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REVIEW ARTICLE

Nasal drug delivery devices: characteristics and performance in a clinical perspective—a review

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Abstract Nasal delivery is the logical choice for topical treatment of local diseases in the nose and paranasal sinuses such as allergic and non-allergic rhinitis and sinusitis. The nose is also considered an attractive route for needle-free vaccination and for systemic drug delivery, especially when rapid absorption and effect are desired. In addition, nasal delivery may help address issues related to poor bioavailability, slow absorption, drug degradation, and adverse events in the gastrointestinal tract and avoids the first-pass metabolism in the liver. However, when considering nasal delivery devices and mechanisms, it is important to keep in mind that the prime purpose of the nasal airway is to protect the delicate lungs from hazardous exposures, not to serve as a delivery route for drugs and vaccines. The narrow nasal valve and the complex convoluted nasal geometry with its dynamic cyclic physiological changes provide efficient filtration and conditioning of the inspired air, enhance olfaction, and optimize gas exchange and fluid retention during exhalation. However, the potential hurdles these functional features impose on efficient nasal drug delivery are often ignored. With this background, the advantages and limitations of existing and emerging nasal delivery devices and dispersion technologies are reviewed with focus on their clinical performance. The role and limitations of the in vitro testing in the FDA guidance for nasal spray pumps and pressurized aerosols (pressurized metered-dose inhalers) with local action are discussed. Moreover, the predictive value and clinical utility of nasal cast studies and computer simulations of nasal airflow and deposition with computer fluid dynamics software are briefly discussed. New and emerging delivery technologies and devices with emphasis on Bi-Directional™ delivery, a novel concept for nasal delivery that can be adapted to a variety of dispersion technologies, are described in more depth.

Keywords Drug delivery · Nasal · Device · Paranasal sinuses · Topical · Systemic · Vaccine · Nasal valve · Particle deposition · Clearance

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Introduction

Intuitively, the nose offers easy access to a large mucosal surface well suited for drug- and vaccine delivery. However, factors related to the nasal anatomy, physiology and aerodynamics that can severely limit this potential, have historically been challenging to address. The most recent FDA guidance for nasal devices provides detailed guidelines for in vitro testing of the physical properties such as in vitro reproducibility and accuracy of plume characteristics and dose uniformity of mechanical liquid spray pumps and pressurized metered-dose inhalers (pMDIs) for nasal use [1]. The guidance primarily addresses in vitro testing of nasal sprays and pressurized aerosols for local action. The reference to in vivo performance is limited to the recommendation of minimizing the fraction of respirable particles below 9 μm in order to avoid lung inhalation of drugs intended for nasal delivery. Thus, although important as measures of the quality and reliability of the spray pump and pMDI mechanics, these in vitro tests do not necessarily predict the in vivo particle deposition, absorption, and clinical response [2]. Furthermore, the guidance offers no or limited guidance on nasal products for systemic absorption and for alternative dispensing methods like drops, liquid jets, nebulized aerosol, vapors, and powder formulations. Finally, it does not address aspects and challenges related to the nasal anatomy and physiology that are highly relevant for the device performance in the clinical setting like body

position, need for coordination, and impact of airflow and breathing patterns at delivery.

The mechanical properties of different modes of aerosol generation are already well described in depth in a previous publication [3]. The anatomy and physiology of the nasal airway has also recently been summarized in an excellent recent review [4]. The aim of this paper is to take a step further by reviewing the characteristics of existing and emerging nasal delivery devices and concepts of aerosol generation from the perspective of achieving the clinical promise of nasal drug and vaccine delivery. Focus is put on describing how the nasal anatomy and physiology present substantial obstacles to efficient delivery, but also on how it may be possible to overcome these hurdles by innovative approaches that permit realization of the therapeutic potential of nasal drug delivery. Specific attention is given to the particular challenge of targeted delivery of drugs to the upper narrow parts of the complex nasal passages housing the middle meatus where the sinuses openings are located, as well as the regions innervated by the olfactory nerve and branches of the trigeminal nerve considered essential for efficient "nose-to-brain" (N2B) transport.

Nasal anatomy and physiology influencing drug delivery

Regulation of nasal airflow

Nasal breathing is vital for most animals and also for human neonates in the first weeks of life. The nose is the normal and preferred airway during sleep, rest, and mild exercise up to an air volume of 20–30 l/min [5]. It is only when exercise becomes more intense and air exchange demands increase that oral breathing supplements nasal breathing. The switch from nasal to oronasal breathing in young adults appears when ventilation is increased to about 35 l/min, about four times resting ventilation [6]. More than 12,000 l of air pass through the nose every day [5]. The functionality of the nose is achieved by its complex structure and aerodynamics. Amazingly, the relatively short air-path in the nose accounts for as much as 50–75 % of the total airway resistance during inhalation [7, 8].

The nasal valve and aerodynamics

The narrow anterior triangular dynamic segment of the nasal anatomy called the nasal valve is the primary flow-limiting segment, and extends anterior and posterior to the head of the inferior turbinate approximately 2–3 cm from the nostril opening [9]. This narrow triangular-shaped slit acts as a dynamic valve to modify the rate and direction of the airflow during respiration [10, 11]. Anatomical studies describe the static valve dimensions as 0.3–0.4 cm^2 on each side, whereas acoustic rhinometry studies report the functional cross-sectional area perpendicular to the acoustic pathway to be between 0.5 and 0.6 cm^2 on each side, in healthy adults, with no, or minimal gender differences [11–14]. The flow rate during tidal breathing creates air velocities at gale force (18 m/s) and can approach the speed of a hurricane (32 m/s) at sniffing [11, 15]. At nasal flow rates found during rest (up to 15 l/min), the flow regimen is predominantly laminar throughout the nasal passages. When the rate increases to 25 l/min, local turbulence occurs downstream of the nasal valve [10, 11, 15]. The dimensions can expand to increase airflow by dilator muscular action known as flaring, or artificially by mechanical expansion by internal or external dilators [16, 17]. During inhalation, Bernoulli forces narrow the valve progressively with increasing inspiratory flow rate and may even cause complete collapse with vigorous sniffing in some subjects [5]. During exhalation, the valve acts as a "brake" to maintain a positive expiratory airway pressure that helps keep the pharyngeal and lower airways open and increase the duration of the expiratory phase. This "braking" allows more time for gas exchange in the alveoli and for retention of fluid and heat from the warm saturated expiratory air [4, 17, 18]. In fact, external dilation of narrow noses in obstructive sleep apnea patients had beneficial effects, whereas dilation of normal noses to "supernormal" dimensions had deleterious effects on sleep parameters [17]. However, in the context of nasal drug delivery, the small dimensions of the nasal valve, and its triangular shape that narrows further during nasal inhalation, represent important obstacles for efficient nasal drug delivery.

The nasal mucosa—filtration and clearance

The region anterior to the valve called the vestibule is lined by non-ciliated squamous epithelium that in the valve region gradually transitions into ciliated epithelium typical of the ciliated respiratory epithelium posterior to the valve region [4, 19]. Beyond the nasal valve, the nasal turbinates divide the nasal cavity into slit-like passages with much larger cross-sectional area and surface area (Figs. 1, 2 and 3). Here, the predominantly laminar airflow is slowed down to speeds of 2–3 m/s and disrupted with eddies promoting deposition of particles carried with the air at and just beyond the valve region [11]. The ciliated respiratory mucosa posterior to the nasal valve is covered by a protective mucous blanket designed to trap particles and microorganisms [4, 19].The beating action of cilia moves the mucous blanket towards the nasopharynx at an average speed of 6 mm/min (3–25 mm/min) [20, 21]. The large surface area and close contact enables effective filtering and conditioning of the inspired air and retention of water during exhalation (Figs. 1, 2 and 3). Oral breathing increases the net loss of water by as much as 42 % compared to nasal breathing [22]. The nasal passages were

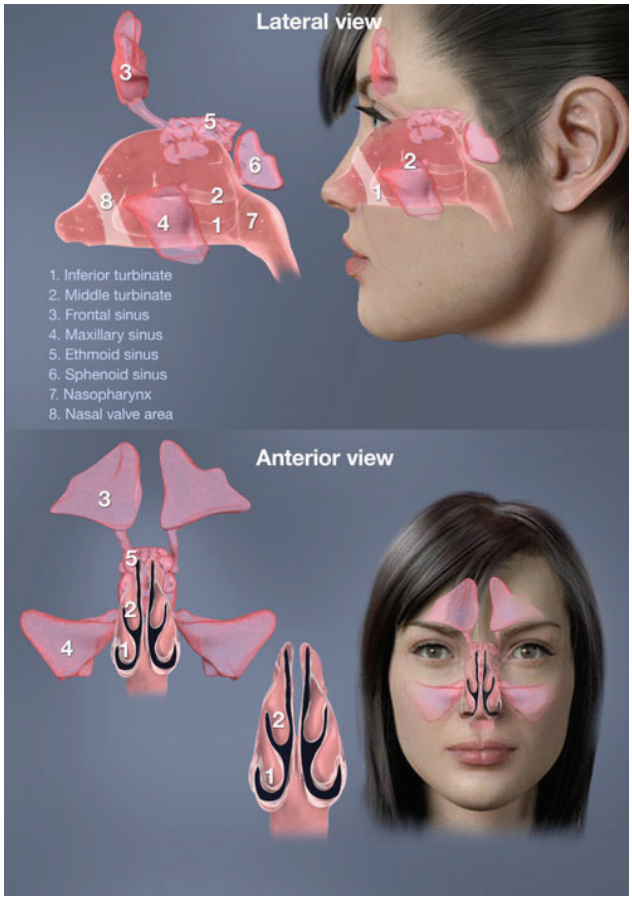

Fig. 1 The complex anatomy of the nasal airways and paranasal sinuses

optimized during evolution to protect the lower airways from the constant exposure to airborne pathogens and particles.

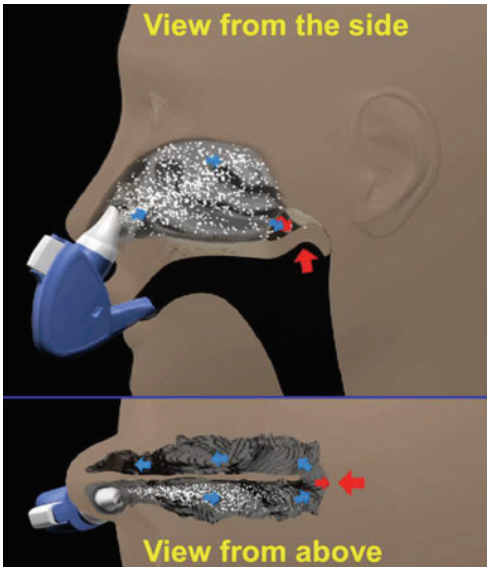

Fig. 2 Illustration of the breath-powered Bi-Directional™ technology. See text for detailed description

Specifically, particles larger than 3–10 μm are efficiently filtered out and trapped by the mucus blanket [19]. The nose also acts as an efficient "gas mask" removing more that 99 % of water-soluble, tissue-damaging gas like sulfur dioxide [23]. Infective agents are presented to the abundant nasal immune system both in the mucous blanket, in the mucosa, and in the adjacent organized lymphatic structures making the nose attractive for vaccine delivery with potential for a longstanding combination of systemic and mucosal immune responses [24]. The highly vascularized respiratory mucosa found beyond the valve allows exchange of heat and moisture with the inspired air within fractions of a second, to transform cold winter air into conditions more reminiscent of a tropical summer [19].

The nasal cycle

The physiological alternating congestion and decongestion observed in at least 80 % of healthy humans is called the nasal cycle [5, 25]. The nasal cycle was first described in the rhinological literature by a German physician in 1895, but was recognized in Yoga literature centuries before [5]. Healthy individuals are normally unaware of the spontaneous and irregular reciprocal 1–4-h cycling of the nasal caliber of the two individual passages, as the total nasal resistance remains fairly constant [26]. The autonomic cyclic change in airflow resistance is mainly dependent on the blood content of the submucosal capacitance vessels that constitute the erectile component at critical sites, notably the nasal valve region. Furthermore, the erectile tissues of the septal and lateral walls and the turbinates respond to a variety of stimuli including physical and sexual activity and emotional states that can modify and override the basic cyclic rhythm [4]. The cycle is present during sleep, but overridden by pressures applied to the lateral body surface during recumbency to decongest the uppermost/contralateral nasal passage. It has been suggested that this phenomenon causes a person to turn from one side to the other while sleeping [5, 27]. The cycle is suppressed in intubated subjects, but restored by resumption of normal nasal breathing [28]. The cycle may also cause accumulation of nitric oxide (NO) in the congested passage and adjacent sinuses and contribute to defense against microbes through direct antimicrobial action and enhanced mucociliary clearance [29]. Measurements have shown that the concentration of NO in the inspired air is relatively constant due to the increase in NO concentration within the more congested cavity, which nearly exactly counterbalances the decrease in nasal airflow [30]. In some patients, as a result of structural deviations and inflammatory mucosal swelling, the nasal cycle may become clinically evident and cause symptomatic obstruction [19]. Due to the cycle, one of the nostrils is considerably more congested than the other most of the time, and the vast majority of the airflow passes through one nostril while the other remains quite narrow especially at the valve region [5].

Consequently, the nasal cycle contributes significantly to the dynamics and resistance in the nasal valve region and must be taken into consideration when the efficiency of nasal drug delivery devices is considered.

Nasal and sinus vasculature and lymphatic system

For nasally delivered substances, the site of deposition may influence the extent and route of absorption along with the target organ distribution. Branches of the ophthalmic and maxillary arteries supply the mucous membranes covering the sinuses, turbinates, meatuses, and septum, whereas the superior labial branch of the facial artery supplies the part of the septum in the region of the vestibule. The turbinates located at the lateral nasal wall are highly vascularized with a very high blood flow and act as a radiator to the airway. They contain erectile tissues and arteriovenous anastomoses that allow shunting and pooling related to temperature and water control and are largely responsible for the mucosal congestion and decongestion in health and disease [19, 31].

Substances absorbed from the anterior regions are more likely to drain via the jugular veins, whereas drugs absorbed from the mucosa beyond the nasal valve are more likely to drain via veins that travel to the sinus cavernous, where the venous blood comes in direct contact with the walls of the carotid artery. A substance absorbed from the nasal cavity to these veins/venous sinuses will be outside the blood–brain barrier (BBB), but for substances such as midazolam, which easily bypass the BBB, this route of local "counter-current transfer" from venous blood may provide a faster and more direct route to the brain. Studies in rats support that a preferential, first-pass distribution to the brain through this mechanism after nasal administration may exist for some, but not all small molecules [32, 33]. The authors suggested that this counter-current transport takes place in the area of the cavernous sinus–carotid artery complex, which has a similar structure in rat and man, but the significance of this mechanism for nasally delivered drugs has not been demonstrated in man [32, 33].

The lymphatic drainage follows a similar pattern as the venous drainage where lymphatic vessels from the vestibule drain to the external nose to submandibular lymph nodes, whereas the more posterior parts of the nose and paranasal sinuses drain towards the nasopharynx and internal deep lymph nodes [4]. In the context of nasal drug delivery, perivascular spaces along the olfactory and trigeminal nerves acting as lymphatic pathways between the CNS and the nose have been implicated in the transport of molecules from the nasal cavity to the CNS [34].

Innervation of the nasal mucosa

The nose is also a delicate and advanced sensory organ designed to provide us with the greatest pleasures, but also to warn and protect us against dangers. An intact sense of smell plays an important role in both social and sexual interactions and is essential for quality of life. The sense of smell also greatly contributes to taste sensations [35]. Taste qualities are greatly refined by odor sensations, and without the rich spectrum of scents, dining and wining and life in general would become dull [36]. The olfactory nerves enter the nose through the cribriform plate and extend downwards on the lateral and medial side of the olfactory cleft. Recent biopsy studies in healthy adults suggest that the olfactory nerves extend at least 1–2 cm further anterior and downwards than the 8–10 mm described in most textbooks (see Figs. 1 and 2) [37, 38]. The density decreases, but olfactory filaments and islets with olfactory epithelium are found in both the anterior and posterior parts at the middle turbinate. In addition, sensory fibers of both the ophthalmic and maxillary branches of the trigeminal nerve contribute to olfaction by mediating a "common chemical sense" [39]. Branches of the ophthalmic branch of the trigeminal nerve provide sensory innervation to the anterior part of the nose including the vestibule, whereas maxillary branches innervate the posterior part of the nose as well as the regions with olfactory epithelium.

The olfactory and trigeminal nerves mutually interact in a complex manner. The trigeminal system can modulate the olfactory receptor activity through local peptide release or via reflex mechanisms designed to minimize the exposure to and effects of potentially noxious substances [39]. This can occur by alteration of the nasal patency and airflow and through changes in the properties of the mucous blanket covering the epithelium. Trigeminal input may amplify odorous sensation through perception of nasal airflow and at the chemosensory level. Interestingly, an area of increased trigeminal chemosensitivity is found in the anterior part of the nose, mediating touch, pressure, temperature, and pain [39]. Pain receptors in the nose are not covered by squamous epithelium, which gives chemical stimuli almost direct access to the free nerve endings. In fact, loss of trigeminal sensitivity and function, and not just olfactory nerve function, may severely reduce the sense of smell [40]. This should not be forgotten when addressing potential causes of reduced or altered olfaction.

The sensitivity of the nasal mucosa as a limiting factor

In addition to the limited access, obstacles imposed by its small dimensions and dynamics, the high sensitivity of the mucosa in the vestibule and in the valve area is very relevant to nasal drug delivery. Direct contact of the tip of the spray nozzle during actuation, in combination with localized concentrated anterior drug deposition on the septum, may create mechanical irritation and injury to the mucosa resulting in nosebleeds and crusting, and potentially erosions or perforation [41]. Furthermore, the

high-speed impaction and low temperature of some pressurized devices may cause unpleasant sensations reducing patient acceptance and compliance.

The role of the high sensitivity of the nasal mucosa as a natural nasal defense is too often neglected when the potential of nasal drug delivery is discussed, in particular when results from animal studies, cast studies, and computer fluid dynamics (CFD) are evaluated. Exposure to chemicals, gases, particles, temperature and pressure changes, as well as direct tactile stimuli, may cause irritation, secretion, tearing, itching, sneezing, and severe pain [39]. Sensory, motor, and parasympathetic nerves are involved in a number of nasal reflexes with relevance to nasal drug delivery [4]. Such sensory inputs and related reflexes are suppressed by the anesthesia and/or sedation often applied to laboratory animals, potentially limiting the clinical predictive value of such studies. Further, the lack of sensory feedback and absence of interaction between the device and human subjects/patients are important limitations of in vitro testing of airflow and deposition patterns in nasal casts and in CFD simulation of deposition. Consequently, deposition studies in nasal casts and CFD simulation of airflow and deposition are of value, but their predictive value for the clinical setting are all too often overestimated.

Targeted nasal delivery

For most purposes, a broad distribution of the drug on the mucosal surfaces appears desirable for drugs intended for local action or systemic absorption and for vaccines [3]. However, in chronic sinusitis and nasal polyposis, targeted delivery to the middle and superior meatuses where the sinus openings are, and where the polyps originate, appears desirable [42, 43]. Another exception may be drugs intended for "nose-to-brain" delivery, where more targeted delivery to the upper parts of the nose housing the olfactory nerves has been believed to be essential. However, recent animal data suggest that some degree of transport can also occur along the branches of the first and second divisions of the trigeminal nerve innervating most of the mucosa at and beyond the nasal valve [44]. This suggests that, in contrast to the prevailing opinion, a combination of targeted delivery to the olfactory region and a broad distribution to the mucosa innervated by the trigeminal nerve may be optimal for N2B delivery. Targeted delivery will be discussed in more detail below.

Nasal drug delivery devices

The details and principles of the mechanics of particle generation for the different types of nasal aerosols have been described in detail by Vidgren and Kublik [3] in their comprehensive review from 1998 and will only be briefly described here, with focus instead on technological features directly impacting particle deposition and on new and emerging technologies and devices. Liquid formulations currently completely dominate the nasal drug market, but nasal powder formulations and devices do exist, and more are in development. Table 1 provides an overview of the main types of liquid and powder delivery devices, their key characteristics, and examples of some key marketed nasal products and emerging devices and drug–device combination products in clinical development (Table 1).

Devices for liquid formulations

The liquid nasal formulations are mainly aqueous solutions, but suspensions and emulsions can also be delivered. Liquid formulations are considered convenient particularly for topical indications where humidification counteracts the dryness and crusting often accompanying chronic nasal diseases [3]. In traditional spray pump systems, preservatives are typically required to maintain microbiological stability in liquid formulations. Studies in tissue cultures and animals have suggested that preservatives, like benzalkonium chloride in particular, could cause irritation and reduced ciliary movement. However, more recent human studies based on long-term and extensive clinical use have concluded that the use of benzalkonium chloride is safe and well tolerated for chronic use [45]. For some liquid formulations, in particular peptides and proteins, limited stability of dissolved drug may represent a challenge [46].

Drops delivered with pipette

Drops and vapor delivery are probably the oldest forms of nasal delivery. Dripping breast milk has been used to treat nasal congestion in infants, vapors of menthol or similar substances were used to wake people that have fainted, and both drops and vapors still exist on the market (e.g., www.vicks.com). Drops were originally administered by sucking liquid into a glass dropper, inserting the dropper into the nostril with an extended neck before squeezing the rubber top to emit the drops. For multi-use purposes, drops have to a large extent been replaced by metered-dose spray pumps, but inexpensive single-dose pipettes produced by "blow-fill-seal" technique are still common for OTC products like decongestants and saline. An advantage is that preservatives are not required. In addition, due to inadequate clinical efficacy of spray pumps in patients with nasal polyps, a nasal drop formulation of fluticasone in single-dose pipettes was introduced in the EU for the treatment of nasal polyps. The rationale for this form of delivery is to improve drug deposition to the middle meatus where the polyps emerge [47, 48]. However, although drops work well for

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