Tumour-specific amplitude-modulated radiofrequency electromagnetic fields induce differentiation of hepatocellular carcinoma via targeting Ca\(_{\text{v}}\)3.2 T-type voltage-gated calcium channels and Ca\(^{2+}\) influx

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**ABSTRACT**

**Background:** Administration of amplitude modulated 27-12 MHz radiofrequency electromagnetic fields (AM RF EMF) by means of a spoon-shaped applicator placed on the patient’s tongue is a newly approved treatment for advanced hepatocellular carcinoma (HCC). The mechanism of action of tumour-specific AM RF EMF is largely unknown.

**Methods:** Whole body and organ-specific human dosimetry analyses were performed. Mice carrying human HCC xenografts were exposed to AM RF EMF using a small animal AM RF EMF exposure system replicating human dosimetry and exposure time. We performed histological analysis of tumours following exposure to AM RF EMF. Using an agnostic genomic approach, we characterized the mechanism of action of AM RF EMF.

**Findings:** Intrabuccal administration results in systemic delivery of athermal AM RF EMF from head to toe at levels lower than those generated by cell phones held close to the body. Tumour shrinkage results from differentiation of HCC cells into quiescent cells with spindle morphology. AM RF EMF targeted antiproliferative effects and cancer stem cell inhibiting effects are mediated by Ca\(^{2+}\) influx through Ca\(_{\text{v}}\)3.2 T-type voltage-gated calcium channels (CACNA1H) resulting in increased intracellular calcium concentration within HCC cells only.

**Interpretation:** Intrabuccally-administered AM RF EMF is a systemic therapy that selectively block the growth of HCC cells. AM RF EMF pronounced inhibitory effects on cancer stem cells may explain the exceptionally long...
1. Introduction

Hepatocellular carcinoma (HCC) death rates in the U.S. are increasing faster than for any other malignancy, having more than doubled in the past decade [1,2]. Worldwide, HCC is the fourth most common cause of cancer death and the second most common cause of absolute years of life lost due to cancer [3]. Despite the development and recent approval of additional treatment modalities [4–6], the outcome of patients with advanced HCC remains poor and new therapeutic approaches are sorely needed [4]. There is growing experimental and clinical evidence that alternating electric fields and amplitude-modulated electromagnetic fields are capable of blocking tumour growth [7]. However, little is known regarding the kHz to THz electromagnetic interactions with biological systems, which do not result in changes in temperature within tumour tissues or in tumour cell membrane electroporation.

We previously hypothesized [8] and subsequently provided experimental evidence that delivery of 27.12 MHz radiofrequency electromagnetic fields, which are amplitude-modulated at tumour-specific frequencies (AM RF EMF), has anticancer activity both in vitro [9] and in patients with advanced HCC and results in clinical benefits with minimal risks, even after several years of continuous daily use [10,11]. These clinical and translational findings led to the regulatory approval of the TheraBionic P1 AM RF EMF emitting device for the treatment of advanced hepatocellular carcinoma [12]. The medical device received European approval as a class Ila low-risk medical device in 2018 and is indicated for patients with advanced hepatocellular carcinoma who have failed or are intolerant to first line and second line therapies.

Using HCC and breast cancer cell lines as well as immortalized hepatocytes and breast epithelial cells, we previously demonstrated that AM RF EMF control the growth of cancer cells at tumour-specific modulation frequencies but do not affect the growth of noncancerous cells [9]. While both alternating electric fields [13] and amplitude-modulated electromagnetic fields [9] have been shown to disrupt the mitotic spindle of tumour cells, the mechanism by which tumour-specific AM RF EMF result in tumour shrinkage and long-term therapeutic responses in patients with cancer is unknown [7]. Furthermore, the human dosimetry of intrabuccal administration has not been characterized.

Here we show that administration of amplitude-modulated radiofrequency electromagnetic fields by means of a spoon-shaped antenna placed on the patient’s tongue results in systemic delivery of AM RF EMF with whole body averaged specific absorption rate (SAR) of 1.35 mW/kg with peak spatial SAR ranging from 146 to 352 mW/kg averaged over 1 g of tissue. Using a mouse exposure system replicating human exposure conditions [14], we show that AM RF EMF-mediated shrinkage of hepatocellular carcinoma results from differentiation of cancer cells into quiescent cells with spindle morphology. We identify Ca²⁺ influx through Ca_{v3·2} T-type voltage calcium channels (CACNA1H) resulting in increased intracellular calcium concentration as the necessary and sufficient initiating event of both AM RF EMF anti-proliferative effects on HCC cells and down-regulation of cancer stem cells, which likely accounts for the long-term responses observed in some patients with advanced HCC.

Research in context

Evidence before study

We previously demonstrated that 27.12 MHz tumour-specific amplitude-modulated radiofrequency electromagnetic fields (AM RF EMF) administered intrabuccally result in tumour shrinkage or tumour control in 50% of patients with advanced hepatocellular carcinoma. We also showed that the same AM RF EMF block the growth of cancer cells in vitro but do not affect the growth of noncancerous and non-corresponding tumour cells. While AM RF EMF have been shown to disrupt the mitotic spindle of tumour cells, the mechanism by which tumour-specific AM RF EMF result in tumour shrinkage and long-term therapeutic responses in patients with cancer is unknown. Additionally, the human dosimetry of AM RF EMF intrabucal administration has not been characterized.

Added value of this study

This study shows that intrabuccally-delivered AM RF EMF result in whole-body absorption below international standards for safety exposure. Hepatocellular carcinoma shrinkage upon treatment with tumour-specific AM RF EMF results from differentiation of tumour cells into quiescent cells with spindle morphology. Targeted inhibition of hepatocellular carcinoma cell growth and downregulation of cancer stem cells is initiated by calcium influx through Ca_{v3·2} T-type voltage-gated calcium channels (CACNA1H).

Implication of all the available evidence

These findings unveil the mechanism of action of tumour-specific AM RF EMF.

2. Materials and methods

2.1. Ethical statement

All procedures and protocols were performed in accordance with institutional guidelines and approved by the Wake Forest Institutional Animal Care and Use Committee (IACUC). The patient was offered compassionate treatment with the TheraBionic P1 device. Written informed consent that includes authorization to publish the patient’s clinical data was obtained and compassionate use was approved by the Ethics Committee of the Cabinet Médical de l’Avenue de la Cane 6, 1003 Lausanne, Switzerland. Additionally, a compassionate use request for use a non-conforming medical device was submitted to and approved by Swissmedic: https://www.swissmedic.ch/swissmedic/en/home/medical-devices/market-access/exemptions-for-non-conforming-medical-devices.html Exemptions for non-conforming medical devices.

2.2. Dosimetry simulation

The primary purpose of the dosimetry assessment is to determine the safety of the device and provide insight into organ-specific absorption of AM RF EMF. The predicted absorption of intrabuccally-
2.4. AM RF EMF exposure in vitro

Cell lines were exposed to 27-12 MHz radiofrequency electromagnetic fields using exposure systems designed to replicate clinical exposure levels. Experiments were conducted at SARs of 30 and 400 mW/kg. Cells were exposed for 3 h daily, seven days in a row. Cells were exposed to tumour-specific modulation frequencies that were previously identified by changes in pulse pressure [8]. Using the same method, we monitored variations in the amplitude of the radial pulse in thirty patients with a diagnosis of cancer and did not observe any change in pulse amplitude during exposure to the randomly chosen frequencies [8].
2.9. Quantitative real-time PCR target primers and machine protocol

CACNA1g (CAV 3·1)-Forward primer: 5′ CTT ACC AAC GCC CTA GAA ATC A 3′; CACNA1g (CAV 3·1)-Reverse primer: 5′ GAT GTA GCC AAA GGG ACC ATA C 3′; CACNA1h (CAV 3·2)-Forward primer: 5′ CA/G GAA TGG ATG GGT GAA CA 3′; CACNA1h (CAV 3·2)-Reverse primer: 5′ GAT GAG CAG GAA GGA GAT GAA G 3′; CACNA1i (CAV 3·3)-Forward primer: 5′ GCC CTA CTA TGC CAC CTA TTG 3′; CACNA1i (CAV 3·3)-Reverse primer: 5′ AGG CAG ATG ATG AAG GTG ATG 3′; GAPDH-Forward primer: 5′ TGC ACC ACC TGC TTA GC 3′; GAPDH-Reverse primer: 5′ GCC ATG GAC TCT GGT CAT GAC G 3′; MIR-1246-Forward primer: 5′ CCC TGT ATC CTT GAA TGG ATT T 3′; MIR-1246-Reverse primer: 5′ CAT TGC TAG CCT ATG GAT TGA TTT 3′; HSA-LET-7G-Forward primer: 5′ GCT GAG GTA GGT TGT ACA GTT 3′; HSA-LET-7G-Reverse primer: 5′ GCA GTG GCC TGT ACA GTT AT 3′; RPLPO-Forward primer: 5′ TTC ATA CCC AGC TAG CCA ATC 3′; RPLPO-Reverse primer: 5′ TTT CCA TCC CAC TCC CTT TC 3′; All primers were purchased from IDT. Roche LightCycler 489 Instrument II Protocol: 1 cycle for 30 min at 50 °C, 1 cycle for 10 min at 95 °C, 40 × (30 s at 95 °C / 1 min at 60 °C), Rest at 4 °C.

2.10. Fluo-4 Ca2+ imaging

Huh7 cells – seeded into six-well plates or 35 mm dishes (Falcon; Corning) – before receiving either AM RF EMF treatment. 300,000 cells were left to adhere overnight and cultured in Dulbecco’s Modified
Eagle's Medium (DMEM; Cellgro) supplemented with heat-inactivated foetal bovine serum (FBS, final concentration 10%; Atlanta Biologicals). Cells were exposed to either HCCMF (hepatocellular carcinoma specific AM RF EMF) or no treatment for 30 min, 1 h, 3 h, or 6 h. 30 min before completion of treatment Fluo-4 stain mix was added directly to each well/dish (Fluo-4 Calcium Imaging Kit; Molecular Probes). Dishes/plate were placed on a rocker at room temperature for 5 min of gentle distribution of Fluo-4 stain. Cells were then placed back into the 37 °C incubator and exposed for 30 min to HCCMF (completing the required time of HCCMF exposure). Following completion of treatment exposure, the dishes/plates were placed at room temperature for 30 min (in the dark). Cells were then washed using 1·5 mL of LCIS (Live Cell Imaging Solution; Molecular Probes) then placed in two millilitres of fresh LCIS and fluorescent intensity was read using a Fluostar fluorescent plate reader (BMG LABTECH) (485 excitation/520 emission). All experiments were performed at least twice with representative experiments shown. Statistics: one-way t-test was utilized.

2.10.1. Fluo-4 Ca$^{2+}$ imaging with VGCC blocker

T-type VGCC 2-ethyl-2-methylsuccinimide (ethosuximide, ETHOS group) (0·5 mM final concentration) (Sigma-Aldrich). Amiodipine besylate (1μM final concentration) (Sigma-Aldrich). Ethosuximide or amiodipine was dissolved in 100% ethanol as the vehicle control (VC) (Fisher) as per Sigma-Aldrich recommendations to create working solution. Ethosuximide, amiodipine or vehicle was added to each well 30 min before start of treatment. Following 30 min of incubation at 37 °C, the Fluo-4 experiment proceeded as stated in the above protocol (three-hour exposure).

2.11. Extracellular Ca$^{2+}$ chelation

Huh7 cells – seeded in 35 mm dishes, six dishes per group – were cultured in the presence or absence of the extracellular Ca$^{2+}$ chelator 1,2-bis(2-aminophenoxy) ethane-N,N,N′,N′-tetraacetic acid (BAPTA; Sigma-Aldrich). BAPTA was dissolved in dimethyl sulfoxide (DMSO; Fisher), as per Sigma-Aldrich recommendations, to create a working solution. The AM RF EMF treatment groups were as follows: HCCMF, randomly chosen, HCCMF + BAPTA, randomly chosen + BAPTA. Cells were left to adhere overnight then were cultured in Dulbecco’s Modified Eagle’s Medium (DMEM; Cellgro) supplemented with heat inactivated foetal bovine serum (FBS, final concentration 10%; Atlanta Biologicals). Cells were exposed to either HCC-specific or randomly chosen frequencies daily for 3 h in a row, either in the presence or absence of BAPTA (final concentration 1 mM). The BAPTA working solution was added to the culture medium within 5 min before exposure to HCC-specific or randomly chosen frequencies. Within 5 min after completion of the three-hour exposure time, the BAPTA-containing media was discarded and replaced with fresh media without BAPTA. On day seven, cell proliferation was assessed with the tritiated thymidine incorporation assay. Experiments were repeated at least twice. Statistics: One-way ANOVA was used to statistically compare the effect of experimental (HCCMF) and control groups (SHAM and randomly chosen frequencies). Post hoc testing was by the Tukey test. Data are expressed as mean ± SEM. Graphpad Prism was the software used for statistical analysis.

2.12. L-type and T-type voltage gated calcium channel blockade

2.12.1. L-type VGCC blockade

Huh7 cells were seeded in 6-well plates at 20,000 cells per dish and cultured in the presence or absence of a pan T-type VGCC 2-ethyl-2-methylsuccinimide (ethosuximide, ETHOS group) (1 mM) (Sigma-Aldrich). Ethosuximide was dissolved in 100% ethanol as the vehicle control (VC) (Fisher) as per Sigma-Aldrich recommendation to create working solution. The treatment groups were as follows: SHAM (VC), RCF (VC), HCCMF, SHAM (ETHOS), RCF (ETHOS) and HCCMF (ETHOS). Cells were left to adhere overnight and were then cultured in Dulbecco’s Modified Eagle’s Medium (DMEM; Cellgro) supplemented with heat inactivated FBS (final concentration 10%). Cells were exposed to either HCC or randomly chosen frequencies (RCF) daily for 3 h in a row, either in the presence or in the absence of nifedipine (final concentration 100 μM or 10 μM). Nifedipine working solution was added to the culture medium within 5 min before exposure to HCCMF or RCF. Within 5 min after completion of the three-hour exposure time, media was removed from all dishes and replaced with fresh media, not containing nifedipine. On day seven, cell proliferation was assessed with the tritiated thymidine incorporation assay. The experiment was repeated twice.

2.12.2. T-type VGCC blockade

Huh7 cells were seeded in six-well plates at 20,000 cells per dish and cultured in the presence or absence of a pan T-type VGCC 2-ethyl-2-methylsuccinimide (ethosuximide, ETHOS group) (1 mM) (Sigma-Aldrich). Ethosuximide was dissolved in 100% ethanol as the vehicle control (VC) (Fisher) as per Sigma-Aldrich recommendation to create working solution. The treatment groups were as follows: SHAM ( VC), RCF (VC), HCCMF ( VC), SHAM (ETHOS), RCF (ETHOS) and HCCMF (ETHOS). Cells were left to adhere overnight and were then cultured in Dulbecco’s Modified Eagle’s Medium (DMEM; Cellgro) supplemented with heat inactivated FBS (final concentration 10%). Cells were exposed to either HCCMF or RCF daily for 3 h in a row or received no treatment, either in the presence or in the absence of ethosuximide (final concentration 1 mM). Ethosuximide working solution was added to the culture medium within 10 min before exposure to HCCMF, RCF, or SHAM groups. Within 5 min after completion of the three-hour exposure time, media was removed from all dishes and replaced with fresh media without ethosuximide. On day seven, cell proliferation was assessed with the tritiated thymidine incorporation assay, flow cytometry markers were stained, or cells were cultured in tumour sphere media for sphere formation assays. Experiments were repeated at least twice. Statistics: One-way ANOVA was used to statistically compare the effect of experimental (HCCMF) and control groups (SHAM and randomly chosen frequencies). Post hoc testing was by the Tukey test. Data are expressed as mean ± SEM. Graphpad Prism was the software used for statistical analysis.

2.13. Flow cytometry analysis

Cells cultured, divided and treated into HCCMF, RCF or SHAM groups. After seven days of treatment cells were labelled for CD44-APC (mouse anti-human 1:20,000 (Huh7) and 1:10 (Hep3B), Cat#103011 Biologend) and CD133-PE (mouse anti-human 1:10 (Huh7) and 1:20 (Hep3B), Cat# 130–098-826 Miltenyi Biotec) markers of cancer stem cell, fixed and analysed via flow cytometry. Data collection was performed on a C6 Accuri flow cytometer while analysis was performed on CFlow Plus software (Becton Dickinson).

2.14. Sphere formation assay

Cells were cultured, divided and treated in HCCMF, RCF or SHAM groups. Cells were plated (200 cells/well) in 96-well ultra-low attachment plates (Corning) with DMEM/F12 supplemented with 2% B27 (Invitrogen), 20 ng/mL EGF (Sigma Aldrich), and 4 μg/mL insulin (Sigma-Aldrich). Cells seeded at a density of 100–500 viable cells per 100μL. Five-seven days post-treatment cells were counted for the number of spheres present in each well and data were represented as the means ± SEM.

2.15. In vivo effects of amplitude-modulated radiofrequency electromagnetic fields

To replicate the dosimetric conditions resulting from intrabuccal administration of AM RF EMF in vivo, we designed and developed a small animal exposure system for AM RF EMF [14]. This exposure system allows for control of SAR levels in the same range as those generated by...
intrabuccal administration [14]. Mice were exposed to RF EMF amplitude-modulated at the previously published hepatocellular carcinoma specific (HCCMF) [9] or randomly chosen (RCF) [9] frequencies 3 h daily. Another group of control mice was not exposed to any RF EMF. A total of 40 non-obese diabetic severe combined immunodeficient (NOD SCID; Jackson labs) mice (male and female) were used. Mice were housed in plastic cages with up to five mice/cage at room temperature and fed a standard mouse diet with water ad libitum (food and water were autoclaved). Mice were injected subcutaneously in the right hind flank with 7-0 x 10^6 Huh7 cells, re-suspended in 200 μL of DPBS, at five-seven weeks of age. Thirty-seven of the 40 (92.5%) mice developed palpable Huh7 tumours. Upon establishment of a palpable tumour, measuring at a minimum of 0.5 cm in one dimension (Length or Width), mice were randomly assigned and exposed to HCCMF or RCF 3 h daily. An additional group of mice were not exposed to any RF EMF (SHAM treatment group). Mice set to receive AM RF EMF exposure were placed in a custom-designed exposure system [14], consisting of two transverse electromagnetic (TEM) cell[s] configurations as half-wave resonators (sXv-27, ITIS, Zurich, Switzerland). Mice were exposed to 27-12 MHz EMF, modulated at HCC [9] or randomly chosen [9] frequencies set to result in an organ-specific SAR of 67 mW/kg within subcutaneous tumours, i.e., tumours located in the subcutaneous fat [14]. Tumours were measured with callipers three times per week. Mice were euthanized when tumour burden was excessive; 2 h before euthanasia, a total of 12 mice (6 exposed to HCCMF, 3 exposed to RCF, 3 not exposed to EMF; SHAM) were injected intraperitoneally with 200 μL bromodeoxyuridine labelling reagent (BrdU; Life Technologies). Mouse tissue and xenograft tumour were collected/fixed for paraffin embedding and evaluated by immunohistochemistry.

### 2.16. Mice carrying patient derived xenografts

10 NSG female mice, with PDX implanted tumours, were provided by Anand Ghanekar M.D. from University Health Network (UHN) (Toronto, Ontario, Canada). Briefly, the patient derived tumour was from a 63-year-old male HCC patient with negative viral serologies, no metastases to lymph nodes, positive for microscopic and large vessel vascular invasions, multiple satellites/intrahepatic metastatic smaller nodules, TNM stage: pT3bN0 and no significant fibrosis or other active parenchymal or biliary injury. The tumour was implanted into immuno-compromised (NSG) mice as previously described [16]. After one month of quarantine, six mice were exposed to HCC-specific AM RF EMF, and four mice were observed as controls. In total, mice received HCCMF for eight weeks.

### 2.17. Statistics

In vivo tumour volume comparisons were accomplished by repeated measures mixed models analysis. In these models, group and time were fixed effects and the individual animals were treated as random effects. A time by group interaction was examined to determine if tumour growth rates were different between groups. If the time by group interaction was significant, post-hoc testing was compared by a Tukey Test. Data for Immunohistochemistry were expressed as mean ± SEM. Graphpad Prism was the software used for statistical analysis. IHC staining was performed by Dr. David Caudell. Visualization and quantification were performed blindly by Dr. Barry DeYoung. Average number of positive staining cells was counted for both control and treated groups. Tumour samples were from mice with established tumour after subcutaneous xenograft injection of the Huh7 cells, having received HCCMF or SHAM treatment for ten weeks. EMT panel staining and GFP tagged IHC slides were prepared and digitally scanned by the Wake Forest Baptist Comprehensive Cancer Centre Tissue Tissue and Pathology Shared Resource. All images were prepared with NanoZoomer Digital pathology software (Hamamatsu Photonics K.K.) from digital slide scans (1x and 20x magnification). IHC staining was performed by Dr. David Caudell. Visualization and quantification were performed blindly by Dr. Barry DeYoung. Average number of positive staining cells was counted for both control and treated groups. Tumour samples were from mice established tumour after subcutaneous xenograft injection of the Huh7 cells, having received HCCMF or SHAM treatment for ten weeks. Statistics: One-way Analysis of Variance (ANOVA), used to statistically compare the effect of experimental (HCCMF) and control groups (SHAM & RCF). Post-Hoc testing was compared by a Tukey Test. Data for Immunohistochemistry were expressed as mean ± SEM. Graphpad Prism was the software used for statistical analysis. IHC was performed on a Leica Bond RX (Leica Biosystems, Buffalo Grove, IL) automated stainer.

### 2.19. RNA-Seq data analysis

We have generated two RNA-Seq data sets using two cell lines, Huh7 and HepG2. The RNA-Seq data of Huh7 include six controls and six treated samples. The HepG2 dataset contains two controls and two treated samples. The alignment and quality control of RNA-Seq data followed the pipeline developed by the NCI’s Genomic Data Commons (GDC, https://gdc.cancer.gov/). The alignment was performed using a two-pass method with STAR2 [17]. The quality assessment was carried out by FASTQC (https://www.bioinformatics.babraham.ac.uk/projects/fastqc/) on the pre-alignment, and RNA-SeQC [18] and Picard tools (http://broadinstitute.github.io/picard/) on the post-alignment. Read Counts were performed by Summarized Experiment of DESeq2 [19]. The count data were normalized by betweenLaneNormalization function of EDAsaeq [20] to normalize the data using upper-quartile (UQ) normalization and then estimate the factors of unwanted variation using empirical control genes, e.g., least significantly differentially expressed (DEGs) genes based on a first-pass DEG analysis performed prior to RUVg normalization [21]. Lastly, DEG analysis is implemented by DESeq2 by adding the factors of unwanted variation into design of DESeq2 in order to remove unwanted variation. MicroRNA arrays: the initial microRNA array analysis did not reach significance. Eighty percent of miRs are not expressed and should not be penalized. After adjustment for the lack of expression of 80% of the miRs, miR-1246 was the most significant miR showing differential expression in both HepG2 and Huh7. There are additional miRs that are invariably significant in addition to miR-1246: miR-4306, 378b, 1973, 3175, which are similarly more expressed upon exposure to HCCMF.
209. Long-term antitumour effect in a patient with advanced hepatocellular carcinoma

A 79-year-old man, diagnosed with hepatocellular carcinoma in January 2011, underwent left hepatectomy in February 2011. Histologic review revealed a 10-cm lesion consistent with poorly differentiated hepatocellular carcinoma with negative margins, pT3N0M0. Recurrent disease was identified by radiologic imaging in May 2011 revealing four new lesions within the right lobe of the liver. The patient underwent chemoembolization of the liver lesions with lipiodol and doxorubicin in June 2011. Follow-up magnetic resonance imaging (MRI) obtained in July 2011 showed intrahepatic progression of disease. The patient started sorafenib on August 15, 2011 and compassionate use treatment with the TheraBionic device on September 15, 2011. As shown on Fig. S4 the patient had a complete response by AFP marker and a partial response as assessed by imaging studies, which lasted more than six years.

3. Results

3.1. Whole-body and organ-specific dosimetry

Intrabuccal administration of AM RF EMF has yielded objective tumour shrinkage in the femur [8], adrenal gland [8], liver [10], and lungs [10] of patients suffering from unresectable or metastatic cancer (Fig. 1a, b). This strongly suggests that intrabuccally-administered 27-12 MHz AM RF EMF have systemic anticancer effects distant from the point of administration, i.e., the bucal mucosa. However, the levels of AM RF EMF exposure in humans have not yet been characterized. Therefore, we tested the hypothesis that intrabuccal administration of AM RF EMFs results in absorption throughout the body because contact between the spoon-shaped “antenna” applicator and the anterior part of the patient’s tongue could result in the patient’s body acting as an extension of the antenna [11].

The RF output of the AM RF EMF emitting device is adjusted to 100 mW into a 50 Ω load using a sinusoidal test signal [8,10]. We assessed the SAR level and distribution inside the human body and quantified the variability depending on device positioning and patient posture (Fig. 1c). Homogeneous and inhomogeneous model simulations show similar SAR distribution patterns (Fig. 1d, e). The whole-body (wbSAR) and the peak spatial SAR (psSAR) over any 10 g (psSAR10g) and 1 g (psSAR1g) of major organs according to IEEE standard [22] are listed in Table 1a. As shown in Fig. 1d and e, intrabuccal delivery of 27-12 MHz AM RF EMF results in whole-body absorption from head to toe and the highest peak spatial SAR (psSAR) is at the interface between the tongue and the spoon-shaped applicator. As shown in Table 1b, there is more radiated power when the device is far away from the body. Conversely, the wbSAR is slightly higher when the device touches the body, regardless of position (Table 1c). Experimental validation measurements based on a tank phantom show that the SAR distribution inside the tank is similar to that of the homogeneous human model (Fig. 1e, Supplemental Fig. S1a, S1b). The wbSAR is 1·35 mW/kg with psSAR over 1 g from 146 to 352 mW/kg when the applicator spoon is perfectly matched, which is significantly below the International Commission on Non-Ionizing Radiation Protection (ICNIRP) standard safety limits of 80 mW/kg wbSAR, or psSAR of 2000 mW/kg (Table 2) [23]. Organ-specific SAR ranges from 0·02 to 1 mW/kg (Table 2).

Uncertainty and variation assessments were conducted with the patient sitting with the device placed away from the body (Fig. 1c). The posture variation based on sitting positions as shown in Fig. 1c introduces 0·06 dB deviation. A ± 10 kg variation in body weight introduces 0·39 dB deviation, the biggest contribution, 2·19 dB comes from the variation of the applicator spoon impedance with posture and device position and its effect on the power delivered to the patient. Therefore, the total variation of 2·21 dB, as shown in Table 1d, mainly depends on the delivered power. The SAR distributions along the centre line inside the tank phantom are compared to the simulations of the same configurations (Supplemental Fig. S1a) to determine the effective power delivered by the spoon-shaped applicator as a function of the positioning of the device. The effective power per device location is shown in Supplemental Table S1a. Based on the delivered power, and the power delivered when matched, the effective return loss can be calculated and is also shown in Supplemental Table S1a. In the real use scenario, the delivered power is between 11 and 51% of the perfectly matched case. Reflection coefficient measurements of the applicator spoon were performed with a portable vector network analyser, Supplemental Fig. S1c, Supplemental Table S1b; when compared to those calculated based on normalized fields, more than one effect must be present, namely, impedance dependent output power variation as well as mismatch. Consideration not only of the induced field levels, but also the field distributions inside the rectangular phantom, shows that the measurements and simulations are generally in agreement, as shown in Supplemental Fig. S1a for configurations 1 and 3 in Fig. 1e, which are equivalent to the sitting position with the device on the thigh and a short distance away from the body, respectively. The differences are larger in locations with low field strength, e.g., at the far end of the phantom from the applicator spoon, as the induced field strengths are close to or below the measurement system noise floor. This is especially evident in cases where the mismatch is largest and delivered power is low. E-field measurements normalized to the same delivered power, for lines in the middle and along the bottom of the phantom for the different positions of the device, are shown in Supplemental Fig. S1b. Away from the immediate vicinity of the applicator spoon, there is not much difference between the two distributions along the tank, as might be expected; locations close to the surface are more sensitive to the device location.

3.2. In vivo effects of amplitude-modulated radiofrequency electromagnetic fields

Having characterized SAR levels delivered to patients during treatment with the AM RF EMF emitting device, we set out to replicate human exposure conditions in vivo. We used a custom-designed small animal AM RF EMF exposure system [14] and exposed tumour-bearing mice with tumours developing in subcutaneous tissue predominantly surrounded by fat. The exposure system RF output was set for delivery of a SAR level of 67 mW/kg. This SAR was selected so that it is 1) within the range of previously demonstrated in vitro activity (30–400 mW/kg) [9] and 2) within the range of wbSAR1g and psSAR1g in patients receiving treatment with the TheraBionic device (1–352 mW/kg) (Table 2). We used Huh7 and patient-derived tumour cells as subcutaneous cellular xenograft models of HCC [24–26]. Thirty-seven of 40 mice injected with Huh7 cells developed palpable tumours and were exposed to HCC-specific AM RF EMF (HCCMF), randomly chosen AM RF EMF (RF), or were not exposed to EMF (SHAM) as controls. Both control subsets (RF and no exposure) were compared to the group exposed to HCC-specific frequencies (N = 20). The treatment by time interaction was highly significant (p < 0·001) showing that tumour growth curves were different among the three groups. Comparison between the two control subsets showed no statistical difference over the course of six weeks; p = 0·655. The two groups were therefore combined as control group. Comparison between the pooled control group (N = 17) and the HCCMF (N = 20) group shows beginning separation between groups at week four (p = 0·08), and significant separation at week five (p = 0·045), and week six (p = 0·019) (Fig. 2a). We applied the commonly used RECIST 1.1 criteria [27] to assess response to treatment. At week six, the volume of 8 (42·1%) of the 19 tumours exposed to HCCMF had decreased by 30% or more. At the same time, none of the 17 tumours of the control group had evidence of shrinkage (Supplementary Fig. S1d).
To characterize in vivo the temporal relationship between exposure to HCCMF and HCC growth, we randomly selected and studied five mice, which had been exposed to RCF 3 h daily for four weeks, all of which had evidence of tumour growth while exposed to RCF. To test the hypothesis that HCCMF only targets the proliferation of HCC cells in mice carrying tumour xenografts, we assessed tumour Ki67 as well as intestinal crypt BrdU staining in mice in which HCCMF exerted sustained control over the growth of HCC tumours in vivo at SAR levels corresponding to the levels delivered in patients with advanced HCC. In contrast, there was no shrinkage in any tumours exposed to randomly chosen frequencies or not exposed to any EMF.

3.3 Tumour shrinkage is associated with HCC cell differentiation into quiescent cells with spindle morphology

In summary, we observed significant tumour shrinkage ranging from near complete and partial responses to tumour stabilization in two different mouse models of HCC, which establishes that HCCMF exert sustained control over the growth of HCC tumours in vivo at SAR levels corresponding to the levels delivered in patients with advanced HCC. In contrast, there was no shrinkage in any tumours exposed to randomly chosen frequencies or not exposed to any EMF.

Table 1

| Organ-specific SAR | Device on thigh (case 1) | Device away (case 3) |
|--------------------|--------------------------|----------------------|
| mW/kg/W | Mean | PS-10 g | PS-1 g | Mean | PS-10 g | PS-1 g |
| Whole body | 13.5 | 2583 | 6900 | 13.4 | 3399 | 9110 |
| Brain grey matter | 2.2 | 10.1 | 15.7 | 2.5 | 142 | 22.1 |
| Brain white matter | 1 | 3 | 4.6 | 1 | 3.5 | 6.3 |
| Midbrain | 3.7 | 3.9 | 5.4 | 3.9 | 4.2 | 5.9 |
| Heart | 7.7 | 13.7 | 15.8 | 4.9 | 8.1 | 9.3 |
| Liver | 8.4 | 16 | 29.2 | 4.2 | 7.5 | 14.7 |
| Lung | 13.9 | 59.7 | 92.1 | 11.2 | 63.7 | 99.6 |

Table 2

| Organs | Mean SAR (mW/kg) | psSAR 1 g (mW/kg) |
|--------|------------------|------------------|
| Whole body | 0.20–1.00 | 146.00–352.00 |
| Brain grey matter | 0.04–0.20 | 0.20–0.60 |
| Brain white matter | 0.02–0.10 | 0.05–0.15 |
| Midbrain | 0.06–0.20 | 0.06–0.20 |
| Heart muscle | 0.05–0.50 | 0.10–1.00 |
| Liver | 0.05–0.50 | 0.10–1.00 |
| Lung | 0.20–1.00 | 1.00–4.00 |

In summary, we observed significant tumour shrinkage ranging from near complete and partial responses to tumour stabilization in two different mouse models of HCC, which establishes that HCCMF exert sustained control over the growth of HCC tumours in vivo at SAR levels corresponding to the levels delivered in patients with advanced HCC. In contrast, there was no shrinkage in any tumours exposed to randomly chosen frequencies or not exposed to any EMF.

3.3 Tumour shrinkage is associated with HCC cell differentiation into quiescent cells with spindle morphology

Having demonstrated that exposure to HCCMF results in shrinkage of Huh7 tumour xenografts, similarly to what has been observed in patients receiving treatment with HCCMF, we examined the histology of shrunken tumours and tumours from the control group. The first difference between tumours treated with HCC-specific AM RF EMF compared with control tumours was the absence of necrosis (Supplementary Fig. S5). Second, we consistently observed accumulation of fibroblast-like cells around and intermeshed with the shrunken HCC xenografts suggesting that fibroblast-like cells had replaced HCC cells (Fig. 3a). To identify the origin of these cells, we used green-fluorescent protein (GFP)-tagged Huh7 cells.

As shown in Fig. 3b, there was strong GFP staining of the fibroblast-like cells surrounding and intermeshed with residual Huh7 cells demonstrating their HCC origin. To further characterize these cells, we performed immunohistochemistry analysis of several fibroblast cell markers. As shown in Fig. 3c–d, marker analysis identified two separate subpopulations of fibroblast-like cells in shrunken tumours compared to control tumours, a peripheral region surrounding a distinct central region. The peripheral cells were positive for E-cadherin, fibronectin, and TWIST, weakly positive for smooth muscle actin (SMA), and faintly positive for SNAIL while the centrally located cells were more intensely positive for fibronectin and SMA but did not stain for E-cadherin, N-cadherin and SNAIL and had decreased staining for TWIST (Fig. 3c).

As shown in Supplementary Fig. S6 the tumours exposed to HCCMF show central hyalinization with increased staining intensity of trichrome, fibronectin and SMA in contrast to control tumours exposed to either RCMF or SHAM, which show multiple foci of necrosis without any evidence of hyalinization. These findings suggest that centripetal tumour shrinkage during exposure to HCCMF results in the differentiation of HCC cells into quiescent cells with spindle morphology at the centre with residual carcinoma-like cells at the periphery of the shrunken tumour.

To test the hypothesis that HCCMF only targets the proliferation of HCC cells in mice carrying tumour xenografts, we assessed tumour Ki67 as well as intestinal crypt BrdU staining in mice in which HCCMF had yielded at least 55% tumour shrinkage as well as in control mice. As shown in Fig. 2d–f, Ki67 and cyclin D1 staining was decreased and p21 increased in the tumours of mice exposed to HCCMF compared to control mice. However, there was no difference in intestinal crypt BrdU staining between mice exposed to HCCMF and control mice (Fig. 2g). Similarly, there were no differences in white blood cells, red blood cells and platelets between HCCMF-exposed and control mice at the time of sacrifice (Supplemental Table S2a).

In summary, HCCMF target HCC cell proliferation in vivo and tumour shrinkage occurs through HCC cells differentiation into quiescent cells with spindle morphology.

3.4 HCCMF antiproliferative effects require calcium influx through Ca,3.2 T-type voltage gated calcium channels (CACNA1H)

To agnostically assess the impact of HCCMF on HCC, we performed a combined review of the previously published RNA-Seq data [9] and new microRNA array assays. Ingenuity pathway analysis identified the IP3/ DAG signalling pathway through differential expression of several genes and microRNAs (Supplemental Fig. S3a). Differential expression
of several key genes and microRNAs modulating this pathway was confirmed in Huh7 cells (Supplemental Fig. S3b). Ca²⁺ modulates several steps of this pathway [28], and we and others [29] have shown that Ca²⁺ flux from brain tissue is enhanced upon exposure to RF EMF but only when modulated at specific frequencies, irrespective of the carrier frequency used (50, 147, and 450 MHz) [30]. We therefore postulated that Ca²⁺ is involved in HCCMF antiproliferative effects on HCC cells. To begin to test this hypothesis, we added BAPTA, a chelator of Ca²⁺, during each HCCMF exposure. As shown in Fig. 5a, chelation of extracellular Ca²⁺ abrogates HCCMF antiproliferative effects without affecting the proliferation of Huh7 cells exposed to RCF demonstrating that extracellular Ca²⁺ plays a central role in this process.

Next, we sought to determine if extracellular Ca²⁺ enters HCC cells upon exposure to HCCMF. As shown in Supplemental Fig. S3c, there was an increase in intracellular Ca²⁺ following exposure to HCCMF. We validated changes in intracellular Ca²⁺ using Fluo-4 calcium imaging. As shown in Fig. 4, intracellular Ca²⁺ was significantly increased after exposure of HCC cells (Huh7) to HCCMF for 30 min, 1 h, 3 h, and 6 h. We additionally validated increased intracellular Ca²⁺ in a second cell line (Hep3B) at the three-hour time point (Fig. 4). However, no increase in intracellular Ca²⁺ was observed after exposure to either RCF or breast cancer-specific AM RF EMF (data not shown). Moreover, there were no changes in intracellular Ca²⁺ levels when culturing cells in Ca²⁺-free medium demonstrating that Ca²⁺ levels when culturing cells in Ca²⁺-free medium demonstrating that Ca²⁺ is involved in HCCMF antiproliferative effects on HCC cell proliferation, we sought to identify (Fig. 5c).

Having demonstrated that extracellular Ca²⁺ influx is necessary for HCCMF inhibition of HCC cell proliferation, we sought to identify how Ca²⁺ enters the cells. Ca²⁺ entry is mainly controlled by voltage-gated Ca²⁺ channels (VGCCs) [31–33]. We used inhibitors of L-type and T-type VGCCs to determine whether these VGCCs are involved in HCCMF Ca²⁺ influx and inhibition of cell proliferation. Amlodipine, which blocks L-type VGCCs, did not alter Ca²⁺ influx (data not shown). In contrast, ethosuximide, which blocks all three T-type VGCCs (Ca₃.1, 3.2, 3.3) [34], abrogated HCCMF Ca²⁺ influx as well as inhibition of Huh7 cell proliferation (Fig. 5b). Having identified T-type VGCCs as the necessary mediators of HCCMF Ca²⁺ influx and inhibition of HCC cell proliferation, we asked which of the three T-type VGCCs isoforms accounted for this effect. While knockdown of Ca₃.1 (CACNA1G) and Ca₃.3 (CACNA1D) did not affect HCCMF-mediated inhibition of HCC cell proliferation, knockdown of Ca₃.3-2 (CACNA1H) abrogated HCCMF antiproliferative effects in Huh7 and Hep3B cell lines (Fig. 5c).

In summary, HCCMF exert their selective antiproliferative effects on HCC cells by targeting CACNA1H, an event contingent on Ca²⁺ influx into HCC cells, an event restricted to HCC cells.

3.5. HCCMF block HCC cancer stem cells

It has been shown that sorafenib and lenvatinib significantly improve the survival of patients with advanced HCC [43,35,36]. However, patients invariably develop resistance to both agents [43–37] as exemplified by the fact that all 954 patients enrolled in a recent study comparing sorafenib and lenvatinib had died 42 months after enrollment [4]. There is growing evidence that HCC cancer stem cells (CSCs) are responsible for tumour recurrence and resistance to sorafenib [38–40]. We have previously reported several long-term responses in patients with advanced HCC receiving intrabuccally administered AM RF EMF. Specifically, 6 (14.6%) of the 41 patients had an overall survival in excess of 26 months, one patient was treated continuously for 44.6 months, and one patient was treated continuously for 62 months without any evidence of disease progression prior to expiring of causes unrelated to her malignancy [10,11]. One additional off-study patient with rapidly progressive disease received continuous treatment with HCCMF for 74 months prior to expiring with minimal progression of disease (Supplemental Fig. S4). These unexpectedly long-lasting responses, which have not been observed with the use of either sorafenib or lenvatinib [4], led us to test the hypothesis that HCCMF target CSCs as therapies affecting CSCs are associated with long-term survival [41].

We first assessed the anti-proliferative effects of HCCMF on hepatitis B virus (HBV) positive cell lines as 53% of HCC cases worldwide are attributable to HBV infection [42]. As shown in Fig. 5d, the proliferation of HBV positive HCC cell lines from patients of Asian (HCCLM3 and MHCC97L) and African-American (Hep3B) ancestry was effectively blocked by HCCMF. Next, we assessed the impact of HCCMF on HBV negative (Huh7) and HBV positive (Hep3B) CSCs. As shown in Fig. 5e, exposure to HCCMF led to 57% and 38% decreases in Huh7 and Hep3B CSCs (CD44 + CD133+) cells, respectively. Sphere formation was similarly decreased by 26% and 28% in Huh7 and Hep3B cells, respectively. However, in the presence of ethosuximide, there were no changes in CSCs or sphere formation in either Huh7 or Hep3B cells demonstrating that inhibition of CSCs is also mediated by T-type VGCCs (Supplemental Fig. S2a-d). The experiments were repeated with cells in which CACNA1H had been knocked down. As shown in Fig. 5f, knockdown of CACNA1H abrogated HCCMF downregulation of CSCs in Huh7 as well as Hep3B cells.

4. Discussion

Dosimetry analysis shows that 27–12 MHz AM RF EMF administered by means of a spoon-shaped applicator results in systemic EMF absorption, which is more than one hundred fold lower than the SAR

Fig. 2. Anti-proliferative effects of HCCMF in vivo. a. Mice were exposed to either HCCMF exposure with a xenograft-specific SAR of 67 mW/kg or are assigned to the control treatment group 3 h per day. Control group is comprised of mice receiving either randomly chosen frequencies (RCF) with a xenograft-specific SAR of 67 mW/kg and those receiving no exposure (SHAM). Tumour volume is measured three times per week and volume is calculated as (Length × Width²)/2. After six weeks of exposure, statistical significance between treated and control groups has been achieved; [Week five (p = 0.045), Week six (p = 0.019) Student’s two-tailed t-test] and [Test for treatment by time interaction (p < 0.001)]. b. Sequential exposure to randomly chosen and HCCMF. Five mice carrying Huh7 xenografts were exposed to RCF (grey line) 3 h per day for ten weeks during which the average tumour volume increased by 483%. Exposure was switched to HCCMF (blue line) after ten weeks. Exposure to EMF was discontinued for one week after four weeks exposure, then resumed. Mice were sacrificed at the end of week 16. c. Patient-derived HCC xenografts (POX) exposed to HCCMF or not exposed to EMF. Patient derived xenografts from a 63-year-old male with hepatocellular carcinoma. Mice received either HCCMF exposure (HCCMF; N = 6) or received no treatment (SHAM; N = 4). Tumour volume measured three times per week and volume is calculated as (Length × Width²)/2. After eight weeks of exposure, statistical significance had been achieved; [Week four (p = 0.0176), Week five (p = 0.0211) Student’s two-tailed t-test]. At week six, all mice in the Sham group expired and tumour volume was imputed, Week six (p = 0.0553) [student’s t-test]. [Test for treatment by time interaction (p = 0.0006)], d, Ki-67 staining of SHAM, RCF and HCCMF treated tumours. [Anova: F = (2, 33) 67.55, p < 0.0001]. [Post-Hoc Tukey Test: Sham vs RCF p = 0.2067, SHAM vs HCCMF p < 0.0001, RCF vs HCCMF p < 0.0001]. e, Cyclin D1 staining of SHAM, RCF and HCCMF treated tumours. [Anova: F = (2, 33) 23–29, p < 0.001]. [Post-Hoc Tukey test: Sham vs RCF p = 0.1379, SHAM vs HCCMF p = 0.0001]. f, p21 staining of SHAM, RCF and HCCMF treated tumours [Anova: F = (2, 33) 6-907, p = 0.001]. [Post-Hoc Tukey test: Sham vs RCF p = 0.0041, RCF vs HCCMF p = 0.0049]. g, IHC of Huh-7 xenograft tumours and all images at 20X (Lens; scale bar is 50 um). Tumour and intestinal crypt cell proliferation in mice exposed to HCCMF, RCF, and mice not exposed to EMF. Representative figures and graphs (d-f) represent mean ± SEM (SHAM: N = 3; RCF: N = 3; HCCMF: N = 6) and three randomly selected fields of view per slide were used to quantify all staining. BRDU staining of SHAM, RCF and HCCMF treated tumours showed positive staining in all crypts; no statistics performed.
generated by cell phones and does not result in heating of any body part. In all conditions studied, the device complies with the two standards for human exposure to RF EMF, the ICNIRP [23] and the IEEE [22]. The results also demonstrate that the human body acts as an antenna resulting in head to toe delivery of AM RF EMF. These findings provide a biophysical rationale for the antitumor effects documented in patients with metastases in the femur, liver, adrenal glands, lungs, and brain (Sharma et al., manuscript co-submitted with this one) [8,10]. Tumour-specific AM RF EMF appear to have a broad therapeutic window as tumour shrinkage was observed in humans [8,10], in human xenografts as presented in this report, and in vitro [9] at SARs ranging from 0-02 mW/kg to 400 mW/kg.

The animal experiments faithfully reproduce the antitumor effects observed in patients with advanced HCC [10] by demonstrating the antitumor activity of HCCMF with partial responses and significant inhibition of cell proliferation in Huh7 as well as patient xenografts derived from surgical samples. These experiments show that the small animal exposure system [14] replicates human AM RF EMF exposure conditions [8,10] in mice and illustrate the targeted antitumor effects of HCCMF resulting in measurable tumour shrinkage without affecting non-tumour proliferating cells. Notably, necrosis was absent among tumours exposed HCCMF while it was a common finding among tumours exposed either to RCF or not exposed to EMF, a phenomenon potentially attributable to the lack of oxygen and blood in larger, growing tumours.

The lack of antiproliferative activity of RCF confirms in vivo the earlier in vitro findings [9] and establishes that radiofrequency electromagnetic fields modulated at randomly chosen frequencies (RCF) do not affect HCC proliferation. We have previously shown that HCCMF in vitro antiproliferative effect occurs after a week of daily three-hour exposures. Similarly, the growth of Huh7 xenografts, which had grown when exposed to randomly chosen frequencies, was stabilized within one week of exposure to HCCMF, which is indicative of in vivo anticancer effect occurring within the same time interval. The systemic targeted effect of HCCMF in mice is illustrated by tumour reduction and changes in tumour Ki67, cyclin D1, and p21 while the proliferation of in-targeted effect of HCCMF in mice is illustrated by tumour reduction and within one week of exposure to HCCMF, which is indicative of in vivo antiproliferative effect occurs after a week of daily three one-hour exposures. The proliferation of HCCMF treated tumours. d, IHC staining images of Huh7 tumours following treatment. Images at 20× (Lens; scale bar is 50 um) with upper right embedded image at 60× (lens).

Our findings establish that tumour reduction mediated by HCCMF results from differentiation of HCC into quiescent cells with spindle morphology with centripetal loss of SNAIL staining. The transformation of HCC into quiescent cells with spindle morphology at the centre of the shrinking tumour contrasts with the well-documented association between the EMT phenotype, increased SNAIL expression, and aggressive HCC [43] and unveils a new treatment-related phenotype.

The data presented in this report show that HCCMF block the growth of HCC cells derived from African-American (Hep3B), Asian (Huh7, HCCLM3, MHCH97L1), and Caucasian (HepG2) [9] patients with HCC, irrespective of HBV status, indicating that HBV positive and negative HCC cells derived from individuals of different ethnic backgrounds respond to the antiproliferative effects of the same HCCMF providing strong support for the novel notion of tumour-specific frequency profile. With respect to CSCs, our results indicate that HCCMF block HBV positive and negative HCC CSCs. This provides a plausible mechanism for the unusually long therapeutic responses observed in several patients with advanced HCC. These findings, together with the observation of a complete response by the alpha-fetoprotein (AFP) tumour marker in a patient receiving a combination of sorafenib and HCCMF provide a strong rationale for new clinical studies combining HCCMF with either multi-kinase inhibitors or immune oncology therapies.

Our genomic-based approach led to the identification of the IP3/DAG signalling pathway and Ca²⁺ as putative mediators of the HCCMF anti-proliferative and CSC-downregulating effects. We identified and characterized Ca²⁺ influx resulting in increased intracellular Ca²⁺. We then showed that Ca²⁺ flows through CACNA1H, which is selectively sensitive for HCCMF frequencies and mediates both antiproliferative and CSC-downregulating effects. Given the fact that CACNA1H mediates the antiproliferative effects and downregulate CSCs in breast cancer following exposure to breast cancer-specific AM RF EMF [44] ("EBioMedicine (companion paper, in press in this issue)"), we conclude that CACNA1H is the bioantenna for tumour-specific AM RF EMF antiproliferative and CSC-downregulating effects in epithelial tumours. To our knowledge this is the first report of the identification and characterization of a bioantenna sensing athermal AM RF EMF. CACNA1H mediates tumour-specific AM RF EMF Ca²⁺ influx, a process that is both tumour- and tissue-specific, which indicates that cytosolic Ca²⁺ oscillations is interpreted by intracellular downstream effectors, which activate different cellular processes [45]. Importantly, no Ca²⁺ influx was detected in HCC cells if randomly chosen or breast cancer-specific frequencies were used instead of HCCMF confirming the absence of AM RF EMF antiproliferative effects on non-corresponding tumour cells or normal cells.

The importance of CACNA1H in cancer proliferation has been reported in several recent studies across a variety of cancer types [46], including breast carcinomas, retinoblastoma, neuroblastoma, glioma melanoma, and HCC [46,47]. However, this effect does not appear to depend on changes in CACNA1H expression during HCC development [48].

We have previously reported that variation in pulse amplitude constitutes the primary method for identification of tumour-specific modulation frequencies [8], which have subsequently been shown to target cancer cell proliferation in a tumour and tissue-specific fashion [9]. CACNA1H is expressed in both endothelial cells and vascular smooth muscle cells of small arteries, which in turn directly affect pulse amplitude [49]. Hence, CACNA1H is a plausible link between the vascular system, crucial to the tumour-specific frequency identification process [8] and the anticancer effects observed in vitro, in vivo and in patients with advanced HCC. CACNA1H is also necessary for the differentiation of HCC into quiescent cells with spindle morphology during tumour regression, a phenotype that can only be observed following long term exposure to HCCMF. Given the central role played by Ca²⁺, the use of calcium channel blockers should be avoided in patients receiving treatment with tumour-specific AM RF EMF, as they are likely to block the anticancer effects of the treatment as most calcium channel blockers block both L-type and T-type VGCCs [50]. The AM RF EMF mechanism reported here is different from that of alternating electric fields (TTFields), which exert their antitumor effects through activation of Cav 1·2 [51], not Cav 3·2 channels. However, both treatment approaches result in increased levels of cytosolic Ca²⁺.

In summary, we have identified increased intracellular Ca²⁺ resulting from Ca²⁺ influx through CACNA1H as the necessary and sufficient mechanism triggering antiproliferative and CSC-downregulating effects of non-ionizing, non-thermal RF EMF, which are amplitude-modulated at HCC-specific frequencies. Identification of CACNA1H as the bioantenna for tumour-specific AM RF EMF may have broad implications for the diagnosis and treatment of various forms of cancer.
Intracellular Ca\(^{2+}\) measurement in Huh7 and Hep3B cells following exposure to AM RF EMF. 

- **a**, Huh7: 30 min HCCMF exposure results in 50·2% increase in fluorescence (\(p = 0.0296\),\(N = 6\) per group).
- **b**, Huh7: one-hour HCCMF results in 18·6% increase in fluorescence (\(p = 0.0337\),\(N = 5\)).
- **c**, Huh7: three-hour HCCMF results in 29·2% increase in fluorescence (\(p = 0.0394\),\(N = 5\) per group).
- **d**, Huh7: three-hour HCCMF exposure results in 23·2% increase in fluorescence (\(p = 0.0201\),\(N = 5\) per group).
- **e**, Huh7 six-hour HCCMF exposure of Huh7 cells results in 14·3% increase in fluorescence (\(p = 0.0089\),\(N = 5\) per group).
- **f**, Huh7 three-hour HCCMF results in 72·8% increase in fluorescence (\(p = 0.0016\),\(N = 6\) per group).
- **g**, Hep3B three-hour HCCMF exposure of Hep3B cells results in 11·68% increase in fluorescence (\(p = 0.0400\), \(N = 10\) HCCMF, \(N = 11\) SHAM).

All fluorescent data was read using a Fluostar fluorescent plate reader (unless otherwise stated i.e. flow cytometry) with 485 excitation/520 emission and calcium staining was accomplished using the Fluo-4 calcium imaging kit (Molecular Probes). All experiments performed at least twice with representative experiments shown. [Student's one-tailed t-test was used to identify statistical significance as Ca\(^{2+}\) influx (directionality) was identified and established].
both groups) \[ \text{Student's two-tailed t-test} \]

The inhibition of cell proliferation by HCCMF in Huh7 and Hep3B cells with selective knockdown of Cav 3·1, 3·2 and 3·3 T-type voltage-gated calcium channels. The three T-type voltage-gated calcium channels Cav 3·1, Cav 3·2, and Cav 3·3 were selectively knocked down using siRNA targeting the CACNA1G (sh3·1), CACNA1H (sh3·2), and CACNA1I (sh3·3) genes, respectively. CACNA1I (sh3·3) expression in Hep3B cells was not detectable by qPCR, as noted in Cav isoform relative expression graph, hence knockdown was not attempted.

Cell proliferation was assessed after one week of exposure to HCCMF. Control cells were not exposed to EMF. The population of cancer stem cells was significantly lower following exposure to HCCMF (\[ \text{Student's two-tailed t-test} N = 4 \) and \[ \text{HCCMF} N = 4 \) ; \[ \text{Post-Hoc Tukey Test} p = 0.0092 \]) showed that only HCCMF block Huh7 cell proliferation. Huh7 cells were exposed to HCCMF 3 h daily for seven days prior to cell proliferation assays. Huh7 cells not exposed to AM RF EMF (SHAM) were used as controls. Experiments were performed in the presence or absence of ethosuximide (Ethos). ANOVA followed by Tukey Post H-Test

\[ \text{ANOVA: } F = (3, 36) = 13·06, p = 0·0011 \]

indicates that only HCCMF block Huh7 cell proliferation. ANOVA vs HCCMF \( p = 0·0001 \).

\[ \text{Inhibition of cell proliferation by HCCMF in Huh7 and Hep3B cells with selective knockdown of Cav 3·1, 3·2 and 3·3 T-type voltage gated calcium channels.} \]

Fig. 5. HCCMF antiproliferative effects on HCC cells and downregulation of CSCs are mediated by Cav 3·2 T-type voltage gated calcium channels (CACNA1H). a, \[ \text{Ca}^{2+} \] chelation abrogates AM RF EMF-mediated inhibition of Huh7 cell proliferation. Huh7 cells were exposed to either randomly chosen (RCF) or hepatocellular carcinoma-specific (HCCMF) AM RF EMF 3 h daily for seven days prior to cell proliferation assays with tritiated thymidine incorporation. ANOVA followed by Tukey post hoc-test; \[ \text{ANOVA: } F = (3, 36) = 13·06, p = 0·0011 \] indicates that only HCCMF block Huh7 cell proliferation. Huh7 cells were exposed to HCCMF 3 h daily for seven days prior to cell proliferation assays. Huh7 cells not exposed to AM RF EMF (SHAM) were used as controls. Experiments were performed in the presence or absence of ethosuximide (Ethos). ANOVA followed by Tukey Post H-Test

\[ \text{ANOVA: } F = (3, 36) = 13·06, p = 0·0011 \]

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\[ \text{H. Jimenez et al. / EBioMedicine 44 (2019) 209–224} \]

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\[ \text{Declarations of interests} \]

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Dr. Barbault reports other from TherAptive Inc., other from TherAptive GmbH, outside the submitted work; In addition, Dr. Barbault has a patent Europe # 2139557 licensed to TherAptive Inc., a patent U.S. # 8,977,365 B2 licensed to TherAptive Inc., a patent Australia # 2008232041 licensed to TherAptive Inc., a patent Brazil # P0810084-5 licensed to TherAptive Inc., a patent Canada # 2,682,322 licensed to TherAptive Inc., a patent China # ZL 200880009864.4 licensed to TherAptive Inc., a patent Macau # J/001431 licensed to TherAptive Inc., a patent Israel # 201099 licensed to TherAptive Inc., a patent Japan # 5435240 licensed to TherAptive Inc., a patent South Korea # 10-1,478,582 licensed to TherAptive Inc., a patent Mexico # 318857 licensed to TherAptive Inc., a patent Russia # 2594824 licensed to TherAptive Inc., a patent Saudi Arabia # 3075 licensed to TherAptive Inc., a patent Singapore # 155671 licensed to TherAptive Inc., a patent South Africa # 2009/06700 licensed to TherAptive Inc., and a patent United Arab Emirates # P849/09 licensed to TherAptive Inc.

Author contributions

Jimenez, H., Wang, M., Zimmerman, J.W., Sharma, S., Xu, Z., Pennison, M., and Surratt, T. contributed directly to data generation and performance of in vitro and in vivo experiments.

Brezovich, I. designed initial cell culture model of EMF exposure device and provided physics related tutoring and initial EMF SAR calculations.

Lin, H.K., Blackstock, A.W., Bonkovsky, H.L. reviewed the manuscript and provided critical comments.

Capstick, M. and Gong, Y. designed and performed dosimetry models, data analysis and write up of final results.

Ghanekar, A. and Chen, K. provided the implanted PDX tumour mouse model.

Watabe, K., Lo, H.W., and Godwin, D.W., provided specialized training in CSC-related cell culture, mouse handling, and Ca2+ related tools and signalling to Jimenez, H.

Merle, P., and Munden, R. provided clinical HCC patient information and data review.

Absher, D., Myers, R.M., Miller, L.D., Olivier, M., Jin, G., Liu, L., and Zhang, W. were involved in microRNA and RNA-Seq data generation, analysis and interpretation.

DeYoung, B. and Caudell, D., Yang, G.Y. performed IHC staining, interpretation and overall pathology review.

Jimenez, H. and D’Agostino Jr., R.B. performed all statistics.

Jimenez, H., Blackman, C., Barbault, A., and Pasche, B. designed all experiments, reviewed all data, and were responsible for write up.

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Appendix A. Supplementary data

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