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Experimental thermal analysis of brake cooling relative to mass flow of air through a ventilated brake disc

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A R T I C L E I N F O

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A B S T R A C T

Individual component testing is an integral part of vehicle development and can be performed in multiple stages of the product development process. One such component assembly that often requires extensive testing is the brake system. The brake system is crucial for vehicle safety and, thus, needs to be validated from a functional perspective.

A test rig setup to accommodate a brake caliper fixture, as well as a funnel housing an anemometer, was purposefully designed and manufactured. This arrangement allows for measuring brake disc performance, surface temperature and quantifying mass airflow through the disc. The results show that the mass flow of air through the disc vanes highly depends on the disc temperature, but can also vary by more than 10 % for discs with the same specifications. Furthermore, the results highlight non-negligible differences in disc cool-down behaviour based on the braking scenario used to heat the disc up.

1. Introduction

Braking systems in passenger cars have significantly evolved over the years, from early drum brakes to modern-day disc brakes. Brakes are one of the most fundamental vehicle subsystems, primarily responsible for efficiently bringing the vehicle to a halt. The electrification of passenger cars has drastically reduced the usage of friction brakes by implementing a regenerative braking system. However, several driving scenarios and governmental laws require every vehicle manufacturer to include friction brakes in production vehicles. This is due to specific load cases where friction brakes are indispensable. Furthermore, excessive heating of the brake discs in vehicles can potentially cause the brake fluid to boil, which can lead to brake failure [1,2]. High temperatures of the braking system can also lead to impairment of neighbouring components [3] as well as thermal stresses on the disc itself and its fatigue life in the long run [4–6]. Thus, it is critical to evaluate and understand the varying temperatures as well as pressures that the brake disc on a passenger vehicle is subjected to.

Modern-day braking systems in passenger cars mostly use ventilated disc brakes which essentially operate as centrifugal air pumps. As the disc rotates, the air is sucked at the vane inlets in proximity to the hub and, after passing through the vanes, is then released on the outermost radius of the disc. When the disc is hot and the vehicle is moving, the forced air convection inside the vanes is responsible for most of the heat dissipation [2,7], compared to cooling from other disc surfaces or other means of heat transfer (i.e., conduction and radiation [8,9]).

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One of the main parameters to study for enabling improvement of the brake cooling performance is the amount of air that radially passes through the vanes based on different operational conditions. The mass flow of air depends highly on the internal vane geometry [10,11], the rotational speed of the disc and disc temperatures. However, variations can occur between discs of an identical specification from the same manufacturing batch. Geometrical tolerancing requirements of the internal vane surfaces are typically more permissive compared to the friction surfaces, as internal vanes are typically left untreated and unmachined after the disc's castings are produced. This leads to differences in the internal volume of air (i.e., empty spaces inside the disc), which produces variations in the operational mass flow.

This study investigates the mass flow of air going through ventilated brake discs and its dependency on various parameters, including the disc's temperature and rotational speed. Additionally, the cooling behaviour of the discs at different rotation rates is also studied. This kind of study is crucial when considering brake cooling performance investigations [12]. The data generated from these experimental tests will later be used to improve numerical modelling approaches and validate simulation results with the final aim of increasing vehicle range and reducing vehicle weight.

2. Experimental setup

The following section summarises the experimental setup used for this study. The test facility utilised in all the experiments is a brake dynamometer. This allows for flexibility when mounting different discs, open access to mass flow measurement and quick dismounting of the brake caliper. The brake dynamometer is controlled via software, which permits control of several parameters such as disc rotational speed, braking pressure, etc. The dynamometer is capable of a maximum disc rotational speed of up to 2400 revolutions per minute (rpm). Additional parts of the test rig mainly consist of two components: a funnel and a caliper fixture.

Firstly, a funnel that was purposefully manufactured for this study can slide into contact with the friction surface of the disc, as shown in Fig. 1. The test rig is designed in such a way to allow the funnel to be placed on a rail for ease of alignment towards the disc. Several different approaches were tested to facilitate a seal between the rotating disc and the stationary funnel whilst reducing air leakage. Consequently, a foam seal is used for the tests conducted at room temperature, and aluminium tape is used for tests with higher disc temperatures. This seal ensures that all of the air passing through the disc vanes also passes through the funnel. However, there is a limitation to these methods used for obtaining a tight seal between a stationary part (i.e., the funnel) and a rotating part (i.e., the brake disc). Even with all the precautions taken during this experimental analysis, there could be slight gaps and leakages in the seal due to disc deflections, vibrations, material wear, etc. Nevertheless, the area of the gaps is significantly smaller compared to the cross-sectional area of the funnel. Hence, any possible flow through these gaps is considered negligible. The flow measurement is conducted using a TSR MC 4.0 vane anemometer (i.e., a flow meter) housed within the funnel setup.

The second purposefully designed fixture for the test rig is a swinging lever arm and a caliper fixture as shown in Fig. 2. The brake caliper houses the brake pads, allowing for the braking force to be applied. The applied pressure is controlled through software which allows for testing various braking pressures while the disc is rotating, hence simulating fast (i.e., high braking pressure) or slow (i.e., low braking pressure) heat-ups. The swing arm enables a quick decoupling method of the brake caliper from the disc, allowing the funnel to slide into contact with the disc surface and the ability to measure the mass flow of air during disc cool-down.

As one of the investigated phenomena is the correlation between disc temperatures and the cooling air mass flow, a single k-type thermocouple is embedded in the friction surface of the brake disc to measure temperatures. It is embedded 2 mm into the disc surface and positioned approximately 1/3rd radially inboard of the friction surface outer circumference. This position is chosen as it enables an adequate approximation for the average temperature of disc friction surfaces [7].

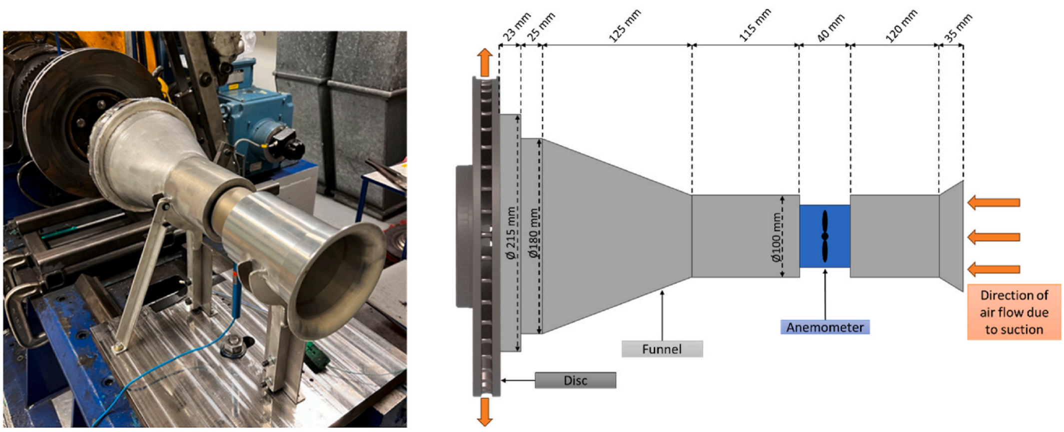

Fig. 1. Experimental rig and a schematic diagram of the funnel setup.

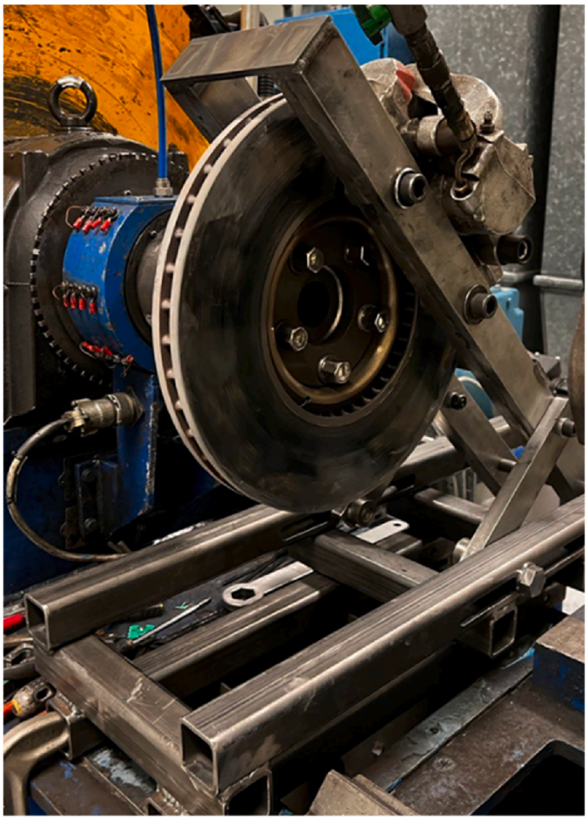

Fig. 2. Specialised test rig with a mounted brake caliper.

3. Experimental procedure

The investigated components used in this analysis were all commercially available, including brake discs with an outer diameter of 320 mm and brake pads utilising a common abrasive type of friction material, also designated as low metallic friction material [13]. In all tests, new components are used, and no bedding in cycles are performed before any of the tests. Two different experimental procedures were used to evaluate brake disc performance: the cold tests and the hot tests.

The cold test is the most effective approach to quantify the mass flow of air through the discs relative to disc speeds. In these tests, the brake caliper is not required as there is no thermal input necessary to the discs. Each cold test is performed by rotating the brake disc at varying speeds and measuring the corresponding air mass flow into the vanes, using the funnel setup and anemometer.

On the other hand, the hot test involved a more complex methodology. In this analysis, parameters such as applied pressure and disc speeds were varied while consistently measuring the disc temperatures and air mass flow. There are two phases during each hot test, namely, heat-up and cool-down. Each test starts by heating the disc to a certain temperature by applying pressure with the brake calipers mounted onto the swing arm. This is defined as the "heat-up" phase. Once the disc reaches a specified temperature, the dynamometer is stopped to release the pressure on the calipers and the caliper arm is moved away from the disc. To proceed with airflow measurements, the funnel setup is then slid close to the disc surface and clamped into position. Finally, disc rotation is resumed, and both the disc temperature and variations in air mass flow through the vanes are recorded. This part of the hot test is defined as the "cool-down" phase. The test concludes when the disc temperature drops close to the ambient temperature.

Table 1
Average mass flow for different discs of the same specifications.

Test Config.	Avg. experimental mass flow [g/s]		
	300 rpm	600 rpm	1200 rpm
Disc 1	22.24	41.66	89.42
Disc 2	23.16	47.73	95.97
Disc 3	22.97	48.77	95.30
Disc 4	23.09	49.80	94.09
Disc 5	23.12	46.71	92.29
Standard deviation	1.64	3.75	5.72

4. Results and discussions

4.1. Experimental repeatability (cold tests)

The main objective of this investigation is to investigate the correlation between disc rotation rates and the amounts of air going through the disc vanes. The vanes define the total exposed internal volume of air and, hence, the cool-down characteristics. The mass flow of air through the vanes is dependent on the vane's geometry, the disc temperature, the ambient temperature and the rotational speed of the disc [10–12]. Table 1 shows the comparison of averaged mass flow of air values at various disc speeds from different ventilated brake discs of identical specifications, labelled disc 1 to disc 5. All of these tests are conducted at an ambient room temperature of 23 ± 2 °C, and the mass flow readings are averaged for 120 s. The results indicate that there is a difference in the mass flow of air through the disc between different discs of the same specifications. For example, disc 1 at 600 rpm gives a mass flow reading of 41.66 g/s and disc 4 at the same speed gives a mass flow reading of 49.80 g/s. This is an 18 % difference in air mass flow between two ventilated discs, although the discs have identical specifications. The variations in weight of discs labelled 1 to 5 are less than 0.1 %, which is negligible. As discussed previously, such variations in mass flows are mainly caused by the manufacturing process used for the discs. Furthermore, Table 1 validates that the dependency of mass flow through the disc varies linearly relative to disc rotational speeds, which is in line with previous work [14].

4.2. Hot tests

As previously stated, during a hot test the main monitored parameters include disc temperature, disc speed, pressure applied to the brake caliper and mass flow of air through the disc during the cool-down part of the test. Fig. 3 shows an example of all the relevant data plots that provide valuable information from a hot test. The disc temperature is shown in red, the measured mass flow through the funnel setup is in purple, the pressure applied to the brake disc is in orange and the disc speed is in green.

In Fig. 3, a sinusoidal behaviour can be noticed in the temperature readings of the friction surface on the disc. This phenomenon is observed to be thermal bands and hot spots [15]. The thermal banding and hot spots are formed due to thermo-elastic instabilities, which are induced due to friction between the disc and the brake pads [10]. Furthermore, Fig. 4 shows a frame from a slow-motion video captured at the brake dynamometer where these hot spotting effects are evident. During the cool-down phase, the mass flow of air increases as the disc temperature decreases. This mainly occurs due to the change in the air density with temperature.

One of the aspects of brake cooling studied in this work is to understand the cooling performance of ventilated brake discs in relation to slow and fast heating. To study the temperature distribution over time, the ventilated brake disc is subjected to six different heating scenarios accomplished by varying applied pressure to the caliper, during various disc speed conditions. In a slow heat-up case, the disc starts at a relatively low applied braking pressure of 5 bar for varying disc speeds of 300, 600 and 1200 rpm. For fast heat-up cases, the pressure of 15 bar is used. Faster heating leads to a relatively uneven heat distribution across the disc's thickness, while with slower heating, the vanes have enough time to heat up together with the friction surfaces. Additionally, the weight measurements are performed before and after the hot tests for all five discs. These measurements show that considering the wear during the experiments, the weight of the discs reduce, on average, by less than 0.07 %.

Fig. 5 represents the cool-down curves obtained for 5 out of 6 different scenarios. For the case of 300 rpm and 5 bar, it is impossible

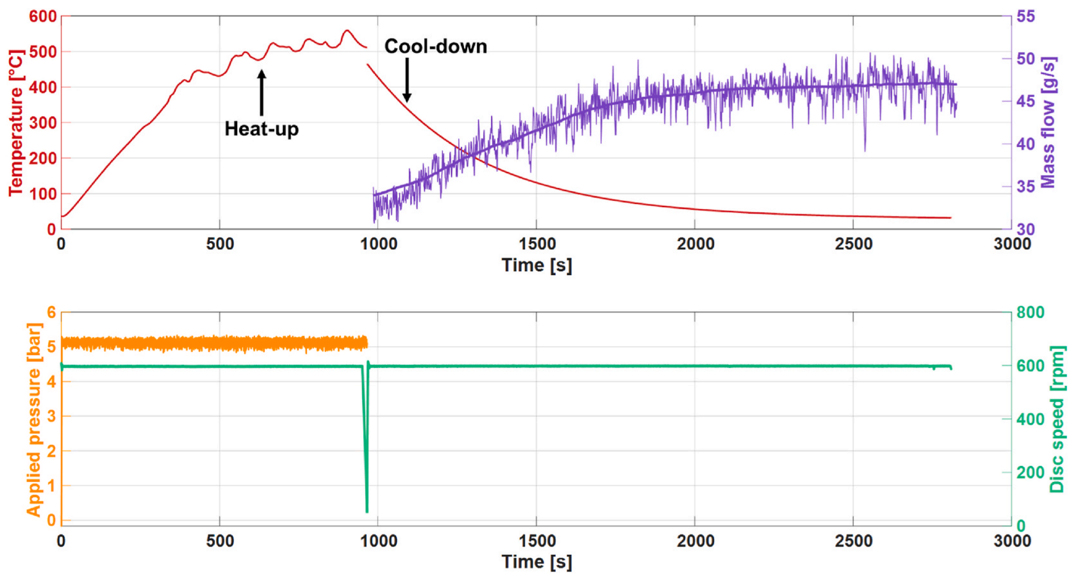

Fig. 3. An example of the data retrieved during a hot test.

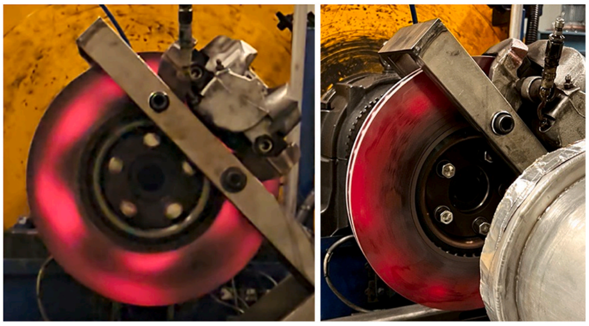

Fig. 4. Formation of hot spots captured in slow-motion and disc temperatures right after the heat-up.

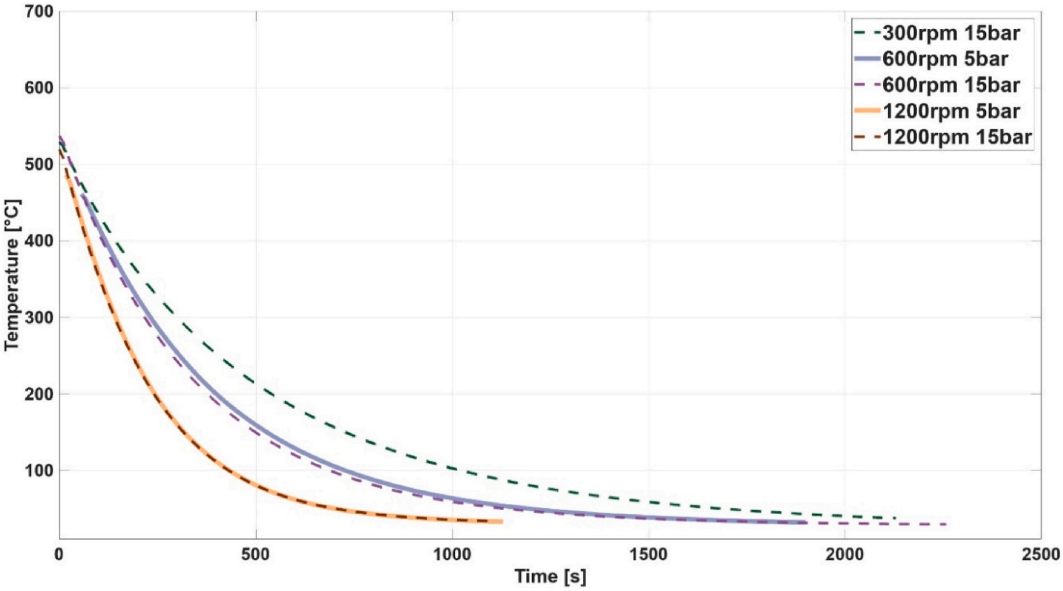

Fig. 5. Comparison of cool-down curves for fast and slow disc heat-up scenarios.

to achieve a high enough starting temperature due to insufficient energy input. Hence, this case has been omitted. As expected, the results show that the disc temperature decreases significantly faster with a higher rotation rate applied. Moreover, the heat-up scenario has an influence on the cool-down curves for the disc temperature, which is not negligible. It is also observed that discs that are heated slower take longer time to cool off. This mainly occurs because slower heating allows for more heat to propagate from the friction surfaces into the thickness of the disc and other parts of the disc and even the dynamometer assembly.

As the air passes through the disc, it heats up, thus its density decreases. As a result, while the disc acts as a centrifugal pump and, hence, a constant volume machine, the mass flow of the air through the system decreases with higher disc temperatures. Fig. 6 provides an understanding of the variations in mass flows produced by all the discs relative to temperature changes. At a disc speed of 300 rpm, the variations in mass flows are minimal due to the lower disc speed. At relatively higher disc speeds (i.e., 600 rpm and 1200 rpm), the differences in mass flow are more prominent. From Fig. 6 at disc speeds of 600 rpm and 1200 rpm, it is evident that the disc labelled “Disc 1” consistently produces a lower mass flow rate compared to other discs. This once again reinforces observations from cold tests. Considering that all of the discs look identical from the outside and weights are also almost exactly the same, this is an interesting observation. To study the reason behind this behaviour destructive testing is required, which is out of the bounds for the scope of this work.

As a forthcoming step, analysing different levels of friction material thickness would provide valuable knowledge regarding the behaviour of the components during real-world use cases. For example, in a car, the friction material thickness will constantly reduce due to wear, altering all paths of conductive heat transfer within the brake system.

5. Conclusions

The air mass flow through the disc is measured by employing an additional funnel and anemometer setup on the brake

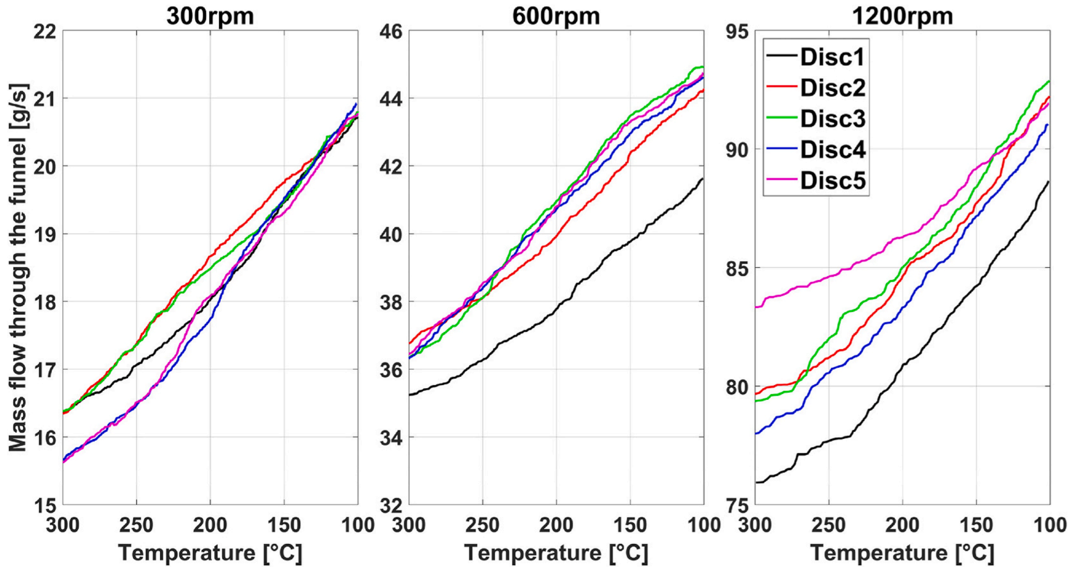

Fig. 6. Graphs of mass flow vs temperature for 300 rpm, 600 rpm and 1200 rpm at 15 bars

dynamometer. This experimental setup provides a quick and easy way of quantifying the mass flow of air through the disc at any given disc speed and temperature, enabling the comparison of different discs as well as simulating different braking and cooling scenarios.

Different samples of identical discs of the same specifications show variations in the maximum mass flow of air (i.e., cold tests) at various disc rotational speeds. For certain disc speeds, these variations between discs are found to be higher than 10 %. For the hot discs a significant temperature dependency of the air mass going through the disc is observed.

This experimental study in the brake dynamometer also allowed thermal bands and hot spots to be captured, a known phenomenon on the friction surface of a brake disc. The hot spots are observed to occur above a disc temperature of approximately 350 °C–400 °C. Furthermore, the mass flow of air depends on the disc's temperature due to variations in air density when the disc is relatively hot compared to ambient conditions. The air mass flow in a hot test when the disc temperature is below 40 °C correlates well with the values obtained in a cold test. Additionally, comparing different cool-down curves of the brake disc subjected to various heat-up scenarios shows a non-negligible difference. The weights of the brake discs were reduced by 0,07 % on average due to wear of the friction surfaces during the experiments.

This study is performed in a brake dynamometer rig, where the external flow field is significantly simpler relative to the flow field in a vehicle's wheelhouse. Multiple components surround the brake disc when it is installed on a vehicle, which affects the airflow next to the disc. Nevertheless, the presented setup allows for fast and quantitative investigations, as exemplified in this paper.

The data generated from these experimental tests will be used to enhance numerical modelling approaches and validate simulation results. Additionally, this study works as a precursor to full-scale experiments in wind tunnels and/or on-road with the final aim of increasing vehicle range and reducing vehicle weight.

CRediT authorship contribution statement

Tarun Kadri Sathiyan: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Alexey Vdovin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Staffan Johansson:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Simone Sebben:** Project administration, Funding acquisition.

Declaration of competing interest

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

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Data availability

The data that has been used is confidential.

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