Bioengineered bacterial vesicles as biological nano-heaters for optoacoustic imaging

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Advances in genetic engineering have enabled the use of bacterial outer membrane vesicles (OMVs) to deliver vaccines, drugs and immunotherapy agents, as a strategy to circumvent biocompatibility and large-scale production issues associated with synthetic nanomaterials. We investigate bioengineered OMVs for contrast enhancement in optoacoustic (photoacoustic) imaging. We produce OMVs encapsulating biopolymer-melanin (OMVMel) using a bacterial strain expressing a tyrosinase transgene. Our results show that upon near-infrared light irradiation, OMVMel generates strong optoacoustic signals appropriate for imaging applications. In addition, we show that OMVMel builds up intense heat from the absorbed laser energy and mediates photothermal effects both in vitro and in vivo. Using multispectral optoacoustic tomography, we noninvasively monitor the spatio-temporal, tumour-associated OMVMel distribution in vivo. This work points to the use of bioengineered vesicles as potent alternatives to synthetic particles more commonly employed for optoacoustic imaging, with the potential to enable both image enhancement and photothermal applications.
A broad range of synthetic nanoparticles made up of inorganic and organic materials such as quantum dots, Au, Ag, Cu and polymeric particles have been reported for diagnostic and therapeutic functionality\textsuperscript{1–9}. Despite the appreciable success of synthetic nanomaterials for efficient disease diagnosis and therapy in preclinical trials, only a few synthetic agents have entered clinical trials. Factors that limit clinical dissemination of most synthetic nanomaterials include challenges involving low biocompatibility, material-associated toxicity, poor clearance and high cost of pilot scale production\textsuperscript{5,19}. To overcome the technical limitations associated with synthetic nanomaterials, researchers in the last decade have shown keen interest in the development of cell-derived, nano-sized vesicles as carrier systems\textsuperscript{11}. Moreover, bioengineering and bioprocessing tools have provided scalable and robust platforms for manufacturing such cells and vesicles to meet clinical and commercial needs.

Cell membrane-derived nano-vesicles have been explored with prokaryotic and eukaryotic cells, including mammalian cell-derived exosomes\textsuperscript{12}, erythrocyte-derived camouflaged particles\textsuperscript{13}, yeast vacuoles\textsuperscript{14}, bacteria-derived mini-cells\textsuperscript{15} and outer membrane vesicles (OMVs)\textsuperscript{16,17}. Exosome-based systems show low stability and yield and require expensive purification and production methods. Erythrocyte-derived particles exhibit excellent biocompatibility because they are taken from the target organism, but their lack of a nucleus means that they cannot be genetically engineered to carry biologically derived cargo. Yeast vacuoles show good ability to penetrate tissues and are easy to scale up, but their long-term stability, immunogenicity and toxicity remain to be clarified. Bacterial OMVs show several advantages as nanocarriers since they attain a rigid membrane, which imparts stability and reduces leakage in systemic circulation. Moreover, OMVs are safe because they are acellular and can be used in vivo in very small quantities. Importantly, OMVs can be customised to carry desired payloads and can easily be produced in large quantities using fermentation and purification procedures previously optimised on a pilot scale. This is particularly beneficial when considering that bacteria can easily be modified genetically to produce desired agents useful in vaccination, bio-sensing, bio-imaging, therapy or targeted delivery; and these agents can be localised specifically in membrane-derived vesicles\textsuperscript{16–20}.

In this work we consider OMVs a platform for optoacoustic applications, which can be employed for contrast-enhancement and therapeutic applications. Multi-spectral optoacoustic tomography (MSOT) is a non-invasive imaging technique that illuminates tissue at many near-infrared (NIR) wavelengths and performs spectral detection of endogenous chromophores based on the absorption spectrum. The method has been shown capable to detect melanin, oxygenated and deoxygenated haemoglobin and lipids or externally administered photo-absorbing synthetic probes, within depths of several millimetres to centimetres\textsuperscript{21–24}. A major challenge for implementing MSOT in basic research and technical limitations associated with synthetic nanomaterials, researchers in the last decade have shown keen interest in the development of cell-derived, nano-sized vesicles as carrier systems\textsuperscript{11}. Moreover, bioengineering and bioprocessing tools have provided scalable and robust platforms for manufacturing such cells and vesicles to meet clinical and commercial needs.

OMV isolation, purification, and characterisation. Figure 1 illustrates our approach to produce OMVM\textsubscript{Mel}. We started with a strain of \textit{E. coli} K12 (derived from W3110) carrying an inactivated \textit{msbB} gene, which leads to underacylated and therefore much less endotoxic lipid A, an integral component of LPS\textsuperscript{16,30,31}. We further engineered the bacteria to express \textit{Escherichia coli} tyrosinase\textsuperscript{32}, which is the rate-limiting enzyme in melanin biosynthesis. The idea was that melanin would be produced and would accumulate in the cytosol and periplasmic space, then it would be packaged into membrane and cytosol of OMVs that would be shed into the culture medium. OMVs were purified from bacteria carrying the \textit{tyrosinase} gene (OMVM\textsubscript{Mel}), from the parental bacteria with an inactivated \textit{msbB} gene (OMV\textsubscript{ΔmsbB}), and from wild-type bacteria (OMV\textsubscript{WT}) through multiple centrifugation steps. Figure 2a shows that the buffer containing isolated OMVM\textsubscript{Mel} appeared black, whereas OMV\textsubscript{WT} appeared light brown. Figure 2b, c shows OMV characterisation in terms of size and morphology. As evident from hydrodynamic size and transmission electron microscope analysis, most vesicles were in the range of 20–100 nm and had a uniform circular, bilayer morphology. Their sub-micron size makes the OMVs suitable for in vivo optoacoustic imaging of tumours. The colour difference between wild-type and melanin-containing vesicles was evident in transmission electron micrographs. OMV\textsubscript{WT} was monitored after negative staining, whereas OMVM\textsubscript{Mel} was visible without staining.
We tested whether the concentrated melanin inside OMV\textsubscript{Mel} could give a strong MSOT signal. Figure 2d shows that phantoms of OMV\textsubscript{Mel} gave \textasciitilde7-fold stronger optoacoustic signal than phantoms of OMV\textsubscript{WT} after illumination at 750 nm. The absorption spectrum of OMV\textsubscript{Mel} resembled that of pure melanin\textsuperscript{33}, consistent with the idea that OMV\textsubscript{Mel} contains encapsulated melanin. These results suggest that OMV\textsubscript{Mel} can be used as an MSOT imaging probe, such as for basic studies of tumour biology, diagnostic studies and longitudinal monitoring of treatment response.

Photothermal heating efficiency and cytotoxicity of OMV\textsubscript{Mel}. Melanin shows promise not only for disease research and diagnosis, but also for treatment. Irradiating the biopolymer can trigger local heating that kills diseased tissue through photothermal ablation or photothermal therapy\textsuperscript{28,34}. We therefore asked whether the melanin packaged within OMV\textsubscript{Mel} shows potential to act as a nanoheater for photothermal therapy. Figure 3a shows that irradiating a suspension of OMV\textsubscript{Mel} led to much greater heating than irradiating OMV\textsubscript{WT} or phosphate-buffered saline (PBS), and that the rate of temperature increase was dependent on the concentration of melanin-carrying vesicles. Figure 3b shows that OMV\textsubscript{Mel} solutions increased by \textasciitilde10 °C from room temperature after only 2 min of laser irradiation, and that this heating effect persisted. This performance is promising, given preclinical studies showing that heating cancer cells to 42–50 °C for more than 5 min can be lethal\textsuperscript{35–37}. Figure 3c shows that the experimentally determined absorption coefficient of OMV\textsubscript{Mel} was 0.75 cm\textsuperscript{−1} (absorbance of 0.31 OD) at 750 nm. This is an order of magnitude greater than the absorption coefficient of tissue (approximately 0.1 cm\textsuperscript{−1})\textsuperscript{33}, suggesting that photothermal effects can be induced selectively where OMV\textsubscript{Mel} deposits and not in neighbouring tissue. Figure 3d shows that OMV\textsubscript{Mel} exhibits photothermal conversion efficiency of 18.65% with a quantity of OMV\textsubscript{Mel} equivalent to approximately 150 µg of OMV\textsubscript{WT} (see Methods); this efficiency depends on melanin’s concentration and molar absorptivity\textsuperscript{1,2,36,39}. To test the potential for photothermal therapy in living cells, we exposed 4T1 breast cancer cultures to OMV\textsubscript{Mel}, then irradiated the treated cells for several minutes with a tunable nanosecond-pulsed laser operating from 730 nm to 830 nm. The total laser operating time was 6 min, which included both wavelength tuning and irradiation time. Figure 3e shows that the number of apoptotic cells, which appeared red because of their ability to bind ethidium homodimer-1, was much greater in cultures treated with OMV\textsubscript{Mel} than in cultures untreated or treated with OMV\textsubscript{WT}.

In vivo optoacoustic imaging of OMV\textsubscript{Mel}. As a first step towards validating the ability of OMV\textsubscript{Mel} to accumulate in tumours in vivo, we injected mice carrying subcutaneous 4T1 mouse mammary gland tumours with PBS, OMV\textsubscript{WT} or OMV\textsubscript{Mel} via the tail vein. Figure 4a shows time-dependent accumulation of OMV\textsubscript{Mel} in tumour tissue using optoacoustic imaging. At 3 h after injection, unmixed melanin signal was much higher in animals treated with OMV\textsubscript{Mel} than in other animals. This strong optoacoustic signal was evident even at 24 h after injection, suggesting persistence in the circulation and, potentially, accumulation in tumours. Next, we defined regions of interest within tumours and quantified levels of melanin present. Figure 4b clearly indicates accumulation of OMV\textsubscript{Mel} in tumours via the EPR effect. Melanin signal was higher at 3 h than at 24 h after injection, indicating that some particles may undergo systemic clearance via the tumour vasculature. Given the overlap in absorption spectra between melanin and deoxyhaemoglobin, we wanted to confirm the presence of melanin based on spectral analysis. The spectral signature of deoxyhaemoglobin and melanin show lower absorption with increasing wavelength and are not orthogonal to each other. Thus, identification of melanin in tumours is a major challenge, in large part because tumours tend to be hypoxic relative to normal tissue, and hence deoxyhaemoglobin concentration is relatively high. Figure 4c, d compared the absorption spectra in the regions of interest in tumours from animals treated with PBS or OMV\textsubscript{Mel}. As wavelength increased from 800 to 900 nm, optoacoustic signal decreased sharply (indicated with a black line) in the OMV\textsubscript{Mel} group but remained constant in the PBS group. These results are consistent with the idea that the spectra obtained from OMV\textsubscript{Mel}-treated tumours are a combination of deoxyhaemoglobin and melanin spectra, whereas the spectra from PBS-treated controls reflect primarily deoxyhaemoglobin, for which the optoacoustic signal has been shown to remain constant between 800 and 900 nm\textsuperscript{33}. In addition, the biodistribution of OMV\textsubscript{Mel} in a mouse was monitored during 120 min after intravenous injection (we did not examine non-tumour biodistribution over longer periods because we had to ensure that the animal did not move between measurements, and ethical considerations limited how long we could maintain the animal anaesthetised inside the MSOT set-up). During this 2 h period, the MSOT signal gradually increased in the tumour, tumour-adjacent region just below the skin as well as in liver and kidney (Supplementary Figure 1a). This provides further evidence that melanin is the primary source of contrast in our MSOT set-up, and it suggests that OMV\textsubscript{Mel} circulates and distributes in various organs. At the same time, the melanin signal in tumours rose consistently even from early time points (Supplementary Figure 1b) and our experiments at 3 and 24 h (Fig. 4a) showed appreciable signal in tumours. This persistent signal in the tumour suggests passive targeting ability of OMV\textsubscript{Mel}, likely due to nanometre size that ensures penetration through the leaky blood vessels and due to EPR effects in the tumour region.

In vivo photothermal therapy. To assess the potential of OMV\textsubscript{Mel} for cancer treatment, we conducted photothermal experiments on nude mice bearing 4T1 tumours. Animals were randomly allocated to receive PBS intravenously or to receive OMV\textsubscript{WT} or OMV\textsubscript{Mel} intravenously or intratumourally. At 3 h after administration, animals were exposed (or not) to a continuous wave laser (1.5 W cm\textsuperscript{−2}, 800 nm) for 6 min. Tumour growth rate and animal body weight were recorded at fixed intervals. As can be seen in Fig. 5a, the tumour surface temperature in the laser-exposed area in animals treated intratumourally with OMV\textsubscript{Mel} reached as high as 56 °C, compared to 47 °C in animals treated intravenously with OMV\textsubscript{Mel} and 39 °C with PBS. This likely reflects much more efficient delivery of OMV\textsubscript{Mel} to tumours when they are injected directly. The much greater heating observed with intratumoural administration of OMV\textsubscript{Mel} was associated with superior therapeutic effect: in
**Fig. 2** Outer membrane vesicle (OMV) purification and characterisation. 

**a** Purified form of OMVWT and OMVMel, isolated from parental bacteria by ultrafiltration and ultracentrifugation. 
**b** Dynamic light-scattering analysis of OMVs confirmed a particle size distribution in the range of 20 to 100 nm. 
**c** Transmission electron micrograph showing the nano-sized (<100 nm), bilayered, circular morphology of OMVWT and OMVMel. Scale bars, 100 nm. 
**d** Mean optoacoustic intensity (coloured line) as a function of wavelength for OMVWT and OMVMel.

**Fig. 3** In vitro photothermal therapy using OMVMel. 

**a** Temperature curves of OMVMel, OMVWT and phosphate-buffered saline (PBS) during exposure to 750 nm light (650 mW cm\(^{-2}\)) over a period of 10 min. 
**b** Plot of temperature change (ΔT) over a period of 10 min as a function of OMVMel concentration. 
**c** Absorbance spectra of OMVMel (~150 µg) solution obtained using a spectrometer. 
**d** Plot of time as a function of −In(θ) for the raw data and a linear fit during cooling after 10 min of irradiation as described for **a**. 
**e** Fluorescence images of 4T1 cells treated with PBS, OMVWT or OMVMel, then irradiated with a laser as described in the Methods. Viable cells were stained green with calcein-acetoxymethyl (AM), while dead cells were stained red with ethidium homodimer-1 (EthD-1). Scale bars, 20 µm.
animals treated intratumourally and exposed to the laser, most tumor tissue appeared necrotic and the tumour mass nearly disappeared; in animals treated intravenously, tumour growth was reduced by approximately 43% as shown in Fig. 5b. No antitumour effects were observed in animals treated with PBS or in animals treated with OMVs in the absence of laser exposure. Throughout these phototherapy experiments, animals in all groups appeared normal and showed stable body weight (Fig. 5c), with no overt signs of toxicity. Our results suggest that OMVMel can be used for in vivo optoacoustic imaging and phototherapy.

In vivo safety and immune responses. To confirm the in vivo safety of OMVs for photothermal therapy, we investigated whether single-dose systemic injection of PBS or OMVs (OMVWT, OMVΔmsbB or OMVMel) would stimulate the immune system in C57BL/6 mice. The dose of OMVs was 75 µg, similar to the therapeutic dose used in our photothermal therapy experiment. Then, levels of the cytokines tumour necrosis factor-α (TNF-α), interleukin-6 (IL-6) and interferon-γ (IFN-γ) in serum were measured by enzyme-linked immunosorbent assay (ELISA). Cytokine levels were evaluated at 2 and 24 h in order to monitor early and delayed immune responses. All three types of OMVs increased serum levels of the three cytokines at 2 h, with OMVWT triggering the greatest increases (Supplementary Figure 2a). In all cases, cytokine levels decreased close to baseline by 24 h. In addition, histology of heart, liver, spleen and kidney at 24 h after injection did not indicate significant organ damage under these treatment conditions (Supplementary Figure 2b). No animal mortality occurred in any of the groups. These results suggest that the underacylated LPS on OMVΔmsbB and OMVMel induce milder systemic inflammation than the intact LPS on OMVWT, and that the modified OMVs are well tolerated upon systemic administration.

Discussion

Here we describe melanin-containing OMVs as a biocompatible contrast agent that may allow longitudinal imaging of tumours in vivo using optoacoustics, which offers several advantages over fluorescence methods for cancer monitoring. Fluorescence imaging does not offer good spatial resolution deeper than 0.5 mm because tissue strongly scatters light. Optoacoustics, in contrast, generates optical images by recording the acoustic waves, which tissue does not strongly scatter. In addition to offering images of higher resolution from deeper-lying tissue, optoacoustics is better suited than fluorescence for theranostics. Fluorescent agents cannot optimally emit fluorescence and heat target tissue locally, because the two processes of fluorescence and nonradioactive decay compete with each other. In the case of optoacoustics, contrast agents can be optimised for photothermal conversion efficiency, such that they simultaneously give strong acoustic signal while also converting light energy to heat.

We showed with transmission electron microscopy that naturally produced OMVs were able to effectively package melanin expressed from a transgene. Melanin was presumably encapsulated into OMVs together with various cytosolic- or periplasmic- or membrane-bound components during vesicle generation and secretion, though the exact mechanism for melanin packaging is not known. Importantly, the generated OMVMel particles remained sub-micrometre in size, with intact circular morphology, which is similar to previously reported bioengineered OMVs under study for cancer-specific drug delivery. OMVMel show good dispersion properties and small particle size, allowing them to remain in circulation for an extended time, which facilitates passive accumulation in the tumour tissue by the EPR effect. We performed these experiments in a bacterial strain with a mutated form of the msbB gene. The resulting under-acylation
of lipid A substantially reduces the endotoxic activity of lipopolysaccharide, leading to weaker Toll-like receptor-dependent host immune reactions and increased in vivo safety.\textsuperscript{16,17,30,47} The same strain has previously been used to develop OMVs for in vivo drug delivery applications.\textsuperscript{16} Using less endotoxic bacterial strains is attractive for facilitating translational research on bacterially derived particles.\textsuperscript{16,17} Furthermore, the produced melanin was non-toxic to the bacterial cells. The entire process of melanin encapsulation is a natural event, so it does not require any sophisticated synthesis skills, and OMV\textsubscript{Mel} can easily be scaled up cost-effectively using well-established large-volume bacterial culture and purification techniques.

The absorption coefficient of OMV\textsubscript{Mel} was found to be several-fold higher than that of tissue. As a result, OMV\textsubscript{Mel} is expected to show strong optoacoustic signal. It appears that the proteolipid envelope of OMVs does not influence the absorption properties of encapsulated melanin biopolymers. In addition to NIR absorption, OMV\textsubscript{Mel} show suitable properties for deep-tissue optoacoustic imaging and photothermal therapy. It offers a photothermal conversion efficiency of 18.6\%, and it allows local heating in a time- and melanin-dependent manner. Within 2 min of NIR laser irradiation, the temperature of OMV\textsubscript{Mel} suspensions increased beyond 45 °C, which is sufficient to kill cancer cells in vivo.\textsuperscript{35-37,48} Since body temperature is around 37 °C, these results suggest that OMV\textsubscript{Mel} that has accumulated into tumours can easily be heated above 45 °C upon NIR irradiation. When we irradiated OMV\textsubscript{Mel}-treated 4T1 cancer cells in culture, massive cytotoxic effects were observed that were consistent with good photothermal conversion efficiency. Next, we demonstrated the efficacy of photothermal therapy in vivo. Maximal temperature on the tumour surface reached 56 and 47 °C after intratumoural or intravenous injection of OMV\textsubscript{Mel} compared to 39 °C in PBS-treated controls. Regardless of whether OMV\textsubscript{Mel} was delivered intratumourally or intravenously, it triggered obvious necrosis after laser exposure, and the tumour was nearly completely destroyed in animals treated intratumourally. These findings demonstrate the potential of OMV\textsubscript{Mel} as an effective nanoheater for diagnostic imaging and thermal therapy. Our in vivo photothermal therapy experiments were performed with continuous wave laser illumination. Our group previously demonstrated that photodynamic therapy can be performed with pulsed laser illumination\textsuperscript{29}, and hence it should be possible to heat tumours with a nanosecond-pulsed laser illumination of MSOT as long as sufficient power can be delivered. In this case, MSOT could be used for image-guided therapy. Optoacoustic measurements can be used to estimate temperature distribution during photothermal therapy\textsuperscript{49}, and hence an ideal theranostic system may combine phototherapy based on OMV\textsubscript{Mel} with continuous monitoring of local temperature and OMV\textsubscript{Mel} distribution using MSOT.

Due to its natural origin, OMV\textsubscript{Mel} is a biocompatible and biodegradable agent that can be produced on a large scale in a cost-effective manner.\textsuperscript{16,50-52} Here we explored its potential as a biologically derived theranostic agent. Our work has shown non-invasive monitoring of OMV\textsubscript{Mel} using MSOT, and we demonstrated light-based heating with OMV\textsubscript{Mel} in vitro and in tumour-bearing athymic nude mice. We used nude mice because their lack of pigmentation and skin hair facilitate optoacoustic analysis. However, this prevented us from determining whether OMV\textsubscript{Mel} can stimulate immune responses against tumours. OMVs have been shown to induce the production of antitumour cytokines, including IFN-\gamma, in tumours of immunocompetent mice.\textsuperscript{17} Repeated administration of OMVs can induce sustained production of IFN-\gamma in tumour tissue as well as long-term immune memory.\textsuperscript{17} Further detailed work is needed to examine whether, as suggested for other OMVs,\textsuperscript{17} our OMV\textsubscript{Mel} can synergistically attack tumours by locally heating the tissue and triggering a long-term immune response to prevent cancer recurrence; indeed, hyperthermia can increase blood flow and immune cell infiltration.
OMVs carry several proteins and LPS on membrane surface, which might trigger systemic toxicity\textsuperscript{16–20}. In order to address safety issues of OMVs, we carried out a separate study using immunocompetent mice. OMV\textsuperscript{WT} induced substantially stronger Toll-like receptor responses than OMV\textsuperscript{ΔΔfl} and OMV\textsuperscript{Δfl} based on serum cytokine assays (Supplementary Figure 2a), reflecting that the latter two OMV types were prepared from a low-endotoxicity \textit{E. coli} that is generally well tolerated. The OMV platform appears less likely to induce chronic systemic toxicity or endotoxicity than the latter two OMV types were prepared from a low-endotoxicity \textit{E. coli} that is generally well tolerated. The OMV platform appears less likely to induce chronic systemic toxicity or endotoxicity.

OMVMel may remain hidden from the immune system because it is embedded within the bacterial membrane. Future work should verify and extend our findings by checking for systemic toxicity or toxic effects in major organs upon repeated administration of modified OMVs in small and large animals. Also, potential synergies between photothermal therapy mediated by melanin and immune responses triggered by the OMVs themselves should be explored. Long-term stability of OMV\textsuperscript{Mel} upon standing should be evaluated, since this is important for clinical applications.

The efficacy of OMV\textsuperscript{Mel} as a specific anti-cancer therapy depends on its ability to target tumours, and here we demonstrate such an ability in vivo. Optoacoustic signal due to OMV\textsuperscript{Mel} was evident in tumours soon after intravenous injection, and this signal increased during 120 min, suggesting tumour accumulation via the EPR effect. At the same time, appreciable melanin signal increased during 120 min, suggesting tumour accumulation and this is embedded within the bacterial membrane. Future work should verify and extend our findings by checking for systemic toxicity or toxic effects in major organs upon repeated administration of modified OMVs in small and large animals. Also, potential synergies between photothermal therapy mediated by melanin and immune responses triggered by the OMVs themselves should be explored. Long-term stability of OMV\textsuperscript{Mel} upon standing should be evaluated, since this is important for clinical applications.

MOSOT operates in the NIR spectral region, where penetration of tissue to depths of several centimetres becomes possible because of low light attenuation, and laser exposure of the sample remains within the ANSI (American National Standards Institute) biosafety limits\textsuperscript{38}. High molecular detection specificity is achieved by resolving (unmixing) multiple spectral signatures in tissues\textsuperscript{22}. Clinical translation of MSOT is limited due to the lack of imaging probes that are biocompatible and scalable. Bioengineered OMVs or similar cell membrane-derived particles exhibit improved theranostic efficacy as well as reduced toxicity\textsuperscript{16,17,19}. Preclinical success of such biological nanoparticles for diagnostic or therapeutic applications can have paradigm-shifting effects on clinical or commercial translation of biological agents.

Here we acquired MSOT data with a transducer array having 256 channels covering a 270° field of view (in a two-dimensional plane). Light was delivered using a fibre bundle with six outputs, but high photothermal efficiency requires delivering light at a specific location of the body with a single output fibre. This can be achieved using handheld systems with single-point illumination or line illumination, but such systems feature limited detection angles, i.e., 145° in a two-dimensional set-up, and 90° in a three-dimensional set-up. As a result, quantification is challenging. Accurate quantification methods are being designed based on sparse recovery\textsuperscript{59}, which may enable real-time three-dimensional theranostic applications of OMV\textsuperscript{Mel}.

We report a bacterial membrane-derived nanoparticle system for optoacoustic imaging. The entirely biological design of this system may effectively avoid the long-term toxicity issues associated with many synthetic agents that deposit in various tissues and exhibit poor clearance. The ability to produce OMV\textsuperscript{Mel} from bacteria means that the vesicles can be loaded with diverse genetically encoded agents suitable for optoacoustic imaging and image-guided therapy\textsuperscript{60}. Potentially useful cargo proteins include fluorescent proteins, several optoacoustic-suitable chromoproteins and phycocyanins\textsuperscript{61,62}, anti-cancer toxins\textsuperscript{63} and peptides (e.g., aptides\textsuperscript{64} or proteins (e.g., affibodies)\textsuperscript{14,16,65} that target specific tissues and therefore provide stronger therapeutic efficacy with weaker side effects. We anticipate that the OMVs presented in this work will be a starting point for future theranostic studies focused on simultaneous optoacoustic imaging and cancer therapeutics.

**Methods**

**Plasmid construction, bacterial strain and growth.** The melA gene of \textit{Rhizobium etli} encoding tyrosinase (kindly provided by Professor Guillermo Gossel, Universidad Nacional Autónoma de México, Mexico)\textsuperscript{22} was cloned into pGEX-4T-1 (GE Healthcare, Freiburg, Germany). The construct pGEX-4T-1-melA was transformed into msbB mutant W3110-K12 \textit{E. coli} (kindly provided by Professor Sangryong Joo, KAIST, South Korea)\textsuperscript{16}. Bacteria were cultured in 1.5-L flasks at 30 °C and 180 rpm for 5 days. Tyrosinase production was induced at OD 0.6 using isopropyl β-D-thiogalactopyranoside (IPTG) at a final concentration of 0.5 mM. To support melanin production the media were supplemented with 94.5 mg CuSO\textsubscript{4} as well as 1 g L-tyrosine. OMV\textsuperscript{Mel} were produced in msbB mutant W3110-K12 \textit{E. coli} transformed with pGEX-4T-1-melA plasmid. OMV\textsuperscript{WT} were produced from untransformed msbB mutant W3110-K12 \textit{E. coli}.

**OMV purification and characterisation.** Based on our previous work\textsuperscript{15,19}, OMVs were produced as follows. \textit{E. coli} were cultured as described above. Next, bacterial cells were removed by centrifugation at 7500 × g for 45 min at 4 °C. The resulting supernatant was filtered by passing through a 0.45-µm membrane filter (Nalgene, Thermo Scientific), and concentrated to 100 mL using 100-K ultrafiltration membrane. The concentrate was further precipitated using ammonium sulphate (at final concentration, 400 g L\textsuperscript{-1}) at 4 °C overnight. Crude OMVs were obtained by centrifugation at 12,000 × g for 45 min, the resulting pellet was resuspended in 1 mL PBS and was layered over a sucrose gradient (1 mL each of 2.5, 1.6 and 0.6 M sucrose) and separated from free melanin by ultracentrifugation at 150,000 × g for 3–5 h at 4 °C. The collected OMV fractions were washed with PBS with centrifugation at 150,000 × g for 1–2 h at 4 °C, resuspended in 1 mL PBS containing 15% glycerol, filtered through 0.45-µm cellulose acetate filters and stored at −20 °C until use. In the case of OMV\textsuperscript{WT}, total protein concentration was estimated using
the bicinchoninic acid (BCA) assay (Thermo Scientific), and this was defined to be the OMVWT concentration. Since black colour prevents protein estimation with the BCA, we developed an alternative OMVMel concentration. Concentrations of OMVMel solutions were estimated based on the size of the pellet relative to the pellet obtained from OMVWT solutions (by ultracentrifugation) of known concentration. We verified the accuracy of this approach by comparing intensities of major protein bands obtained after fractionating OMVWT and OMVMel on sodium dodecyl sulphate-polyacrylamide gel electrophoresis. OMV samples were characterised with respect to size and morphology using an electrophoretic light-scattering apparatus (Malvern Zetasizer) and transmission electron microscope (Zeiss Libra 120 Plus, Carl Zeiss NTS GmbH, Oberkochen, Germany).

**Cell culture and in vivo tumour experiments.** 4T1 mammary gland carcinoma (CRL-2359, ATCC, Manassas, VA, USA) was cultured in RPMI-1640 medium supplemented with 10% foetal bovine serum and antibiotics. Cells were incubated at 37 °C in 5% CO2. Animal procedures were reviewed and approved by the Animal Care and Handling Office of Helmholtz Zentrum München and by the Government of Upper Bavaria. Sample sizes were chosen based on guidance from the literature. Investigators were not blinded to the identity of groups. Female athymic Fox-N-1 nude mice 6 weeks old (EnviGro, Germany) were implanted subcutaneously with 4T1 murine breast cancer cells (0.8 × 10⁶ cells per animal). Tumour volume was calculated as (width)² × (length) × 1/2. A colour filter with cut-off frequencies of 0.1–7 MHz. The acquired acoustic data were filtered using a Chebyshev filter with cut-off frequencies of 0.1–7 MHz. The filtered optoacoustic data; the regularisation parameter was chosen automatically using L-curve methods. The Tikhonov method was implemented using the least-squares QR method to reconstruct an image at each wavelength. The MSOT set-up and data acquisition. Phantom and mice data were acquired using a commercially available MSOT scanner (MSOT256-TF, iThera Medical GmbH, Munich, Germany). Nanosecond-pulsed light was generated from a tunable optical parametric oscillator (OPO) laser and delivered to the sample through a ring-type fibre bundle. The wavelength used for imaging was from 680 to 900 nm with a step size of 10 nm and 10 averages. Light is absorbed by the sample and generates an acoustic signal that propagates through the sample and is detected outside the sample. In our experiments, acoustic signals were detected as time-series pressure readouts at 2030 discrete time points at 40 Mega samples per second using a 256-element transducer. The transducer array had a central frequency of 5 MHz (~ 6.8B was approximately 90%) with a radius of curvature of 40 mm and an angular coverage of 270°.

Acoustic data were measured using a transducer array with 256 elements and 27° coverage at multiple laser wavelengths. The acquired acoustic data were filtered using a Chebyshev filter with cut-off frequencies of 0.1–7 MHz. Optoacoustic images were reconstructed using a Tikhonov regularisation-based scheme using filtered optoacoustic data; the regularisation parameter was chosen automatically using L-curve methods. The Tikhonov method was implemented using the least-squares QR method to reconstruct an image at each wavelength. These optoacoustic images were used to unmix melanin chromophores through a linear unmixing method that assumed that fluence did not influence unmixing. Melanin quantification was then performed on the unmixed melanin image from the tumour region by plotting mean intensity from a defined region of interest (corresponding to a similar tissue area in all animals) over time. Differences in mean melanin levels were considered significant if p < 0.01. Advanced unmixing methods are being developed to quantify biomolecules, but these methods have been extensively validated only for oxy- and deoxygenation. Efforts are underway to extend these methods to other biomolecules such as melanin and lipids.

**MSOT imaging of phantoms.** A cylindrical agar phantom was prepared with two cylindrical holes, one for OMVWT and another for OMVMel. The cylindrical phantom contained 1.3% (w/v) agar (Sigma-Aldrich, St. Louis, MO, USA) to provide solidity and 6% (v/v) intralipid emulsion (20%, Sigma-Aldrich) for light diffusion to enable uniform illumination of the holes. The added intralipid gives a reduced scattering coefficient of 10 cm⁻¹, mimicking scattering in tissue. The two cylindrical holes were 3 mm in diameter. MSOT data were acquired as described above to allow transversal plane imaging at a single position, located approximately in the middle of the phantom.

**Measurement of photothermal activity.** Photothermal activity was measured by placing PBS or OMVWT (150 µg mL⁻¹) or OMVMel solution (75, 150 or 300 µg mL⁻¹ equivalent concentration) in a quartz cuvette, and then exposing solutions to an NIR light source at 750 nm (Tunable Optical Parametric Oscillator Laser, InnoLas Laser, Karlsruhe, Germany) while monitoring temperature changes with a digital thermometer for up to 10 min. Concentration-response experiments were performed at a fixed laser power (650 mW cm⁻²) and compared with PBS as a control.

**Cytotoxicity study.** Fluorescence-based live/dead cell assays were carried out using the molecular probes calcine-acetoxyethyl (AM) and ethidium homodimer-1 (Invitrogen). Briefly, cells were seeded into 96-well plates and incubated with or without OMVWT or OMVMel for 6 h. After the media were replaced with fresh media, cells were exposed to nanosecond-pulsed laser treatment (730–830 nm, 630 mW cm⁻²) for 6 min and then stained with calcine-AM and ethidium homodimer-1 following the manufacturer’s instructions. Cells were examined under a fluorescence microscope to determine numbers of live and dead cells (Thermo Scientific).

**MSOT imaging of mice and estimation of melanin.** Animal procedures were reviewed and approved by the Animal Care and Handling Office of Helmholtz Zentrum München and by the Government of Upper Bavaria. To examine in vivo calcine-AM staining, mice bearing 4T1 tumours (~130 mm³) were given a single injection of either PBS, OMVWT (~150 µg) or an equivalent amount of OMVMel via the tail vein (n = 4 for OMV treatment and n = 3 for PBS treatment). An additional mouse was scanned to monitor distribution of OMVMel in tumour, liver and kidney from 0 to 120 min after intravenous injection of OMVMel (mouse was killed immediately after imaging). Mice were anaesthetised with 1.8% isoflurane in oxygen, which was delivered throughout MSOT data acquisition. Ultrasound gel was applied to the mice before acquisition to enable coupling between the tissue and water medium. Tissue homing and retention were monitored at 3 h and 24 h post injection with MSOT. In a separate experiment, OMVWT (~75 µg) was injected via the tail vein, and then the tumour and nearby region (just below the skin) were monitored with MSOT continuously for 120 min without moving the mouse (mouse was killed immediately after imaging). Melanin intensities are averages calculated from 6 adjacent slices from the tumour centre. Sample sizes for animal studies were chosen based on institutional recommendations with guidance from the literature. Investigators were not blinded to animal group allocations.

**In vivo photothermal therapy.** Tumour volume and body weight were recorded at regular intervals. Once the tumour volume reached approximately 100 mm³, mice were divided into eight groups (n = 4 mice/group). The groups were treated with PBS intravenously, with or without laser treatment; with OMVWT or OMVMel (each ~75 µg) intravenously, with or without laser treatment; and with OMVWT or OMVMel intratumorally, with laser treatment. At 3 h after injection, tumours were irradiated with a continuous wave laser (1.5 W cm⁻², 800 nm) for 6 min. Temperature at tumour sites was recorded immediately before and after laser irradiation using an IR thermal camera (FLIR i60). Investigators were not blinded to the identity of groups.

**In vivo safety and immune responses.** The safety and immune responses to OMVs were assessed in female C57Bl/6 mice 6 weeks old. Animals were divided into four groups (n = 5 mice/group): (1) vehicle control (PBS), (2) OMVWT, (3) OMVMel and (4) OMVMel. OMVs were administered intravenously, then blood was collected via cardiac puncture (under surgical anaesthesia) at 2 and 24 h. Levels of the TNF-α, IL-6 and IFN-γ in serum were quantified at 450 nm using commercial ELISA kits (R&D Systems) according to the manufacturer’s instructions. Vital organs including heart, liver, spleen and kidney were extracted, fixed and frozen in OCT embedding gel. Tissue blocks were sectioned to 10 µm, and stained with haematoxylin and eosin. Images were obtained by light microscopy (Carl Zeiss). Investigators were not blinded to the identity of the groups.

**Statistics.** Sample sizes were chosen based on guidance from the literature. Animals of the same gender, age and genetic background were randomised for grouping. Statistical analyses were performed using SPSS 18.0 (IBM, Chicago, IL, USA). Inter-group differences were assessed for significance using the paired t-test. Results were expressed as mean ± SD, and differences were considered significant if p < 0.01.

**Data availability**

All data presented in the paper are available from the authors upon reasonable request.

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Author contributions
V.G. conceived the OMVMel system and designed the study. V.G. and J.P. performed the experiments, J.P. processed the MSOT data and helped analyse the data. J.M.-N. assisted with in vivo experiments and MSOT data analysis. A.S. subcloned the melA gene and assisted with bacterial culture. U.K. assisted with in vivo experiments and animal maintenance. G.M. and V.G. performed transmission electron microscopy, which M.A. and A.W. supervised. V.N. provided significant intellectual input, helped interpret the results and supervised the research. All authors contributed to writing the paper.

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