The art of singing, and the art of researching singing

Arias for science

What do we know about singing? "Far too little," says Matthias Echternach, who is both a trained singer and a medical doctor. That's why he has professional vocalists sing in an MRI scanner.

by Helga Rietz
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Before he can start with the experiments, Matthias Echternach first has to hold hands with his proband. The scanner's large magnetic coils and narrow hole, into which the patient table is to be inserted, have given the volunteer a pinch of claustrophobia. So the doctor readily casts off both lab coat and shoes, watch and cufflinks - anything metallic will disturb the magnetic field and may therefore not be taken into the MRI room - and reaches a calming hand out to his volunteer, as best as he can, given the circumstances. Louisa Traser takes over his duties in the control room. She fumbles with her phone, starting up a piano app to get the correct pitch of a few notes listed on the log, humming them in a low voice. Via microphone and speakers she can speak directly with the volunteer.

"Ms. Behle, the first task is a very simple one," says Traser. "We would like to ask you to sing a downwards scale on the vowel 'a'. Start with pitch that is comfortable for you and continue to lower notes as far as you can."

Sieglinde in a Scanner

This is not an unusual scene at the Institute for Musicians' Medicine in Freiburg. Echternach researches the physiology of the voice. His tools are high-speed cameras and endoscopes, through which he can watch vocal cords swinging. Custom-made masks that, when held over mouth and nose, measure pressure and airflow in the throat. Devices with melodious names, such as the "electroglottograph." And magnetic resonance imaging (MRI).

"Was that too fast?" asks Ms. Behle. "No, no, that was wonderful," Echternach reassures. "And now, please, the same thing again, only starting from the bottom up to the highest pitch."

Renate Behle is one of the greatest opera singers of our time. From the mid-1980's through the 2000s, she has sung on the most prestigious stages in the world. Her speciality are the dramatic soprano roles: Leonore, Elektra, Isolde, Sieglinde; Brünnhilde in Richard Wagner's "Ring der Nibelungen" (The Ring of the Nibelung). Meanwhile, Behle has reached the end of her 60s and still performs on a regular basis. Last summer she sang at The Scala in Milan. Analyzing her voice, Echternach is looking for evidence for what constitutes, physiologically, a dramatic operatic voice.

Once inside the scanner, her initial disconcertment is gone after just a few tones. You can tell by the tone of her voice that she now feels safe and comfortable in the scanner. Echternach and Traser swap places, so that the director of studies himself can specify the next assignments from the control room. The computer screens now show a cross-section of the singer's throat. Twenty-four frames per second meticulously plot out the ups and downs of her larynx, the position and form of the tongue, mouth and throat. Echternach now asks Behle to sing long, sustained tones that swell in volume and then subside again: "Messa di voce," as singers say.

Images such as the ones recorded here are only possible with real-time MRI-scanners. These devices not only produce static images of the body but entire movies. Once a singer uses vibrato, a technique that vests the voice with incredible volume, the MRI will register every tremor of the larynx associated with it. However, when Ms. Behle sings, nothing trembles, despite vibrato.

"We haven't yet understood how and where exactly vibrato is produced," shrugs Louisa Traser. Apparently, singers can control the tiny pitch oscillations that lie at the heart of the vibrato both with a movement of the larynx or with the vocal cords only.

The physiology of the voice nowadays has far more questions than answers to offer. Take vocal registers, for example. Because a natural human voice does not sound the same in different pitches, vocal pedagogists and vocal physiologists divide it into different vocal registers. While the chest voice, which produces the lower tones, sounds rich and full and is similar in tone to the speaking voice, the head voice sounds thin and pure. It is used for the highest pitches in music. In male voices, it is also called 'falsetto'.

Asking different vocal instructors about what a register change actually is notoriously leads to largely divergent, often contradictory statements. The same is true for questions about what happens at the larynx (the voice-box) and pharynx during singing, and about how to achieve a singing voice that sounds beautiful in all pitches. Echternach tackles this confusion with scientific means. What happens when a singer changes register is the question at the very centre of his research.

Not an easy task

That's why he now asks Behle to sing a G major scale. Right between the third and fourth tone, he wants her to switch hard from chest voice to head voice. That's not an easy exercise, especially for a trained singer, since in classical singing, vocalists instead learn to conceal this transition between the registers. Obviously, nobody wants to hear a voice break on stage. A professional voice is expected to fill the concert hall with clear and powerful sound even at the highest pitches instead.

It takes singers years of practice to master their vocal organ in a way that it sounds full and clear at the lower as well as at the higher and highest pitches. The very same technique allows professional singers to predominate a full-fledged opera orchestra with their voice.

That's why Echternach's request to let her voice break on purpose – for the sake of research – came a little unexpected to Behle: "Is it even possible for me to do that?" she asks.

Echternach, who is in his early 40's, is an otorhinolaryngologist, a doctor in phoniatrics (that is, he has specialized in the organs of the voice and singing) and also a trained vocalist. He took his first singing lessons as a child - and until today, singing takes up a fixed place in his life: In addition to his work at the University Hospital, Echternach sings in professional ensembles and chamber choirs.

It so happens that researcher and volunteer have, long ago, met on an opera stage. That was in 1985, at the State Theatre Hannover, when Renate Behle was not yet as famous as she is now. Echternach performed as one of the "Three child-spirits" in Mozart's "Magic Flute", while Behle took on the role of the second amongst the "Three ladys" in the same staging.

Almost 30 years later, the long since adult child looks spellbound at the magnetic resonance images of the vocal tract of the primadonna, whom he admires now just as he did back then. Through the means of the MRI, he watches her following his instructions, singing away into higher and higher tonal domains. This time, she compensates for the change of register, sings with full blown stage voice. Nobody could tell where and when she transitions from chest voice to head voice.

"Wonderful, just wonderful!", Echternach yells into the microphone. "How did you do that?"

"At high pitches, I lift the soft palate in the back of my throat", explains Behle. "And at the same time I put some slight pressure on the lower abdomen – that is, I make some sort of movement that counters the ascending tones."

The MRI image clearly shows the exact opposite: the soft palate fell down towards the tongue. Echternach laughs. "I'll let you know the truth later."

But before that, the log requests an aria: Behle chooses "Du bist der Lenz" from Richard Wagner's "Valkyrie" – which, apart from the fact that "research should be fun, too," as Echternach stresses, has nothing to do with the study. All ears are pricked as the tomograph tapes every detail.

World Stars as volunteers

It is not unusual, says Echternach, that there is a huge discrepancy between what singers perceive and what the MRI shows, as was the case for Behle. The perception of the singer doesn't necessarily line up with what happens physiologically in the vocal tract. But that's not the point of his research, Echternach explains. He is not going after correcting the test-subjects. "We may know a lot about the human voice", says the researcher, "but still, we are at the beginning of a real understanding. We're just about to get to know voice." The beginnings of the research on singing and the voice date back roughly 200 years, but the advanced methods and scientific instruments that put researchers in a position where they can analyse voices quantitatively came around fairly recently, says Echternach: "Few are able to analyse a voice as precisely as we can thanks to our technical capabilities" Lay people are not eligible as test-subjects – at least for the time being. Echternach even focuses his research on the voices of the best and most successful singers around. "Those who win the daily competition on the market must be doing something right," he explains, "and we want to find out what exactly that is."

Inevitably, these constraints make his research field one in which statistics are growing slowly. Singers who can perform the Queen of the Night aren't exactly common on the ground; and vocalists such as Renate Behle, who deliver brilliant performances of the dramatic Wagner roles, are even rarer. The three-part Brünnhilde in Wagners "Ring der Nibelungen" belongs to the most difficult roles the entire opera literature has in stock. "If you wanted to stage all three operas of The Ring at the same time, there would be about twelve to fifteen singers in the whole world who could take on Brünnhilde," says Echternach. "And for top scenes like New York's Met or The Scala in Milan, that elitist circle would shrink to a handful of sopranos." Not surprisingly, Echternach's studies of professional opera singers encompass typically ten or fewer volunteers; in pilot studies there are usually only two to four test-subjects.

Vocal researchers are few and far in between, too. Only a handful of institutions worldwide are working on the field, even fewer use dynamic MRIs. Echternach greatly benefits from the goodwill of the neuroradiological section of the University Hospital, he says. More funds trickle in from the German Research Foundation. With their money, the scientists in Freiburg have built the fastest laryngoscope the world to date.

At the heart of that contraption sits a camera that was originally developed for the crash tests of the automobile industry. In optimal light conditions, it captures a million frames per second. "It's a luxury liner," says Echternach.

That luxury liner lets Echternach watch the larynx of his volunteers in super-slow motion, thereby disclosing what remains invisible in the MRI scanner: the rapid vibrations of the vocal cords, which produce the sound waves during singing and speaking. He works at "only" 20'000 frames per second – after all, there are hardly ever optimal light conditions in a human throat.

At the Institute of Musicians' Medicine, a flexible endoscope has been mounted onto the camera lens. Echternach now pushes it carefully into Ms. Behles right nostril. At the top of the nose, the endoscope bends down, in the direction of the larynx.

"We'll start on the vowel 'i'," says Echternach, "that'll tickle less on your palate."

Then he assigns the next task ahead, an elongated chirp that starts in middle pitch and then glides up to the highest pitches possible. Musicians call this a "glissando". Echternach checks the position of endoscope one last time: "Relax as best as you can."

Behle chirps. The exercise takes less than ten seconds. After that, 186'000 images have to be transferred from the camera's memory chips to the computer. That takes nine minutes. Echternach takes out the endoscope. Ms. Behle rubs her nostrils.

It was only with this camera system, says Echternach, that the observation of vocal fold oscillations in the highest soprano pitches finally came into reach – for instance the devilishly high-pitched coloraturas that Mozart wrote for his "Queen of the Night": That part extends up to F6. The corresponding sound wave oscillates 1'397 times per second, meaning that the vocal folds of the soprano open and close 1'397 times per second to produce these extremely high-pitched notes.

At least ten times as many images per second are needed to make these rapid vibrations clearly visible in slow motion. This can only be done with the luxury liner.

The second and third exercise are like the first, except that they require chirping on the vowels 'u' and then 'a'. The endoscope is threaded in, Ms. Behle chirps, the endoscope is taken out. 186'000 images are transmitted. Ms. Behle sniffling a bit, rubbing her nostrils. "It's not as bad as that," she says. "Only the tickling at the palate, that's rather uncomfortable."

Pitches above C6 – which is the equivalent to 1'046 hertz and lies in an area that laymen hardly ever reach – professional sopranos transit to yet another register, called the whistle register. According to the textbooks, at these pitches the vocal folds no longer oscillate, and the high notes are produced by air flowing continuously through the thin gap between the vocal folds (the glottis) instead, making the whistle register technically a flute. At least, that is what was believed until recently. But in 2012, Echternach showed that this isn't quite the case. By now, he has examined six sopranos, he says, and for all of them, the vocal folds vibrated even in the whistle register, even all the way up to 1'568 Hertz. Last October, Echternach was awarded the "European phoniatrics Voice Award" for that piece of research.

Voices are trumpets

Today's research log doesn't go quite so high, at least not when it comes to pitch. The last tests on the log turn out to be the most innocuous: Ms. Behle sings into a mask which she holds over her mouth and nose. Sensors therein measure air pressure and airflow as she sings, and a microphone records the audio signal. Echternach hums the pitch he needs for this exercise, Behle sings: "Pa, pa, pa, pa. . ." Then they repeat in higher pitches.

Simultaneously, a collar with electrode measures the electrical resistance of Behles larynx. That is because vocal folds conduct electricity better when they are closed than when they are open. The measurement of resistance, called an "electroglottograph", therefore shows whether the vocal folds open and close evenly for every cycle of the sound wave. If they don't, the voice sounds bleak and shady.

After that, it's again time for the transition between the chest and head voice: "Pa-ah - pi-ih – Pe-eh - pu-uh," sings Behle, allowing her voice to break into the weak natural head voice. This ends today's research program. The vocal researcher looks very satisfied.

Over the following weeks and months, Echternach will use all of that data to reconstruct Renate Behle's vocal tract. Electroglottograph and the measurements with the mask will provide information about the frequencies that the vocal folds produce, while the pictures from the MRI scanner add the exact shape of Behle's vocal tract at different pitches and vowels. Only the combination of the two lends a voice its characteristic timbre.

Technically, the musical instrument that the human voice works just like a trumpet: vibrant lips (or vocal cords) produce the sound waves – that is, a uniformly pulsating air current whose fundamental frequency determines the pitch. In addition to the keynote, there are always many overtones resonating along with it. Their relative intensity determines the timbre, and in singing also the vowel. But the intensity of each overtone will change once the sound wave passes the cavities of the vocal tract – which are, technically speaking, resonators. This amplifies certain overtones, and suppresses others. That's how vocalists change timbre and vowels of their singing voice.

Echternach collects plaster models of his volunteers' vocal tracts, that serve to re-enact the physics of the voice. Reconstructed based on MRI data, then printed out with a 3D-printing machine, they sit neatly lined up on his shelves. With their recognizable lips, teeth and tongue but weird looking, reconstructed vocal tracts bulging at their backs, they add a morbid touch to the room. The F6 of a coloratura soprano stands out in that strange collection: she contracted her throat to a straw-thin, clunky tube to give her voice the desired sound in those extreme tonal altitudes.

The larynx itself is mimicked by a small loudspeaker membrane. Echternach makes it resonate at the exact frequency spectrum of a specific singer and analyses how that spectrum gets changed in the plaster cavities, thereby checking the findings from the collected data with a physical model.

If it were up to him, the findings of his research would soon find their way into vocal pedagogy, says Echternach – even though his current focus is on medical care for professional singers. One of his next projects will be devoted to vocal cord thickening that mainly professional sopranos are afflicted with and that can cause severe discomfort.

In any case, Echternach himself has fundamentally changed his own singing over the course of his research, the physician and scientist recalls. Analysing the techniques professional singers use, he has trained his own voice in a way that made singing a lot easier for him. "My own technique has greatly benefited from my research, actually", he laughs.

Lending every note a soul

Not everyone believes that studying the physiology of the voice can be useful to that end. Renate Behle says that frankly, all her knowledge about the physiology of the voice doesn't help her sing: "I can't be thinking about what muscle I have to relax next on stage!" who also devoted a lot of time to vocal physiology during her years as a professor at the Academy of Music in Hamburg.

Also, she's totally unimpressed by the fact that the changes she perceived in her vocal tract didn't match with what the MRI measured. The experienced singer has deliberately chosen not to put too much thought into what's going on in her throat. "You have to master vocal technique, that's true," says Behle. But she stresses that the expression of emotions is just as important to her: "I call that 'lending the tones a soul!'," she says.

"Anyway, the essence of song, that's all the emotions and the aesthesia, isn't it?", Behle smiles. At that point, not even a scientist would want to disagree.