of R-CD-Tf via the BBB into the CNS as compared to R-CD in zebrafish. Created with BioRender.com

652

653 **4.** Conclusion

654 For the first time, we have synthesized a new type of red-emitting CDs derived from 655 mixture of the organic fluorophore ICG, citric acid, and PEG. Ultimately, the red emission was attributed due to the decrease of conjugation of the fluorophore that passivates the CD. 656 657 Additionally, this is the first report of far-red emission CDs whose applications are favorable in water leading to excellent biocompatibility in comparison to previous reports^{115,116}. This 658 659 type of CD was proven to exhibit low toxicity in both GBM and MSCs and was showcased 660 as suitable materials for enhanced fluorescent imaging of cancer cells including GSCs. 661 Furthermore, post-conjugation we were able to both selectively increase the cellular uptake 662 of CDs into GSC as well as cross the BBB in the zebrafish model. To our knowledge, the this is the first account of CDs bound with AKRGARSTA to increase tumor selectivity. In 663

- 664 further application, we believe the potential of both drug delivery and drug tracking is the
- 665 next step field of study for these types of CDs in the field of theranostics 117,118.

666 Credit authorship contribution statement

- 667 Justin Domena: Conceptualization, Methodology, Validation, Formal Analysis, Investigation,
- 668 Writing- original draft, Writing- review & editing, Project administration.
- 669 **Braulio C.L.B. Ferreira:** Formal analysis, Methodology, Writing-review & editing.
- 670 Emel K. Cilingir: Methodology, Formal analysis
- 671 Yiqun Zhou: Methodology, Formal analysis, Writing-review & editing
- 672 Jiuyan Chen: Methodology, Formal analysis
- 673 **Qiaxian R. Johnson:** Formal analysis.
- 674 Bhanu P.S. Chauhan: Formal analysis
- 675 Mattia. Bartoli: Methodology, Formal analysis, Writing-review & editing
- 676 Alberto Tagliaferro: Methodology, Formal analysis, Writing-review & editing
- 677 Steven Vanni: Methodology, Formal analysis
- 678 Regina M. Graham: Methodology, Validation, Formal Analysis, Investigation, Writing-
- 679 original draft, Writing- review & editing.
- 680 **Roger M. Leblanc:** Conceptualization, Methodology, Validation, Writing-review & editing.
- 681 Declaration of Competing Interest

682 The authors declare that they have no known competing financial interests or personal683 relationships that could have appeared to influence the work reported in this paper.

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