Clinical Cancer Research

Safety and Feasibility of Repeated and Transient Blood–Brain Barrier Disruption by Pulsed Ultrasound in Patients with Recurrent Glioblastoma

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Abstract

Purpose: The blood–brain barrier (BBB) limits the efficacy of drug therapies for glioblastoma (GBM). Preclinical data indicate that low-intensity pulsed ultrasound (LIPU) can transiently disrupt the BBB and increase intracerebral drug concentrations.

Patients and Methods: A first-in-man, single-arm, single-center trial (NCT02253212) was initiated to investigate the transient disruption of the BBB in patients with recurrent GBM. Patients were implanted with a 1-MHz, 11.5-mm diameter cranial ultrasound device (SonoCloud-1, CarThera). The device was activated monthly to transiently disrupt the BBB before intravenous carboplatin chemotherapy.

Results: Between 2014 and 2016, 21 patients were registered for the study and implanted with the SonoCloud-1; 19 patients received at least one sonication. In 65 ultrasound sessions, BBB disruption was visible on T1w MRI for 52 sonications. Treatment-related adverse events observed were transient and manageable: a transient edema at H1 and at D15. No carboplatin-related neurotoxicity was observed. Patients with no or poor BBB disruption ($n = 8$) visible on MRI had a median progression-free survival (PFS) of 2.73 months, and a median overall survival (OS) of 8.64 months. Patients with clear BBB disruption ($n = 11$) had a median PFS of 4.11 months, and a median OS of 12.94 months.

Conclusions: SonoCloud-1 treatments were well tolerated and may increase the effectiveness of systemic drug therapies, such as carboplatin, in the brain without inducing neurotoxicity.

See related commentary by Sonabend and Stupp, p. 3750

Introduction

Glioblastoma (GBM) is the most aggressive diffuse glioma of astrocytic lineage with an annual incidence of three per 100,000 people. The standard-of-care, maximal safe surgical resection followed by radiotherapy with concomitant and maintenance temozolomide chemotherapy, was introduced in 2005 and has been shown to extend overall survival (OS) from 12 to 15 months (1). The introduction of the tumor-treating field device has recently been shown to further extend OS to 20.5 months in newly diagnosed patients not progressing after chemoradiation therapy (2).

At recurrence, a range of treatment options are available and include additional debulking surgery, if possible, with administration of chemotherapies such as nitrosoureas with/without antiangiogenic therapy using bevacizumab. These additional treatment strategies have not been standardized, and results in randomized clinical trials have failed to show a significant survival benefit, leading many patients to participate in clinical trials of investigational therapies (3–5).

GBM is a diffuse and infiltrative tumor, making complete surgical resection impossible. At recurrence, a range of treatment options are available and include additional debulking surgery, if

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Translational Relevance

Numerous clinical trials with new drug therapies and/or combination treatments in glioblastoma (GBM) patients have failed over the past several decades. The last drug to significantly improve overall survival in a randomized trial was temozolomide, which was introduced 20 years ago. One of the major limitations of new GBM therapies is their penetration within the tumor and surrounding region due to the presence of the blood–brain barrier (BBB). This study was designed to evaluate a new technique for improving drug penetration into the tumor and infiltrative regions using pulsed ultrasound to first transiently disrupt the BBB. This work demonstrates that a new technique for treating patients with GBM was safe and not burdensome in a cohort of 21 patients. The pulsed ultrasound add-on treatment presented herein can be extended and used with numerous other existing and novel drug therapies to enhance drug penetration in patients with GBM.

possible, with administration of chemotherapies such as nitrosoureas with/without antiangiogenic therapy using bevacizumab. In infiltrative regions, where the BBB remains intact, intravenously administered drugs do not consistently reach adequate therapeutic concentrations in the brain. Results of clinical trials of both new and existing drug therapies for recurrent GBM have failed to show a significant survival benefit, likely due to the BBB (3).

One method to enhance drug delivery to the brain is to disrupt the BBB, allowing for drug therapies to penetrate in increasing concentrations using low-intensity pulsed ultrasound (LIPU) in combination with systemic administration of micron-sized bubbles (6). LIPU can be used to disrupt the BBB (7), increase the concentrations of systemically administered drug therapies in the brain parenchyma (8–14), and enhance survival in preclinical glioma models (15). LIPU has furthermore been shown to be safe in long-term studies after repeated BBB disruption in nonhuman primates (16–18).

In this article, results from the first safety and feasibility study using an implantable LIPU device, SonoCloud-1, are presented. The SonoCloud-1 device was used to repeatedly and temporarily disrupt the BBB in 21 patients with recurrent glioblastoma prior to carboplatin infusion. Safety and efficacy data after a 1-year follow-up period are reported.

Patients and Methods

Study design and participants

This study is a prospective, open-label, single-center, single-arm, dose escalation, phase I/IIa clinical trial, enrolling patients with GBM at any recurrence. This investigator-driven study was developed, conceived, and performed at the Assistance Publique–Hôpitaux de Paris (AP-HP) University Hospital La Pitié-Salpêtriere, Paris, France. All patients provided written informed consent and the study was conducted in accordance with Good Clinical Practices guidelines and the Declaration of Helsinki. In addition, an Independent Safety Committee was formed to assure that patient safety was maintained and that current standards for clinical research were met. Approval was obtained from the French National Agency for Medicines and Health Products (ANSM) and Ile-de-France VI ethical committee (ref. CPP/38-14). The trial was registered as NCT02253212, EudraCT 2014-000393-19, and IDRCB: 2014-A00140-47. Preliminary data for the first 15 patients treated (41 sonications) in the first five cohorts up to the end of January 2016 were previously reported (19). Here, data from all 21 patients recruited into the trial (7 cohorts, 65 sonications) are reported, including follow-up of safety and efficacy.

The trial was designed as an ultrasound-escalation study, in which the ultrasound pressure was increased throughout the study, starting at 0.41 MPa and increasing to 1.15 MPa through seven different levels (0.41, 0.53, 0.66, 0.78, 0.90, 1.03, 1.15 MPa). A minimum of 3 patients were treated at each ultrasound pressure level.

Patients experiencing recurrence (first, second, or third) of a histologically proven *de novo* GBM, after at least the first-line standard-of-care (radiation with concurrent and adjuvant temozolomide) were recruited. Qualifying patients were required to have a growing contrast-enhanced tumor of less than 35 mm in diameter and be eligible for carboplatin-based chemotherapy.

Procedures

The procedures were described previously (19). The SonoCloud-1 device (Fig. 1) was implanted within the skull bone overlying the tumor area [contrast-enhancing region or high-signal fluid-attenuated inversion recovery (FLAIR) region]. If the patient was eligible for a debulking surgery under general anesthesia, the device was implanted during this surgical procedure within a burr hole after dura mater closing and before skin closure. If surgical resection was not indicated, the device was implanted during a dedicated surgical procedure in an ambulatory fashion under local anesthesia. This procedure consisted of a 3-cm skin opening, creation of a burr hole without dura mater opening, and, finally, implantation of the device and closure of the skin. In all cases, neuronavigation systems could be used to position the device in the desired location. As a result, the transducer was in contact with the external face of the dura mater with no residual bone in between to have no distortion and no attenuation of emitted ultrasound. The ultrasound output intensity was then known from a calibration of the implant performed during its production, so no MRI monitoring during sonications was required.

Patients received ultrasound for BBB disruption followed by IV carboplatin chemotherapy every 4 weeks. Carboplatin was started after BBB disruption and was intravenously infused for 60 to 90 minutes. Carboplatin dose was calculated on the basis of the area under the curve (AUC) with the Calvert formula taking the renal function into account (20). The starting dose was AUC5, further adapted (AUC4 or AUC6) on the basis of clinical and biological monitoring. Carboplatin is prescribed as a third-line chemotherapy for GBM with limited efficacy; however, the clinical literature provides significant evidence that carboplatin is effective against gliomas when sufficient brain concentrations are reached, and without major brain toxicity at high doses (21–27).

Patients were treated monthly until dose-limiting toxicity (DLT), serious adverse event (SAE), or evidence of disease progression. Intrapatient dose escalation was allowed. The first treatment was performed at the initial ultrasound dose level for the inclusion group, the second treatment was performed at the next highest ultrasound dose level, and escalation was continued in subsequent cycles in the absence of toxicity. Patients were treated

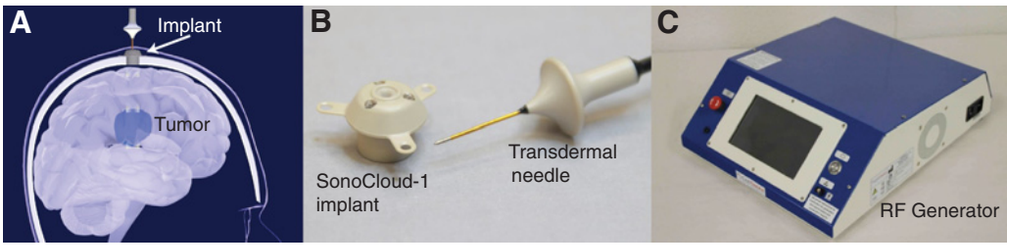

Figure 1.

A, SonoCloud-1 device illustration. **B,** The SonoCloud-1 implant, a 11.5-mm diameter biocompatible implant containing a 1-MHz planar ultrasound emitter, is implanted in the skull bone and connected to an external RF generator (**C**) using a transdermal needle. At each treatment session, the device was activated to send LIPU for a duration of 150–270 seconds to disrupt the BBB prior to carboplatin chemotherapy.

monthly for up to a maximum of 6 treatments or beyond if clinical benefit was expected by investigators or until there was evidence of tumor progression.

DLT was defined as the occurrence of an adverse effect directly related to the ultrasound emission during the first cycle of treatment, which would include the following: a neurologic deficit starting within 2 days after the procedure and persisting at day 15, localized brain edema not preexisting before the procedure, occurrence of cerebral midline shift not controlled by routine treatment or requiring a salvage surgical procedure, partial epilepsy induced or enhanced after the procedure and not controlled by routine therapy, irreversible focal encephalopathy in the area of the BBB disruption, bleeding or ischemia of more than 1 cm in diameter in the area of the BBB disruption occurring within 2 days of the procedure, and brain herniation requiring salvage surgery. Dose level cohort size was 3 patients, although the first 3 patients were included sequentially following an accelerated titration design (28). If none of the patients experienced DLT, the next dose level was opened. If 1 patient experienced DLT, 3 additional patients would have been enrolled at the same dose level. If no additional patients experienced DLT, the dose level was increased after approval by the independent scientific monitoring committee. The MTD is defined as the highest dose level at which 6 patients are started and fewer than two experience first-course DLT.

Blood biological parameters were assessed for all patients to monitor for potential carboplatin toxicity. Patients were treated with carboplatin only when platelet counts reached >100,000 cells/mL.

All patients were assessed monthly using MRI, blood sampling, and clinical neurologic evaluation. Two days before each planned ultrasound treatment, tumor status was evaluated by MRI according to the Response Assessment in Neuro-Oncology (RANO) criteria (29). If tumor progression was observed, the patient exited the trial and received alternative therapies. In the absence of tumor progression and toxicity, the BBB disruption session was scheduled before the carboplatin infusion. A subsequent MRI exam was performed starting within 10 minutes after ultrasound treatment to assess BBB disruption and safety of the ultrasound procedure.

A 3.0T GE Signa MRI (GE Medical Systems) was used for the imaging exams. At each exam, standard FLAIR, T1-weighted gadolinium contrast-enhanced (0.2 mL/kg, Dotarem), susceptibility-weighted angiography (SWAN), and diffusion sequences were obtained. T1-weighted MR images were analyzed to grade the magnitude of BBB disruption observed after sonications. Four different grading stages were defined as follows, as described previously (19, 30): grade 0, no BBB opening; grade 1, contrast enhancement in subarachnoid space; grade 2, contrast enhancement in subarachnoid space and gray matter; and grade 3, contrast enhancement in subarachnoid space, gray matter, and white matter. Two neuroradiologists (B. Law-Ye and D. Leclercq) and a neurosurgeon (A. Carpentier.) independently reviewed the grading of BBB disruption. When discordant, consensus was performed by all three readers.

The SonoCloud-1 device

The SonoCloud-1 implant (CarThera) consisted of a 10-mm-diameter ultrasound emitter with a resonance frequency of 1.05 MHz, encased in an 11.5-mm-diameter biocompatible housing, as shown in Fig. 1. The emitter was operated with a burst length of 25,000 cycles (23.8 ms) at a pulse repetition frequency of either 0.5 or 1 Hz (1.2 or 2.4% duty cycle) for a total duration of 150–270 seconds. To activate the device, a transdermal needle connection device is connected to the implant and plugged into a proprietary external radiofrequency (RF) generator. The external generator is custom-designed with a graphical user interface that guides the user step-by-step through the treatment protocol. As part of efforts to refine the calibration procedure for the SonoCloud-1, new measurements were performed, which give a more accurate and reliable estimation of the absolute nominal treatment pressures previously reported (19). These values are reported in Supplementary Table S1.

The sonication was initiated at the beginning of a bolus injection of SonoVue Microbubbles (Bracco). The initial clinical protocol calls for a dose of SonoVue corresponding to 0.1 mL/kg with a maximum dose of 4.8 mL (one vial of SonoVue). After 18 treatments in 9 patients who showed limited BBB disruption, the Agence Nationale de Sécurité du Médicament et des produits de santé (ANSM) authorized an increase in SonoVue based on the weight of the patient to 0.1 mL/kg.

Outcomes

The primary objective of the study was to evaluate the safety and tolerance to sonication with the SonoCloud-1 device and to determine the MTD of ultrasound. The secondary objectives are as follows: (i) to evaluate the disruption of the BBB using the SonoCloud-1 system, (ii) to estimate the PFS and the OS of the patients treated with SonoCloud-1 device, (iii) to determine the biocompatibility of the device, and (iv) to document the practical feasibility for future clinical trials.

Statistical analysis

Qualitative variables were described by frequencies and quantitative variables were described by their medians with range. OS was defined as the time elapsed between the date of inclusion and the date of death for any cause. PFS was defined as the time elapsed between the date of inclusion and the date of progression according to the RANO criteria or death. Patients still alive without progression were censored at their last known contact date. Survival functions were estimated using the Kaplan–Meier method, survival rates and 95% confidence interval (CI) were provided using Greenwood variance. To study the prognostic value of BBB disruption on PFS and OS, BBB disruption was used as time-dependent variable in a Cox model to estimate the HR and its 95% CI. Graphical representation of this result has been obtained using the Simon and Makuch estimate of survival curves (31).

Results

Patient enrollment and treatment characteristics

Between July 2014, and September 2016, 21 patients were enrolled in the trial (Table 1). Two patients were judged ineligible after implantation due to radionecrosis ($n = 1$) and detection of microhemorrhages on presonication MRI ($n = 1$). In the 19 remaining patients, the 11.5-mm SonoCloud-1 ultrasound device was implanted within the skull bone either during a planned debulking procedure ($n = 12$) or in a dedicated procedure ($n = 9$).

The procedure and ultrasound device were well tolerated by patients. The entire BBB disruption procedure from the needle connection, preparation of microbubbles, and sonication procedure lasted a median duration of 9 minutes (range = 4–16 minutes). The only minimal irritation was some pain reported during the transdermal needle connection process (median visual analog scale pain was 2 of a range of 0–7). No patients complained of the device implantation (median visual analog scale pain was 3 of a range of 0–5) and none of them asked for device removal after progression/end of treatment.

Safety of repeated BBB disruption

A total of 65 sonication procedures were performed in 19 patients. The median number of monthly sonications per patient was three, with a range of 1–10 sonications. No DLTs were reported during the study, even in the patients sonicated at a maximum ultrasound dose of 1.15 MPa. Neurologic deficits (Common Terminology Criteria for Adverse Events, CTCAE grade 2) did appear within 2 days after ultrasound in 1 patient treated at 0.90 MPa and in another treated at 1.03 MPa, but these events resolved within 15 days. Thus, the maximum dose of ultrasound was not reached in the study.

Table 2 provides a full summary of adverse events (AE) reported in sonicated patients. Sixty-seven percent (67%) of the AEs reported during the study were of CTCAE grade 1 or 2. The most frequently reported AEs include hematologic disorders (32%) and general complaints, such as fatigue (23%). Nervous system disorders that represent 19% of overall events include headaches (26%), brain edema (11%), and faintness (11%). No severe neurologic AEs occurred during or after the sonications, even in patients sonicated in eloquent zones. A transient neurologic deficit (transient facial palsy) occurred immediately after sonication at cycles 7–10 in Patient 15 at an acoustic pressure of 0.90 MPa but resolved within two hours under steroids. Patients with no history of seizures did not present any ultrasound-induced epileptic seizures and did not require any antiepileptic drugs. No patients complained of the device implantation or the treatment process. A few patients complained of pain during the needle insertion. Nine patients were explanted at the end of 6 months as requested by the protocol, 12 patients asked to not remove the device even after treatments were finished. No AE had been documented during explantation. One patient had a device that had technical issues, and which was replaced during a

Table 1. Baseline patient characteristics, by BBB disruption grade

Characteristic	Grade 0/1 ($n = 8$)	Grade 2/3 ($n = 11$)	All patients ($n = 19$)
Age (years)	73 (38–77)	58 (41–67)	59 (38–77)
Sex			
Men	4	9	13
Women	4	2	6
Time from initial diagnosis (months)	24.8 (14.1–74.9)	20.3 (8.3–54.2)	20.7 (8.3–74.9)
Recurrence			
1	2	6	8
2	6	5	11
Karnofsky index	80 (70–100)	90 (70–100)	90 (70–100)
Extent of surgery (at device implantation)			
None	4	4	8
Additional resection	4	7	11
Corticosteroid therapy at inclusion	2	4	6
Antiepileptic therapy at inclusion	6	6	12
Diameter of maximum enhancing tumor at inclusion (mm)	32.5 (20–35)	30 (25–35)	30 (20–35)
IDH1			
Wild-type	7	10	17
Mutated	1	0	1
Not done/unknown	0	1	1
IDH2			
Wild-type	8	10	18
Mutated	0	0	0
Not done/unknown	0	1	1

NOTE: Data are median (range).

Table 2. Treatment-emergent AEs that occurred during treatment or up to 30 days after the end of therapy

	Events by grade, *n*			
***n* = 19 Patients**	**Grade 1–2**	**Grade 3**	**Grade 4**	**Patients, *n***
Hematologic AEs				
Thrombocytopenia	6	1	0	5 (26%)
Neutropenia	4			3 (16%)
Leukopenia	3	1		2 (11%)
Anemia	1			1 (5%)
Lymphopenia	1	1	0	1 (5%)
Central nervous system AEs				
Headache	4	1		5 (26%)
Edema cerebral			2	2 (11%)
Syncope		2		2 (11%)
Dizziness	1			1 (5%)
Drowsiness	1			1 (5%)
Facial palsy	3			1 (5%)
Ischemic stroke	1			1 (5%)
Left sensorimotor deficit	1			1 (5%)
Other AEs				
Fatigue	8			8 (42%)
Nausea	3			3 (16%)
Urinary urgency	2			2 (11%)
Vomiting	2			2 (11%)
Alteration of general status			1	1 (5%)
Appendicitis			1	1 (5%)
Chemotherapy-induced phlebitis		1		1 (5%)
Cystic evolution	1			1 (5%)
Device failure		1		1 (5%)
Nausea and vomiting	1			1 (5%)
Pain (transdermal needle)	1			1 (5%)
Papular erythema	1			1 (5%)
Pulmonary embolism			1	1 (5%)
Scar tissue pain	1			1 (5%)
Subdural hygroma	1			1 (5%)
Tinnitus	1			1 (5%)

NOTE: The occurrence of each AE is listed as well as the total number of patients affected, as some patients might have experienced the same AE multiple times over the course of therapy.

dedicated surgical procedure (Patient 19). After device replacement, the patient resumed treatments.

Two occurrences of transient edema occurred (grade 4) and were considered by the Data Safety Monitoring Board as related to the procedure. Patient 14 reported a local, transient, steroid-responding edema at 15 days after sonication (cycle 1, 0.78 MPa) and was hospitalized. It resolved within 48 hours after the event. Patient 19 had transient, steroid-responding edema at 1 hour after sonication (cycle 1, 1.03 MPa) that resolved within two hours. In both cases, the edema was resolved within several hours of the event and steroid levels returned to presonication levels. Neither of these patients underwent additional surgical debulking/resection of the tumor during device implantation and both patients had a large residual tumor diameter of >30 mm. One death other than for disease progression occurred during the trial. Patient 10, who received four ultrasound treatments (from 0.66 to 0.90 MPa) followed by carboplatin at AUC5, died from systemic B-cell lymphoma 1 year after the last sonication.

Overall, the ultrasound treatment followed by carboplatin was well tolerated. Carboplatin infusion was started at an average of 106 minutes after sonications (range 24–185 minutes). The dose of carboplatin (mg/mL/minute) was AUC4 in 16 procedures and AUC5 in 48 procedures. One patient did not receive carboplatin after BBB disruption. SAEs tended to be related to tumor progression or known side effects of carboplatin chemotherapy. No ultrasound dose dependence or cumulative toxicity of repeated sonications was observed in events reported.

Efficacy

A representative image of a grade 3 BBB disruption is shown in Fig. 2 for Patient 15. This patient received a total of 10 sonications over the course of 12 months at an acoustic pressure of 0.90 MPa. At each sonication, the BBB was repeatedly disrupted on MRI and was reclosed in appearance on each subsequent presonication MRI.

Of the 65 sonication procedures performed in 19 patients, 52 showed evidence of BBB disruption on post T1w contrast-enhanced imaging (grade 1–3) and 34 showed evidence of at least grade 2 BBB disruption. The degree of BBB disruption increased with acoustic pressure as 0% (0.41 MPa), 0% (0.53 MPa), 18% (0.66 MPa), 57% (0.78 MPa), 80% (0.90 MPa), 77% (1.03 MPa), and 66% (1.15 MPa) of sonications show at least a grade 2–3 of BBB disruption (Supplementary Table S2). No decrease in BBB disruption was observed after repeated monthly treatments (with up to 10 treatments for 2 patients).

Representative FLAIR and SWAN MR images for Patients 15 and 18 are shown in Fig. 2. Patient 15 showed no changes in SWAN or FLAIR MR images after repeated disruption of the BBB at an acoustic pressure of 0.90 MPa. Patient 18 received three sonications—one at 1.03 MPa and two at the highest acoustic pressure of 1.15 MPa. No evidence of additional edema or microbleeding was observed on postsonication MRIs in this patient or any others treated at the highest acoustic pressures.

Overall median PFS for all sonication patients ($n = 19$) was 3.45 months while OS was 10 months (Supplementary Table S3).

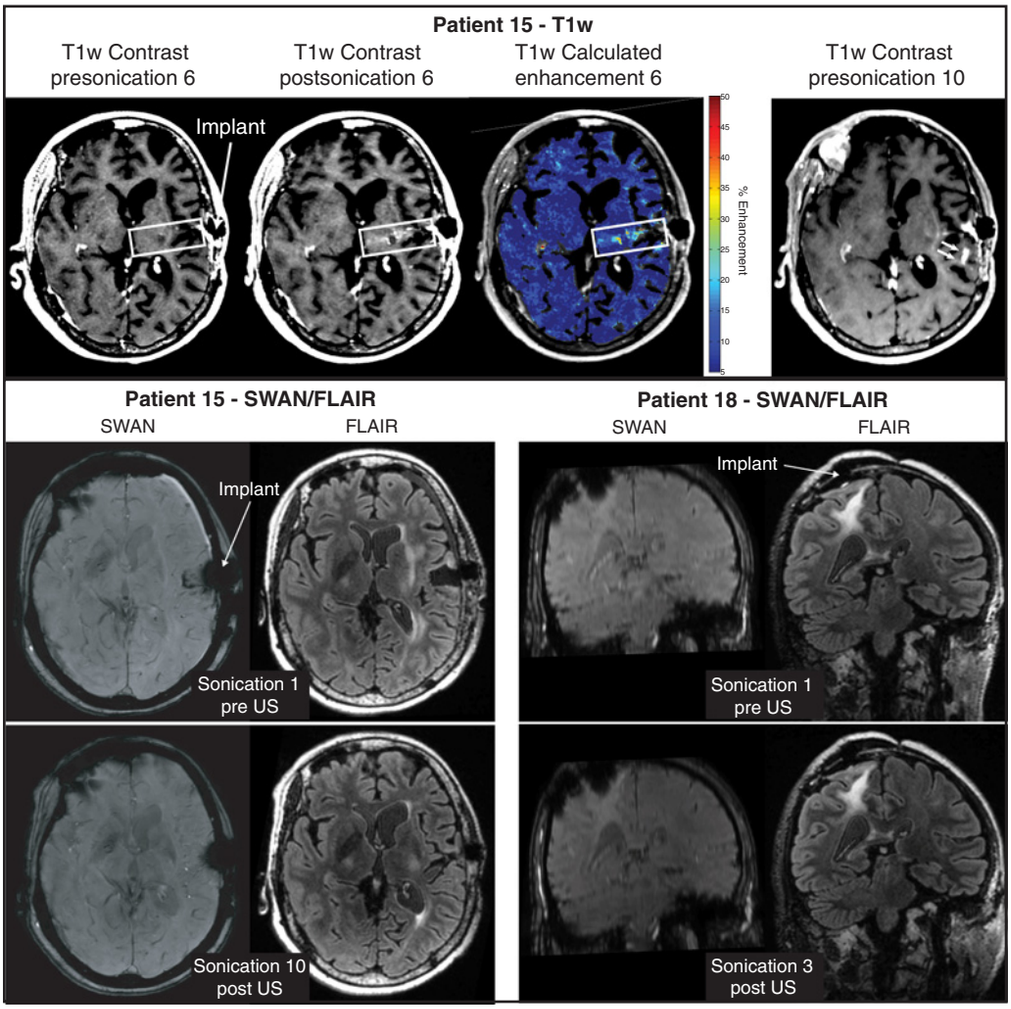

Figure 2.

MR imaging of BBB disruption and safety of repeat sonications. Top, BBB disruption on T1w contrast-enhanced MRI at 2 days before ("presonication") and within 30 minutes after BBB disruption ("postsonication") by pulsed ultrasound (US) in patient 15. This patient received a total of 10 monthly sonications to disrupt the BBB. The T1w images shown and enhancement are from the sixth sonication session. The presonication T1w contrast-enhanced MRI before sonication 10 is also shown to illustrate the location of tumor recurrence (white arrows), which was outside the region of BBB disruption (shown in the white rectangle). Bottom, MRI using SWAN (to show any signs of bleeding) and FLAIR (to show any signs of edema/inflammation) sequences in patients 15 and 18 are shown. No signs of microhemorrhages were observed on SWAN images, including in patient 15, who received 10 sonications. Patient 18 was treated at the highest acoustic pressure level (1.15 MPa) and did not show any signs of adverse effects.

Sonicated patients who had clear BBB disruption extending beyond the subarachnoid space (grade 2/3 BBB disruption after sonication on MRI) had a trend toward longer PFS and OS. As shown in Fig. 3, patients with grade 2/3 disruption had a PFS of 4.11 months versus a PFS of 2.73 months in patients with a grade 0/1 opening. OS was increased to 12.94 months from 8.64 months in patients that had clear BBB disruption. The HR for PFS with clear BBB disruption after at least one sonication group was 0.39 (95% CI, 0.11–0.94; $P = 0.03$) and 0.49 (95% CI, 0.16–1.14; $P = 0.09$) for survival.

Discussion

Historically, patients with recurrent GBM receiving additional chemotherapy have had limited additional benefit (32). In studies of patients with GBM treated by carboplatin monotherapy, PFS of 2–3 months and OS of 6–9 months were reported (21–26). The PFS and OS results for patients experiencing minimal or no BBB disruption (grade 0/1, median PFS = 2.73 months, median OS = 8.64 months) align with this historical data. For patients with greater BBB disruption (grade 2/3), median PFS and OS were extended to 4.11 months and 12.94 months, respectively. The results herein suggest a potentially greater efficacy of carboplatin when used in combination with ultrasound-induced disruption of the BBB, though results are limited by the small number of patients in this trial receiving treatment ($n = 19$) and must be confirmed in a larger clinical trial.

To our knowledge, the study results herein are the only reported safety results showing large regions of repeated BBB disruption using this technique in patients with GBM. In our previous

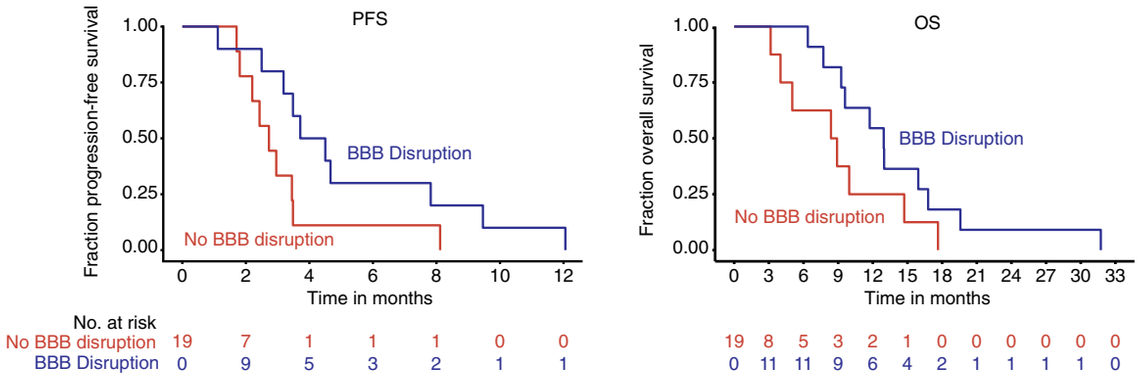

Figure 3.

PFS (left) and OS (right) estimated by the Simon and Makuch method (31). Nineteen (19) patients were separated according to BBB disruption grade based on T1w contrast-enhanced MRI immediately after sonications, with 8 patients having grade 0/1 ("No BBB disruption") and 11 patients having grade 2/3 ("BBB disruption"). Overall median PFS for all patients was 3.45 months, whereas overall median OS was 10 months. Patients with at least grade 2/3 disruption on postsonication MRI had a PFS of 4.11 months versus a PFS of 2.73 months in patients with a grade 0/1 opening; OS was also increased in this group to 12.94 months from 8.64 months.

publication (19), the interim safety results from 41 sonications in 15 patients were reported. Herein, we completed the recruitment of this study with 21 patients recruited and 65 sonications performed in 19 of these patients. These results further confirm the safety of BBB disruption using LIPU prior to carboplatin infusion and point toward the potential efficacy of this technique, as shown in Fig. 3.

It has been estimated that 90% of recurrences for GBM are within 2 cm of the primary site (33). When progression was observed on MRI in FLAIR or contrast-enhanced T1w sequences, it tended to occur outside the zone of the acoustic field of the ultrasound implant, as shown in Figs. 2 and 4. This sonication volume was generally not large enough to cover the entire tumor and infiltrative region. Nevertheless, as shown in Fig. 4, repeated sonications in some patients showed tumor reduction in the field of the SonoCloud-1 implant. This effect was quantified in Patient 19, who received 10 monthly sonications prior to receiving carboplatin chemotherapy. Preultrasound contrast-enhanced T1 hypersignal (+15% threshold) volume was measured inside a 25-mm diameter cylindrical zone around the implant axis (emitter ROI), and outside this zone. Compared with the first treatment, the hypersignal volume decreased progressively up to treatment 8 by 49% inside the sonication ROI, and by only 2% outside this volume. This indicates that tumor progression may have been controlled more efficiently in the sonicated zone and its surroundings, which corresponds well to the zone with enhanced

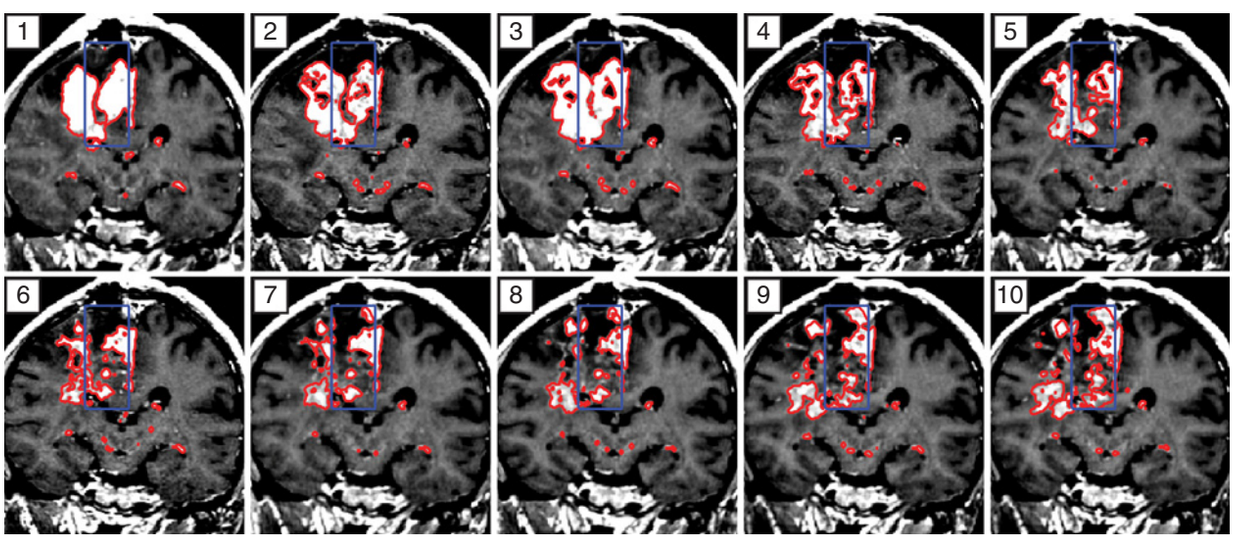

Figure 4.

Tumor response to 10 repeated monthly treatments to disrupt the BBB before carboplatin administration (patient 19). The monthly presonication (2 days before) T1w images are shown. Gadolinium-enhanced T1 hypersignal from the contrast-enhancing tumor (red contour) was used as a surrogate measurement of tumor volume, and decreased by up to 49% in the sonication zone (blue box), whereas the calculated tumor volume decreased by only 2% outside of the sonication zone.

carboplatin concentration observed in primates treated with the SonoCloud device (34). In future studies, a device with a larger sonication area is being developed to improve the efficacy of this approach and to enhance drug delivery to a larger region of the brain.

An additional limitation of this study was the time from sonication to start of carboplatin infusion (mean = 106 minutes), which was longer than initially planned for in the clinical protocol (60 minutes maximum). Although the BBB has been shown to close in 6 to 24 hours (35), partial closing begins immediately after sonication, thus the ideal time to begin chemotherapy is immediately after sonications. In future clinical trials, chemotherapy will be started immediately after sonications as a postsonication MRI will no longer be necessary to verify safety.

The safety data from our study in patients with GBM have been used to initiate an additional study in patients with Alzheimer's disease (NCT03119961) at the optimal acoustic pressures reported here (0.90 MPa–1.03 MPa). Although a lower proportion of grade 3 BBB disruption was reported at the highest pressure levels (Supplementary Table S2), these findings were primarily due to a single patient that had a large residual tumor that obscured grading and the optimal acoustic pressure was determined to be 1.03 MPa. BBB disruption by ultrasound without additional drug administration has been shown to reduce β-amyloid and tau pathology in animal models of Alzheimer's disease. Recently, a team using a transcranial focused ultrasound approach has shown the safety of this technique in 5 patients with Alzheimer's disease (36). Future studies will further evaluate the value of this technique in additional brain indications as well as in a larger group of patients, potentially using other drug therapies.

Disclosure of Potential Conflicts of Interest

A. Idbaih reports receiving other commercial research support from and is a consultant/advisory board member for CarThera. M. Canney holds ownership interest (including patents) in and is a consultant/advisory board member for CarThera. C. Desseaux, C. Lafon, and J.-Y. Chapelon hold ownership interest (including patents) in CarThera. A. Carpentier reports receiving commercial research grants from, holds ownership interest (including patents) in, and is a consultant/advisory board member for CarThera. No potential conflicts of interest were disclosed by the other authors.

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