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Sonalleve MR-HIFU with DISC

Philips MR-guided High Intensity Focused Ultrasound with Direct Skin Cooling

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High Intensity Focused Ultrasound guided by Magnetic Resonance Imaging (also known as MR-guided HIFU, MRgHIFU, or MRgFUS) is a therapy technique which uses focused ultrasound waves to heat and coagulate tissue deep inside the body without damaging intervening tissue and offers an novel, non-invasive treatment option for solid tumors. The Philips Sonalleve MR-HIFU system, initially released in 2010, introduced a new approach to MRI-guided HIFU ablation, whereby volumetric sonications are used to achieve very efficient dose formation and predictable lesion volumes. In this article, we discuss a new Direct Skin Cooling (DISC) device and Dual Mode Thermometry (DMT), which enable a true patient-adaptive treatment and further improve system efficiency and present results from example cases out of the first 50 treatments performed at the time of writing.

Introduction and background

For over fifty years, it's been known that focusing ultrasound waves into the human body offers the possibility to heat deep-lying tissue non-invasively.¹ Combined with guidance by MR imaging, with its excellent soft tissue contrast, 3D imaging capabilities, and real-time temperature measurement techniques^{2,3,4,5}, HIFU enables accurate, localized heat deposition and selective ablation of tissue. MR-guided HIFU currently represents a non-invasive treatment alternative for women affected by uterine fibroids, and multiple oncology indications are being explored and gradually finding their way into clinical use.⁶

When uterine fibroids are targeted, tissue ablation speeds have traditionally been rather low.^{7,8} The main factor limiting the ablation speed has been the undesired heating of the skin and subcutaneous tissues (also called the near-field) through which the ultrasound travels before reaching the target. To keep the heating of these regions at an acceptable level, cooling periods after each individual sonication must be observed. Without a reliable method for measuring the temperatures of these near-field tissues, conservatively long cooling times have been necessary.

The introduction of a volumetric sonication method has made it possible to reach higher ablation volumes without increasing the total amount of ultrasound energy delivered through the skin. For a given therapy, fewer sonications are needed, but more energy is delivered per sonication, requiring longer cooling times after each individual sonication.^{9,10,11,12} In this article, we introduce a new approach. Known as Direct Skin Cooling combined with Dual Mode Thermometry, it helps further increase tissue ablation efficiency while optimizing cooling times and improving protection of the skin and the subcutaneous fat layer.

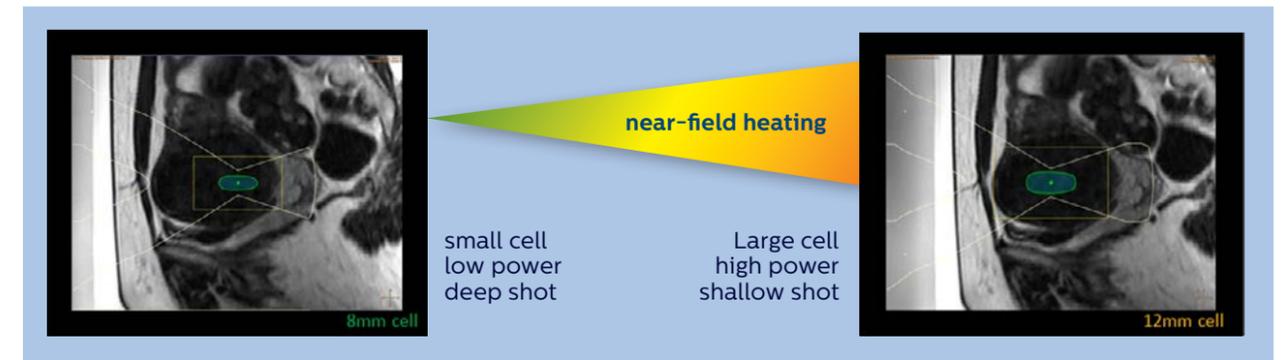


Figure 1. Accumulation of heat in the near field tissues depends on the size, power, and location of the treatment cells.

Near-field heating

Even though MR-HIFU is non-invasive, the ultrasonic energy still needs to travel through the cutaneous, subcutaneous, and other intermediate tissue layers. When energy is absorbed in these near-field tissue layers, local heating takes place.¹³ Of particular concern are the skin, due to its high ultrasound absorption coefficient, and the subcutaneous fat layer. The fat layer acts as a thermal insulator, resulting in a slow cumulative build-up of heat over the duration of the treatment. The more energy is needed to complete the treatment, the more the operator needs to take near-field heating into account (see Figure 1).

As the thickness of the subcutaneous fat layer and other anatomical and physiological factors vary considerably among patients, the degree of near-field tissue heating also varies from patient to patient. Until now, the actual patient-specific near-field tissue temperature has usually been unknown. This has forced medical professionals to choose cooling times conservatively. In many cases, this lengthens the procedures unnecessarily. To overcome these problems, methods are being introduced to lower the near-field tissue temperatures and to better adapt the cooling times to the individual patient. The first aim is achieved by actively cooling the near-field tissues, while the second aim is addressed by employing T2-based fat tissue thermometry during therapy.

Direct Skin Cooling

During HIFU therapy, a Direct Skin Cooling (DISC) device is introduced to cool down the patient's skin by circulating cooled water between two membranes forming the patient contact (see Figure 2). Integrated into the Sonalleve tabletop, the DISC device replaces the conventional ultrasound window and gel pads as the ultrasonic contact medium (see Figure 3). A small amount of ultrasound gel mixed with water is used to create acoustic contact between the outer membrane of the DISC device and the patient's skin. Besides saving costs, eliminating the need for gel pads for most patients simplifies patient setup and reduces the preparation time needed before the first sonication.

The effect of skin cooling is demonstrated in Figure 4, which shows T2-based fat tissue thermometry data acquired during therapies with and without DISC. While the details of these two treatments differ, the fat thickness, cell sizes, and the rate of energy transfer through the skin over time are comparable. In the treatment performed without DISC, a steady increase is clearly visible in the background temperature and accumulation of heat in the region through which ultrasound has passed.

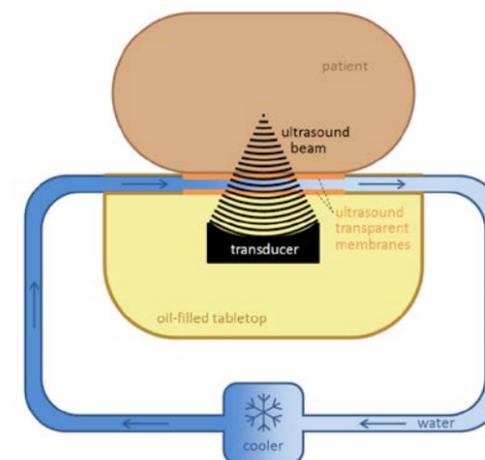


Figure 2. Principle of the Direct Skin Cooling (DISC) device



Figure 3. The ultrasonic window of the Sonalleve MR-HIFU system with integrated DISC device .

In the treatment performed with DISC, active cooling began a few minutes before the first sonication. Due to the insulating nature of the fat tissue, the cooling needs almost 30 minutes to reach its full effect, but the baseline temperature is lowered already during the first sonications. Throughout the therapy, the observed fat tissue temperatures in the background are lower; in the region through which ultrasound has passed, they are comparable or lower than in the therapy performed without DISC.

Dual Mode Thermometry

Along with DISC, we have introduced an innovative Dual Mode Thermometry (DMT). With DMT, heating in the targeted fibroid tissue and the abdominal muscle is measured using proton resonance frequency shift (PRFS) thermometry, while the temperature distribution in the subcutaneous fat layer is monitored using T2-based thermometry.^{14,15} The profound difference is that T2-based fat tissue thermometry measurement is absolute and, as such, allows observation of cumulative heating, as demonstrated in Figure 4.

Dual Mode Thermometry has been fully integrated into the Sonalleve system. Caregivers position the imaging planes in the beginning of the treatment. No further user interaction is required during the therapy, as the scans are started automatically when needed. The interplay of the sonications and the PRFS and T2 thermometry data acquisition is illustrated in Figure 5. PRFS thermometry is used during sonication to guide the volumetric energy delivery. After the sonication, the system automatically acquires a T2-based data set

to evaluate the current near-field tissue temperature. During the T2 data acquisition, caregivers can proceed with therapy planning on the therapy console as they need to.

Patient-adaptive cooling times

The system's knowledge of the cumulative near-field heating, as measured by DMT, allows it to adapt cooling times to the individual patient (see Figure 6). A temperature rise margin is reserved for the next treatment cell based on the cell's size, position, and power level. Cooling times are then calculated so that temperatures remain below pre-defined limits. The user interface displays the cooling time recommended before the start of the next sonication.

T2-based fat tissue thermometry works best with patients who exhibit a subcutaneous fat layer of at least 6-8 mm. For patients who exhibit a subcutaneous fat layer of less than 15 mm, use of T2 thermometry typically results in shorter cooling times and faster overall therapy procedures than the computational approach. If the patient's subcutaneous fat layer measures 20 mm or more, or if the tissues are otherwise prone to heating, using T2 thermometry offers improved safety by increasing cooling times as needed. Should the patient have a fat layer measuring less than 6 mm, the system then employs a fully computational model. As the DISC device's cooling effect is strongest on the superficial tissue layers, the highest temperatures are observed in the deepest areas of the fat tissue. For best tissue protection, the T2 thermometry slices should be positioned over these deep parts, close to the abdominal muscle (see Figure 7).

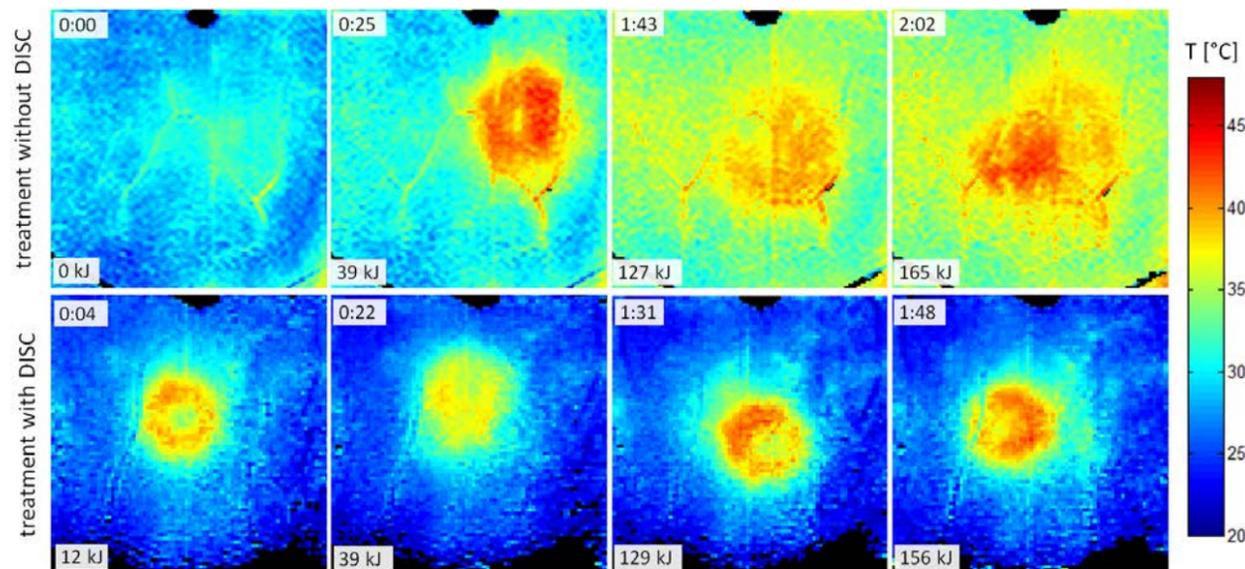


Figure 4. Near-field temperature evolution in a treatment without DISC (top) and with DISC (bottom). The temperature within the subcutaneous fat layer was measured using T2-based fat thermometry. Treatments with comparable sonication rate and thickness of the subcutaneous fat layer (12-13 mm) were chosen. Note the lowered temperature in the therapy where DISC is used. The insets in the top left and bottom left corner of each image show the elapsed time since the beginning of the therapy (hours:minutes) and the total ultrasound energy delivered. Fat temperatures of 41-43 °C have been routinely observed without clinical implications.

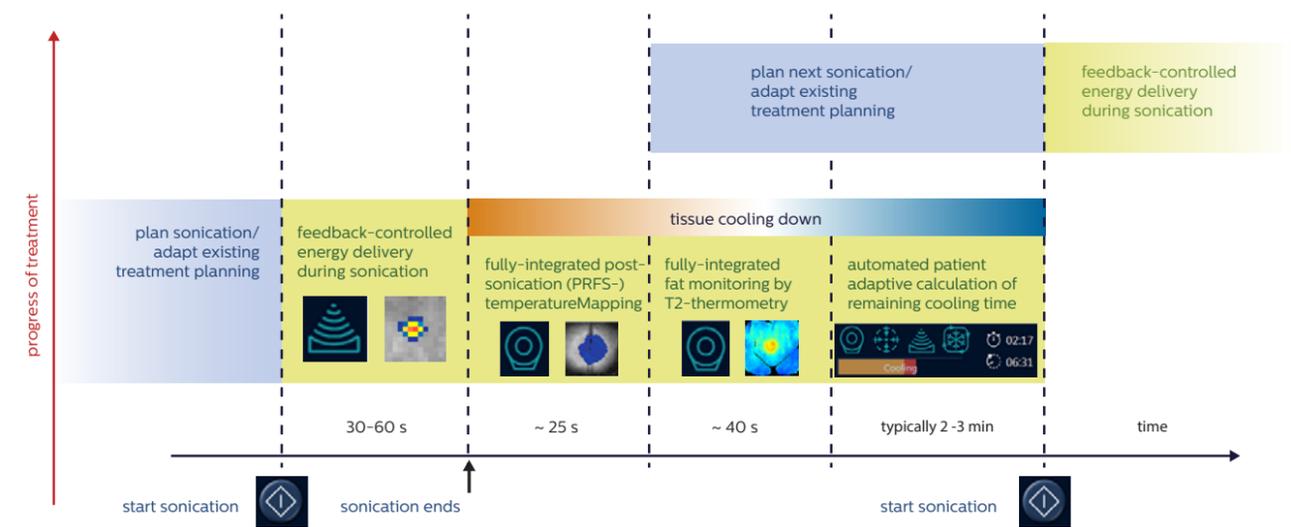


Figure 5. Sonication workflow with Dual Mode Thermometry. Events related to one sonication are shown on a single horizontal line. User interaction is depicted in blue while automated software tasks are written in green. Note the possibility to plan the next sonication during the cooling time of the previous sonication.

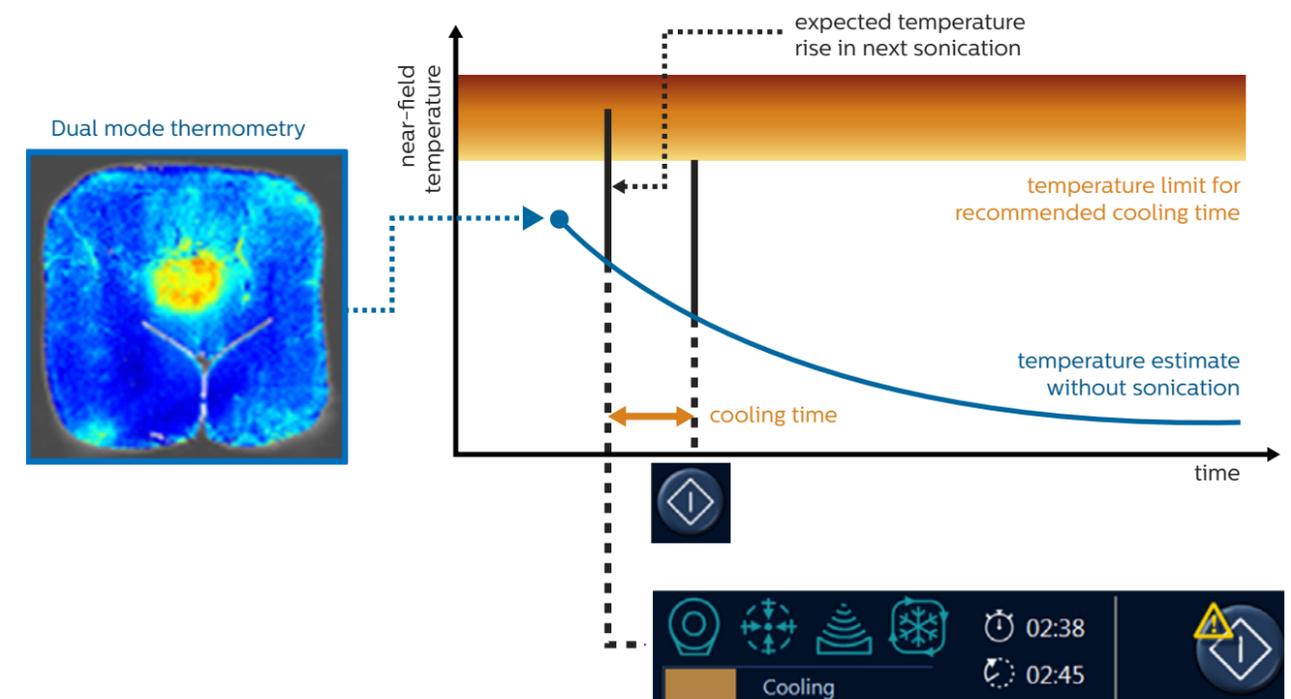


Figure 6. Cooling times are adapted to individual patient based on the observed abdominal fat heating and the selected volumetric treatment cell.

Pilot study

The safety and usability of the DISC system was first established in a pilot study with eight patients conducted at the University Medical Center Utrecht, the Netherlands.¹⁶ During these therapies, T2-based fat tissue thermometry was first used to verify the expected cooling effect without adaptation of cooling times. Cooling was sufficient to maintain a reduced skin temperature throughout the therapy. In the subcutaneous fat layer, the cooling effect extended to a depth of 1–2 cm. As compared to representative treatments of comparable treatment speed without DISC, the fat temperatures could be reduced by an additional four degrees on average in between two sonications.

This gained temperature margin can be used in two ways: either to reduce the cooling time before the next sonication or to enable a higher energy in the next sonication. These findings were applied to fine-tune the patient adaptive cooling time estimations before bringing the complete solution to clinical evaluation.

Following the pilot study, systems were installed at two additional sites (Marienhospital, Stuttgart, Germany and Krankenhaus der Barmherzigen Brüder, Vienna, Austria) to gather further clinical experience.

First clinical experience

At the time of writing, about 50 therapies have been conducted with encouraging results, showing improved workflow and clear reduction in the skin and fat tissue temperatures.

Automated acquisition and analysis of T2 thermometry data has enabled operators to use the cooling times productively for treatment planning. In an increasing portion of treatments, sonications have proceeded at a faster pace compared to ablation speeds of treatments conducted prior to the installation of DISC and DMT. Care teams operating the system appreciate the workflow simplification brought by the absence of a gel pad. Patients generally report that the cooled contact surface feels pleasant. The frequency at which patients stop sonications due to the sensation of skin heating has been greatly reduced.

No instances of skin burn or post-therapy skin reddening have been observed in any of the therapies for which DISC has been in use.

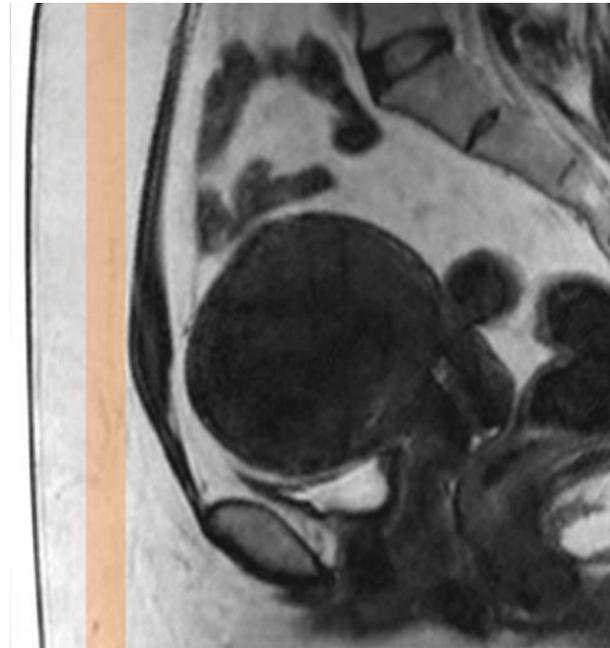


Figure 7. Appropriate positioning of the T2 thermometry slices on top of the deepest (hottest) part of the subcutaneous fat layer

Patient cases*

Figure 8 shows a selection of patient cases treated using the DISC device and Dual Mode Thermometry.

Case 1: A single large (815 mL) fibroid of Funaki type I, presenting with slight inhomogeneity in the T2w image. The single session therapy was completed in a sonication time of 3:09 h reaching an NPV of 66%. Together with the ablation speed of 171 mL/h, this demonstrates that very high efficiencies can be achieved given suitable fibroid characteristics, facilitating therapies of very large fibroids within a single session.

Case 2: Therapy was performed on a relatively standard size (200 mL) fibroid of Funaki type II with some inhomogeneity. In this case, a sonication time of 1:10 h was sufficient to reach an NPV of 100%.

Case 3: To protect the relatively thick fat layer of 30–35 mm with its insulation effect, the system suggested longer cooling times. Despite this, a sonication time of 2:32 h and 82% NPV was achieved in this 155 mL fibroid.

Case 4: A very large inhomogeneous (920 mL), Funaki type II fibroid shown here, a less than ideal candidate for MR-HIFU treatment. MR-HIFU was, however, the patient's preference, and a two-session approach was agreed upon. In spite of the higher energy demand of a Funaki type II fibroid, an ablation speed of 86 mL/h could be achieved. Although the second session was planned for three months later, the patient has passed that interval (at the time of writing) and is still taking a "wait and see" approach as she is almost free of symptoms.¹⁷

Pre-treatment
(T2 weighted planning image)

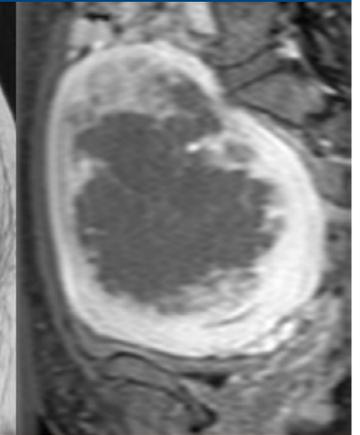
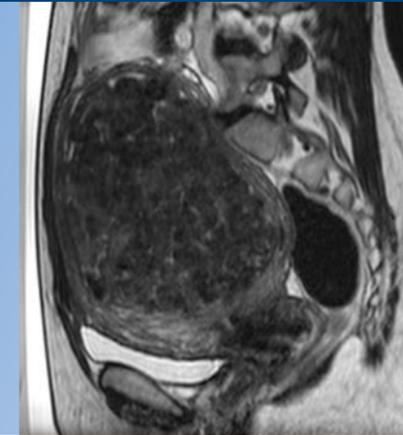
Post-therapy
(Contrast enhanced T1 THRIVE)

Case 1

Patient had a single large (815 mL) fibroid of Funaki type I, showing slight inhomogeneity in the T2w image.

Therapy was performed in a single session with sonication time of 3:09 h from the first to last sonication. NPV of 66% was reached, with ablation speed of 171 mL/h.

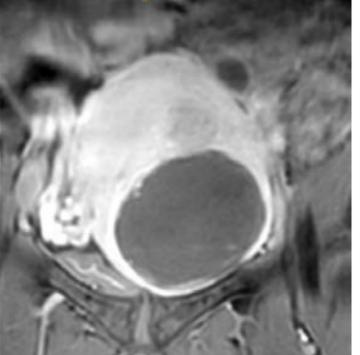
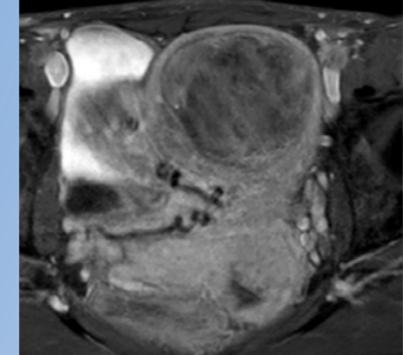
The NPV reaches very close to the spine, even though no ablation was performed there. This may be due to mechanical compression or other physiological effects.



Case 2

Patient had single fibroid with a volume of 200 mL. Fibroid was of Funaki type II and slightly inhomogeneous in the T2w image.

Therapy was performed in a single session with sonication time of 1:10 h from the first to last sonication with an NPV of 100%.

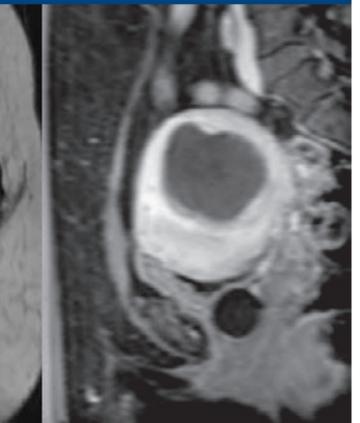
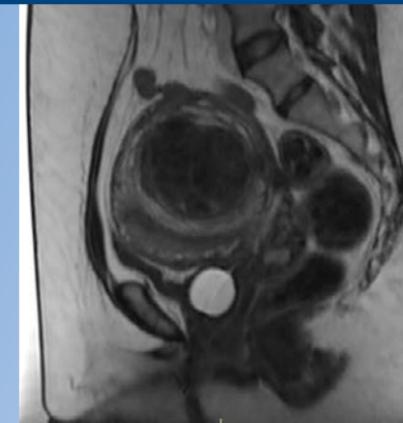


Case 3

Patient had a single fibroid with a volume of 155 mL. Fibroid was of Funaki type I and homogeneous in the T2w image. Thickness of the abdominal fat layer was 30–35 mm.

Therapy was performed in a single session with sonication time of 2:32 h from the first to last sonication. NPV of 82% was reached, with ablation speed of 50 mL/h.

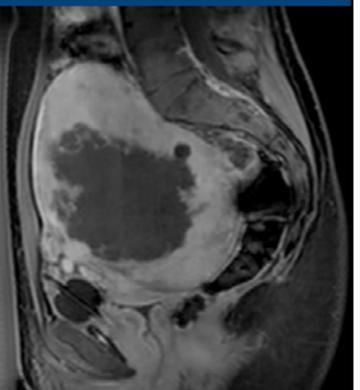
To protect the fat layer, the system suggested longer cooling times in this case.



Case 4

Patient had a single fibroid with a volume of 920 mL. Fibroid was of Funaki type II and inhomogeneous in the T2w image.

Therapy was planned for two sessions. Result of the first session shown here, with an ablation volume of 265 mL in 3:05 h, resulting in an ablation speed of 86 mL/h. At time of writing, the patient is past the three-month planned second session. As she is almost free of symptoms, she has adopted a "wait and see" approach.



Conclusions

The Sonalleve MR-HIFU system with DISC clearly lowers the near-field tissue temperatures and enables therapies with shorter cooling times. Active cooling by DISC protects the skin from reaching overly high temperatures. This translates directly into better control of the near-field tissue temperatures. As the device removes the need for a gel pad for most patients, positioning the patient is simplified and faster. Cooling combined with the absence of gel pad improves patient comfort.

Dual Mode Thermometry enables treatment to be adapted to the individual patient. The system measures cumulative heating in the subcutaneous fat layer in real time. It also adjusts cooling time recommendations based on observed temperatures instead of relying on conservative estimates. Image acquisition and processing are automated and occur in the background, allowing the operator to concentrate on the patient and further therapy planning. For patients with a thick fat layer, Dual Mode Thermometry allows the therapy strategy to be optimally adapted to the patient anatomy. For patients with a thin fat layer, the advantage of this adaptive approach lies in considerably shorter procedure times.

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* Results from case studies are not predictive of results in other cases. Results in other cases may vary

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