A time-driven activity-based costing approach of magnetic resonance-guided high-intensity focused ultrasound for cancer-induced bone pain

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ABSTRACT

Objective: To determine resource consumption and total costs for providing magnetic resonance-guided high-intensity focused ultrasound (MR-HIFU) treatment to a patient with cancer-induced bone pain (CIBP).

Methods: We conducted a time-driven activity-based costing (TD-ABC) of MR-HIFU treatments for CIBP from a hospital perspective. A European care-pathway (including a macro-, meso-, and micro-level) was designed to incorporate the care–delivery value chain. Time estimates were obtained from medical records and from prospective direct observations. To calculate the capacity cost rate, data from the controlling department of a German university hospital were allocated to the modules of the care pathway. Best- and worst-case scenarios were calculated by applying lower and upper bounds of time measurements.

Results: The macro-level care pathway consisted of eight modules (i.e., outpatient consultations, pre-treatment imaging, preparation, optimization, sonication, post-treatment, recovery, and anesthesia). The total cost of an MR-HIFU treatment amounted to €5147 per patient. Best- and worst-case scenarios yielded a total cost of €4092 and to €5876. According to cost categories, costs due to equipment accounted for 41% of total costs, followed by costs with personnel (32%), overhead (16%) and materials (11%).

Conclusion: MR-HIFU is an emerging noninvasive treatment for alleviating CIBP, with increasing evidence on treatment efficacy. This costing study can support MR-HIFU reimbursement negotiations and facilitate the adoption of MR-HIFU as first-line treatment for CIBP. The present TD-ABC model creates the opportunity of benchmarking the provision of MR-HIFU to bone tumor.

KEY POINTS

- Magnetic resonance-guided high-intensity focused ultrasound (MR-HIFU) is an emerging noninvasive treatment modality for alleviating cancer-induced bone pain (CIBP).
- From a hospital perspective, the total cost of MR-HIFU amounted to €5147 per treatment.
- This time-driven activity-based costing model creates the opportunity of benchmarking the provision of MR-HIFU to bone tumor.

Introduction

Cancer-induced bone pain (CIBP) is a condition associated with bone metastases or other musculoskeletal tumors that affects the quality of life and the functionality of patients [1–3]. For patients with persistent CIBP despite the use of opioids, palliative loco regional external beam radiotherapy (EBRT) is the treatment of choice [1,4,5]. Although approximately 60–70% of patients respond to radiotherapy, it takes on average four weeks for EBRT to achieve adequate pain relief [6–8]. Because immediate and efficient pain relief is the main treatment goal, particularly in the palliative setting, patients may benefit from treatment alternatives offering a faster pain palliation.

Magnetic resonance-guided high intensity focused ultrasound (MR-HIFU) is an emerging noninvasive treatment modality that can be performed either as alternative or in addition to EBRT [9,10]. HIFU delivers targeted acoustic energy to increase temperature (T > 56°C) at the intended treatment region to thermally ablate the periosteal nerve and tumor. HIFU can be performed under the guidance of magnetic resonance imaging (MRI), which provides excellent...
soft tissue contrast images for treatment planning. During treatment, MRI thermometry provides a near real-time assessment of temperature and thermal-dose distribution on soft tissues. This enables monitoring the thermal damage on the treated and surrounding healthy tissues, and modulation of the energy level in case the temperature rise is insufficient [11].

MR-HIFU has shown promising results for the management of CIBP, caused by bone metastasis or other musculoskeletal tumors [11,12]. Evidence on the safety and effectiveness of MR-HIFU as a first-line modality for pain palliation in skeletal metastases was demonstrated in an early prospective cohort, in which complete pain control was achieved in 13 of the 18 treated patients (72.2%) [13]. In addition, a randomized placebo-controlled trial including 147 patients demonstrated effectiveness of MR-HIFU in alleviating pain within few days after treatment in about two-thirds of patients. In this trial, 47% of patients reduced or stopped opioid consumption [14]. The beforementioned emerging evidence on safety and effectiveness provides strong impetus for further uptake in clinical practice. However, the costs and cost-effectiveness of MR-HIFU for CIBP are still uncertain.

European countries increasingly move toward payments based on diagnosis-related-groups (DRG) (e.g., Germany, the Netherlands, Finland) [15]. To promote the integration of innovative medical devices such as MR-HIFU into the DRG scheme, hospitals have to collect cost-accounting data, to adjust and update the DRG-tariffs, and therefore allow fair reimbursement [16]. Additionally, an exact cost calculation is the precondition for health-economic analyses aiming at comparing health outcomes and costs [5]. Defining resource consumption and the resulting costs is one of the critical first steps for adopting MR-HIFU into the treatment of painful bone lesions.

The objective of the present micro-costing study was to estimate resource consumption and the total costs of MR-HIFU service provision for a patient with cancer-induced bone pain from a hospital perspective.

Materials and methods

To calculate the costs associated with the MR-HIFU treatment from a hospital perspective, this micro-costing study followed a stepwise approach to the application of time driven activity-based costing (TD-ABC) in health-care settings [17,18]. TD-ABC is a micro-costing method developed to allocate resource costs to products through observing the activities performed in the production process [19]. TD-ABC uses time as the unique driver of resource utilization which allows efficient and precise cost estimations. In addition, it enables health-care providers to capture actual cost savings from lean initiatives and process improvements [20].

The following seven steps were undertaken. First, process maps outlining the patient care trajectory were developed. Second, a care pathway was designed to allocate all relevant resources consumption, thus reflecting the care delivery value-chain. Third, time measurements were performed. Fourth, the cost of each resource component was summed up. Fifth, the capacity cost rate (CCR) of each resource component was calculated, considering its annual availability. Sixth, we calculated the total costs of each resource by multiplying the CCRs and duration of resource consumption. Finally, the total cost of a MR-HIFU treatment for CIBP was calculated and allocated according to the modules of the care pathway.

In view of subsequent implementation in a European multi-centric clinical trial setting (Clinical.trials.gov registration number NCT04307914), we aimed at building a cost allocation framework that would be applicable across different European centers (i.e., steps one and two). Then, to demonstrate the potential of the cost allocation framework, we conducted a micro costing study by applying data on costs and time measurements from the University Hospital of Cologne (UHC), Germany (i.e., steps three to seven).

Development of the care pathway

With the objective to map out the current practices of MR-HIFU in five European centers, personnel responsible for delivering MR-HIFU treatments in each center were asked to describe their activities from the referral to MR-HIFU treatment until discharge from the hospital. Description of the participants is available on Supplementary Table 1A (ESM). Process maps were created using Microsoft Visio and submitted to the personnel iteratively, until no new activity was added. Macro-, meso- and micro-level care pathways were developed, containing all activities performed during the provision of MR-HIFU at an increasing level of details.

Measurement of resource consumption

Resource consumption was based on observations at the UHC. Because the units of observation were the processes that compose patient care, no individual patient data were collected. The personnel responsible for delivering MR-HIFU treatments at UHC provided estimations of time spent on each activity of the process map and probability that each activity takes place. Additionally, time measurements were collected both prospectively and retrospectively.

Duration of activities and resource consumption were prospectively measured for eight consecutive MR-HIFU bone treatments performed from June 2020 to May 2021. Retrospective time estimates were retrieved from technical records of 10 consecutive cases treated from 2018 to 2019. From these records, information about logistics (i.e., MRI room occupancy, usage of gel pad) and treatment duration (i.e., technical report generated by the HIFU equipment) was obtained. Duration of resource consumption for all modules and activities was provided as mean times (with 5% and 95%-percentiles), calculated using SPSS (IBM Corp. IBM SPSS Statistics for Macintosh, Version 27.0. Armonk, NY). Table 1 summarizes all probabilities and time variables. A comparative analysis of the prospective and retrospective case series is shown in Figures 1 and 2(A) in the ESM.

For the base case, the total costs of MR-HIFU were calculated based on prospectively measured mean time estimates
preferably. In case these were not available, we applied retrospectively collected data or estimations from experts, in that order. Best- and worst-case scenarios were calculated by applying the lower and upper bounds of time measurements (i.e., 5% and 95% percentiles).

**Valuation of resource consumption**

Data on prices were collected from the controlling department of the UHC, cost components separated into cost categories (i.e., personnel, equipment, disposables and overhead). Personnel costs included gross salary, capital-forming benefits and social contributions. Overhead costs (i.e., the costs of energy, housing, maintenance, and administration) were calculated considering the facility size in square meters and the average capacity of the departments. Costs of housing and administration were approximated according to the hospital accounting practices (€17.65 per day), while energy costs were calculated per square meters (m²) of net floor space [21]. Equipment costs referred to the replacement costs obtained from the providers, adjusted for the lifespan of the equipment and expected depreciation; expenses with maintenance were also considered.

Based on the capacity (availability) and full cost of each resource component, we calculated the respective capacity cost rate (CCR) in €/min. Cost input parameters are described in Table 2. For personnel, available capacity was estimated by subtracting vacations, holidays, breaks and weekends as per institutional policies from the full calendar year. For equipment, the operational capacity was the expected capacity of a given resource to operate. The current operational hours HIFU equipment is 10 h/day, 1 day/week (MRI equipment: 10 h/day, 250 days/year). In addition, we calculated an alternative scenario where the HIFU operational capacity was doubled (i.e., two days a week).

Costs of anesthesia were derived from a previous study, that calculated case-related revenues per minute for specific DRGs in a German hospital [22]. All costs were adjusted for the target year of 2021.
stay at the recovery room, overnight at the clinical ward and \(\text{ing the MRI room}. \) Lastly, the recovery module includes a post-treatment module includes one control MRI and clean-

ting the therapeutic sonications and respective cooling time. The \(\text{post-treatment module}\) includes one control MRI and clean-

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Figure 1 shows the macro-, meso- and micro-level care path-

ways that accounted for all activities performed during patient care at increasing level of detail. Entry point to the care pathway was determined by the referral to the MR-HIFU treatment. Exit point was the patient’s discharge from hospital after full recovery from the procedure. Follow-up con-

sultations are performed in outpatient setting by the assisting physician (e.g., clinical oncologist or orthopedic oncologist) and were not considered.

The macro-level consisted of eight modules (i.e., out-

patient consultations, pretreatment imaging, preparation, optimization, sonication, post-treatment, recovery and anes-

thesia). Outpatient consultation referred to the appointment with the interventional radiologist for medical assessment and informed consent. Pretreatment imaging consist of any imaging needed before treatment day and may involve MRI or computerized tomography, according to the case require-

ments and depending on the availability of images from the ongoing oncologic follow-up. The MR-HIFU treatment was separated in three modules: (i) the preparation module contains all activities for preparing the patient and the MRI room (e.g., dressing for treatment, quality assurance test); (ii) the optimization module starts with positioning the patient at the HIFU table, includes the planning MRI, and finishes with the test sonication; (iii) the sonication module refers to the therapeutic sonications and respective cooling time. The post-treatment module includes one control MRI and cleaning the MRI room. Lastly, the recovery module includes a stay at the recovery room, overnight at the clinical ward and the assessment of meanwhile occurred adverse events by a medical professional before discharge.

We considered ‘anesthesia’ as a quasi-detached module. The choice of the anesthesia is at the discretion of the anesthesiologist on duty, and the practices varies among the five centers studied (Supplementary Table 2A, ESM). As per institutional practices at the UHC, all patients undergoing MR-HIFU treatment undergo general anesthesia.

**Microcosting of MR-HIFU**

In the base case, the total costs per patient with cancer-

induced bone pain treated with MR-HIFU were \(\text{€5147}. \) Figure 2 shows the costs per patient per module of the care path-

way. Costs of outpatient consultations (mainly personnel costs) accounted for only 2% of total costs. The modules that yielded the higher costs were: preparation module accounted for 11% of costs, optimization for 26% and sonication for 23%. Costs allocated to anesthesia (i.e., personnel, overhead and disposables) represented 17% of the total costs.

According to cost categories, costs in the base case with equipment accounted for 41% of total costs (€2112), followed by costs with personnel (32%, €1621), overhead (16%, €842) and materials (11%, €572). Medical personnel (i.e., interventional radiologist and the anesthesiologist) represented 56% of personnel costs. Figure 3 shows how costs were distributed in each module of the care pathway, according to cost categories.

Best- and worst-case scenarios yielded total costs of €4092 and €5876, respectively. If the operational hours of HIFU were increased to two days/week, without changing CCR of the MRI equipment, the total costs per patient would reduce from €5147 to €4443. Assuming this increased capacity of HIFU equipment, (i.e., CCR of the HIFU equipment of 2.55 €/min) would impact the most costly modules of the care pathway, saving €262 on optimization module and €227 on sonication module (Figure 3(A) in the ESM).

**Discussion**

There is growing evidence on the effectiveness of MR-HIFU treatment for patients with CIBP [13,14]. To support the adoption of MR-HIFU in the clinical practice, an early evaluation of the technology from a health economic perspective was needed. By applying a TD-ABC approach, our results show that the hospital costs for the provision of MR-HIFU for patients with bone tumors at the UHC currently amounts to €5146 per patient (i.e., €4092 and €5876 on best- and worst-case scenarios).

In Germany, the G-DRG system and its standardized cost-

accounting scheme are used for both national reimburse-

ment and strategic management decisions in hospitals [23]. To calculate costs at different aggregation levels (e.g., depart-

ment, DRG group, case), the traditional cost accounting scheme dictated by the German Institute for the Hospital Remuneration System (InEK) relies on cost categories and cost centers [23].

There were two differences to the traditional cost accounting scheme in our analysis. First, the cost categories were anchored to a care pathway, what results in more transparency on resource utilization [24]. Second, capital

| Cost category | Capacity cost rate (CCR) |
|---------------|-------------------------|
| Personnel (€/min) | 1.54 |
| Interventional radiologist | 0.64 |
| Technician | 1.25 |
| Anesthesiologist | 0.61 |
| Equipment (€/min) | 3.72 |
| MRI Ingenia 3 T | 5.11 |
| HIFU Profound (Sonalleve) | |
| Materials | |
| Gel pad 40 mm | 325 €/unit |
| Gel pad 15 mm | 152 €/unit |
| Degassed water | 10 € |
| Anesthesia | 119 € |
| Intravenous contrast media (Gadoteric acid 15 ml) | 109 € |
| Overhead (€/min) | |
| MRI room | 1.53 |
| Outpatient consultation | 0.25 |
| Recovery room | 0.28 |
| Clinical ward | 0.19 |

All costs obtained from the controlling department of the University Hospital of Cologne, exception for:

*Replacement cost obtained from providers.

*Estimated based on literature [22].

*Considering energy, housing, maintenance and administration.

MRI: magnetic resonance imaging; HIFU: high-intensity focused ultrasound.
costs are not usually included in the G-DRG calculation, because German hospitals are funded according to the dual financing scheme, while statutory health insurance incur operating costs, capital costs are financed by the German states or federal grants through tax revenues [15]. However, capital costs are relevant for the hospital, and its consideration in the G-DRG calculation could lead to more efficient capital asset utilization, transparent and efficient cost- and activity control [25].

In German hospitals, reimbursement via DRG-based payments account for 80% of hospital costs [15]. However, the time-lag until an innovative technology is integrated in the DRG scheme may take up to three years [26]. To promote faster adoption of potentially beneficial innovative medical

Figure 2. Costs (€) per patient per module of the care pathway (macro-level). The line represents cumulative costs as the care pathway progresses.

Figure 3. Costs (€) allocated according to cost categories in each module of the care pathway (macro-level).
devices, German hospitals can negotiate for additional funding (i.e., innovation payments). In order to receive an innovation payment the hospital is required to prove that the current DRG-tariff does not cover the costs for the procedure [26]. Although this early assessment of costs associated with MR-HIFU treatment should not be used to set reimbursement policy, it may serve as a guide for hospitals to inform reimbursement negotiations.

While the costs of adverse events should be taken into account in costing studies of medical procedures, in our analysis, no resource consumption related to adverse events were observed, presumably because adverse events related to MR-HIFU are rare. In a phase III trial, the most clinically significant adverse event, and possibly the one associated with higher costs, was a third-degree skin burn, observed in one out of 112 patients due to noncompliance with treatment guidelines [14]. However, the developed care pathway would capture the main costs associated with adverse events, given that most adverse events are transient and resolved on treatment day [14].

The operational capacity of the HIFU equipment applied in our base case (i.e., one day per week) reflects the early implementation phase of this technology. As the technology is further implemented into clinical practice, a trend to cost reduction can be assumed. In a scenario analysis, and the cost per patient treated with MR-HIFU dropped €540 when an increased operational capacity was considered, particularly because it leads to better capital asset utilization. Besides, cost reduction may result from incremental innovation of the MR-HIFU technology (e.g., reducing treatment duration or dismissing the need for pretreatment or control imaging). However, the dynamic nature of innovation is particularly challenging to capture in economic evaluations of medical devices [27].

Moreover, because MR-HIFU is still on early phase of implementation, an overestimation of costs may exist due to the learning curve. While the treatment providers gain in experience, selection of the most optimal cases for HIFU treatment from the positioning perspective (i.e., target experience, selection of the most optimal cases for HIFU the learning curve. While the treatment providers gain in experience, selection of the most optimal cases for HIFU treatment from the positioning perspective (i.e., target experience, selection of the most optimal cases for HIFU the learning curve. However, the difference in methods for time measurements (i.e., retrospective versus prospective) does not allow to draw firm conclusions.

Attempts to allocate health-care costs to processes such as activity-based costing (ABC) have shown to be challenging and resource consuming [20]. Hence, the TD-ABC method was proposed as an evolution of the ABC method that still accommodates the complexity inherent to health care organizations to the patient level, but uses time as main cost-driver [19]. In recent years, TD-ABC has most often been used to calculate costs of inpatient procedures, to identify improvement opportunities in the workflow, or to support value-based initiatives [30]. In addition, TD-ABC enables health-care providers to direct the attention of clinicians and managers to expensive and inefficient processes [31].

The TD-ABC approach creates the opportunity of benchmarking the provision of MR-HIFU to bone tumors. Benchmarking can not only support the identification of cost-saving initiatives but also improve the quality of care [18,24]. Because the developed pathway reflects care practices from several European centers, it should be applicable to other centers and allow cost comparisons. It is noteworthy that the care pathway loses generalizability from macro- to the micro-level, whereas it gains in specificity for the care practices of the centers studied.

Among the centers that contributed to the development of the care pathway, the choice of the anesthesia technique varied the most, with potential impact on costs. While at the UHC all patients undergo a general anesthesia, spinal anesthesia with conscious sedation is preferred in other countries. In open surgeries, spinal anesthesia has shown to be cost saving when compared to general anesthesia, due to faster recovery and less blood loss [32,33]. However, for the purpose of MR-HIFU, general anesthesia may facilitate positioning and reduce motion during treatment [34], which could reduce the duration of the procedure, thereby reducing costs. Therefore, centers that prefer spinal anesthesia for radiologic procedures should pursue measuring time locally, instead of transposing the input parameters from the UHC.

A previous cost-effectiveness modeling study from the US showed that MR-HIFU for patients with CIBP results in both additional costs and quality-adjusted life years (QALY), yielding an incremental cost-effectiveness ratio of $54,160 per QALY [35]. In that study, the costs of MR-HIFU applied to the model considered microcosting from two institutions and reimbursement data from Medicare, and varied widely from $5680 to $20,000. Moreover, the uncertainty around the real costs of MR-HIFU affected the result (e.g., the incremental cost-effectiveness ratio improved 25% if the MR-HIFU costs were $10,000 instead of $15,000) [35]. Hence, a precise cost calculation of MR-HIFU may improve the validity of future cost-effectiveness analysis that aim to compare MR-HIFU with other treatment alternatives such as radiotherapy.

Some limitations to our time input parameters must be acknowledged. First, for some activities of the care pathway (i.e., outpatient consultations), we relied on estimations from personnel, which are less precise due to potential recollection bias. However, the impact on total costs is probably negligible because the cost variables associated to these activities were the lowest. Second, we did not evaluate if clinical variables and patient characteristics can predict longer treatment duration and higher costs. The impact of clinical variables, such as tumor volume or target lesion size, on costs will be assessed by applying this TD-ABC approach in a European multicentric clinical trial setting (NCT04307914), in
which treatment duration will be prospectively measured for patients with bone metastasis.

Third, in our analysis, the time measurements were performed for all types of bone tumors, including bone metastasis, desmoid tumors and osteoid osteomas. Unfortunately, the small sample size did not allow to observe trends for resource use in different subgroups. To solve the remaining uncertainties regarding learning curve and cost trends per tumor subgroup, a larger number of observations and time measurements is needed.

In conclusion, the adoption of MR-HIFU as a first-line treatment alternative for the treatment of CIBP will follow the growing evidence on its clinical effectiveness. This TD-ABC approach provides a reproducible tool for cost-accounting of MR-HIFU and an early assessment of costs incurred by the provision of MR-HIFU for patients with bone tumors at the UHC, what will play an important role in driving adoption from a health economic perspective.

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Ethical approval
Institutional Review Board approval was not required because no individual patient data was collected.

Informed consent
Written informed consent was not required for this study because no individual patient data was collected.

Disclosure statement
Sin Yuin Yeo has a part time position with Profound Medical GmbH, outside of the submitted work.

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