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# Evaluation of tracheostomy tube degradation processes using scanning microscopy and X-ray spectrometry in patients following ENT surgery

## Ocena procesów degradacji rurek tracheostomijnych przy użyciu metod mikroskopii skaningowej i spektrometrii rentgenowskiej u pacjentów po zabiegach laryngologicznych

*Tracheostomy tubes are commonly used not only in emergencies involving airflow obstruction in the upper airways, but also during rehabilitation after ENT surgery, particularly in patients following radical laryngectomy due to cancer. Unfortunately, tracheostomy tubes used in the specific mucosal environment of the trachea and oesophagus show a limited lifespan of up to 6 months. This means that inserted tubes must be replaced regularly due to deterioration. Limitations in the function of the tubes over the course of their use are caused by various material factors that depend on the properties of the tubes or on the condition of the environment in the human body. The purpose of this paper is to evaluate the surface condition of tracheostomy tubes after 2 days and after 3 months of use.*

Keywords: *tracheostomy tubes, deterioration of tracheostomy tubes*

*Rurki tracheostomijne są powszechnie stosowane nie tylko w nagłych przypadkach zablokowania przepływu powietrza przez górny odcinek dróg oddechowych, ale także podczas rehabilitacji po zabiegach laryngologicznych, w szczególności u chorych po radykalnym usunięciu krtani w przebiegu choroby nowotworowej. Specyficzne środowisko śluzówek tchawicy i przełyku wpływa niestety na ograniczenie żywotności rurek tracheostomijnych maksymalnie do 6 miesięcy. Oznacza to, że założone rurki wymagają okresowej wymiany z powodu obniżenia ich jakości. Ograniczenia funkcjonowania rurek w miarę ich użytkowania są spowodowane różnymi czynnikami materiałowymi, zależnymi od właściwości rurek lub zależnymi od stanu środowiska w organizmie człowieka. Przedmiotem badań w prezentowanej pracy jest ocena stanu powierzchni rurek tracheostomijnych po użytkowaniu przez 2 dni i przez 3 miesiące.*

Słowa kluczowe: *rurki tracheostomijne, niszczenie rurek tracheostomijnych*

### 1. Introduction

The larynx is an essential part of the upper respiratory tract, allowing both the free flow of air to the trachea and bronchi and the formation of voice and speech, which is an important aspect of normal social functioning in humans.

A tracheotomy is a surgical procedure in which a vertical or horizontal skin incision is made at the level of the cricoid cartilage. The thyroid gland is then exposed after dissection of the subglenoid muscles in the area of the isthmus. The exposed anterior wall of the trachea is incised between the second and third cartilages. A tracheostomy tube is inserted into the trachea to

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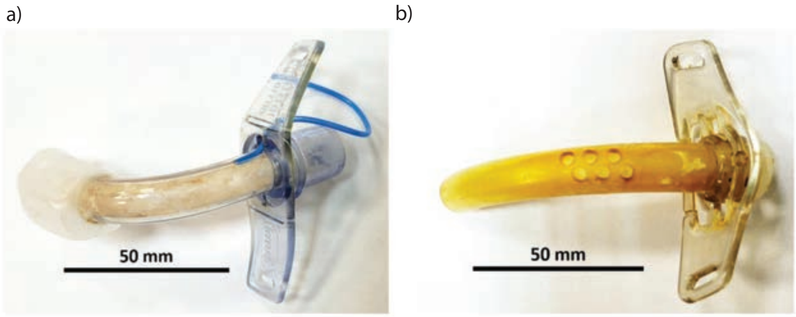



Fig. 1. General view of tracheostomy tubes after use by patients for: a) 2 days, b) 3 months

Rys. 1. Widok ogólny rurek tracheostomijnych po użytkowaniu przez pacjentów przez: a) 2 dni, b) 3 miesiące

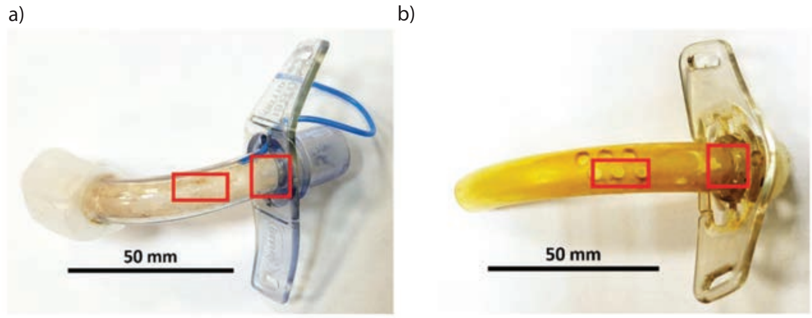



Fig. 2. General view of tracheostomy tubes with marked SEM + EDS analysis areas (1 and 2) after use by patients for: a) 2 days, b) 3 months

Rys. 2. Widok ogólny rurek tracheostomijnych z zaznaczonymi obszarami analizy SEM + EDS (1 i 2) po użytkowaniu przez pacjentów przez: a) 2 dni, b) 3 miesiące

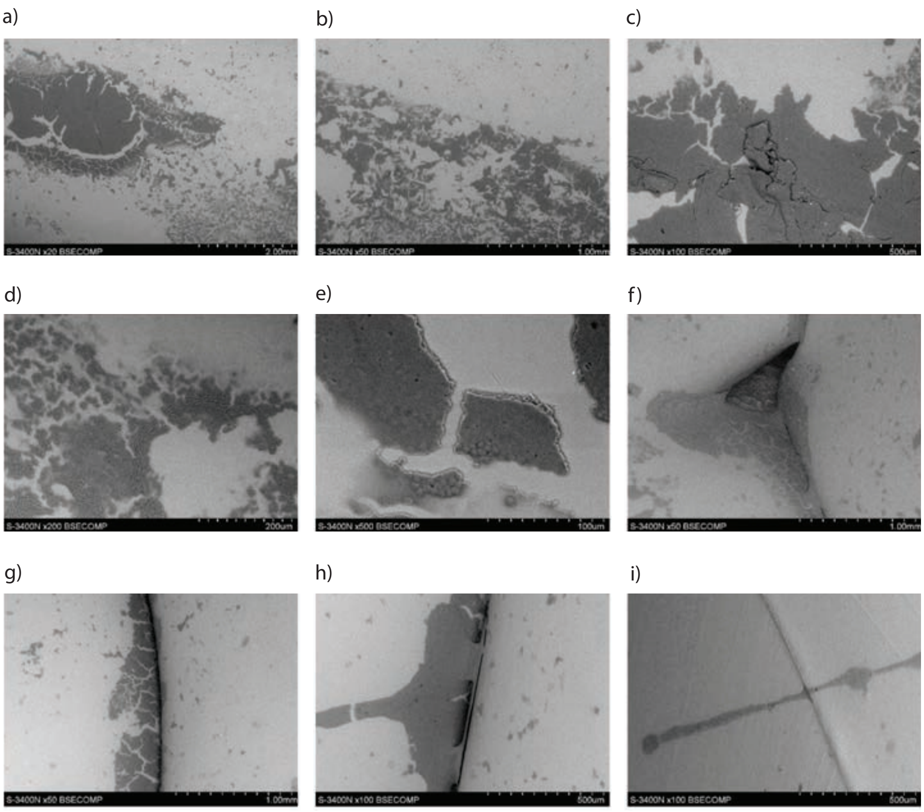



Fig. 3. Morphology of the surface of a tracheostomy tube after 2 days of use: a)–e) surface on the arch of the tube (site 1), f)–i) area around the tube collar (site 2)

Fig. 3. Morfologia powierzchni rurki tracheostomijnej po 2 dniach użytkowania: a)–e) powierzchnia na łuku rurki (miejsce 1), f)–i) powierzchnia w okolicach tzw. kołnierza rurki (miejsce 2)

provide adequate ventilation and allow free breathing by bypassing the upper airway. Tracheotomy is often performed as an urgent, life-saving procedure. Indications for tracheotomy include: mechanical airway obstruction due to tumours of the lower pharynx and larynx, acute laryngeal trauma, congenital laryngeal malformations, foreign bodies in the lower pharynx and larynx, inflammation and abscess of the epiglottis. Between 2020 and 2023, tracheotomy was also performed in patients with complications caused by COVID-19 [1]. Tracheotomy may also be necessary when intubation is not possible or when permanent intubation is not advisable.

Laryngeal cancer most often presents as head and neck squamous cell carcinoma (HNSCC). In Poland, laryngeal cancer is the ninth most common cancer in men, after lung, prostate, skin, colorectal, bladder, stomach, rectal and kidney cancers. It accounts for about 2.7% of all cancers in men and about 0.4% of cancers in women. It is a much more common cancer in men. According to the National Cancer Registry, 2197 new cases of laryngeal cancer were reported in Poland in 2011, including 1925 in men and about 272 in women [2].

Despite advances in chemoradiotherapy, radical laryngectomy remains the treatment of choice for clinically advanced laryngeal cancer. Removal of the larynx causes permanent changes in the patient's breathing – the airway begins its course in the trachea, and the inhaled air is no longer cleared through the nose and throat as before.

After a total laryngectomy, a tracheostomy tube is essential to maintain a clear airway. It enables direct air access to the trachea and lungs. The main indications for the use of a tracheostomy tube after surgery include: ensuring airway patency, improving air exchange (a tracheostomy tube helps to maintain effective gas exchange by allowing air to enter the airway directly), facilitating the removal of secretions by draining and removing excess secretions from the airway, which is important for maintaining patency and preventing infection.

There are different types of tracheostomy tubes:

- Metal tubes, usually made of stainless steel or titanium, are used as temporary tubes or when more stability is needed. They are durable and reusable, but require regular disinfection and care.
- Soft plastic tubes, often made of PVC or silicone, are popular because they are flexible, lightweight and comfortable for the patient. They can be used as

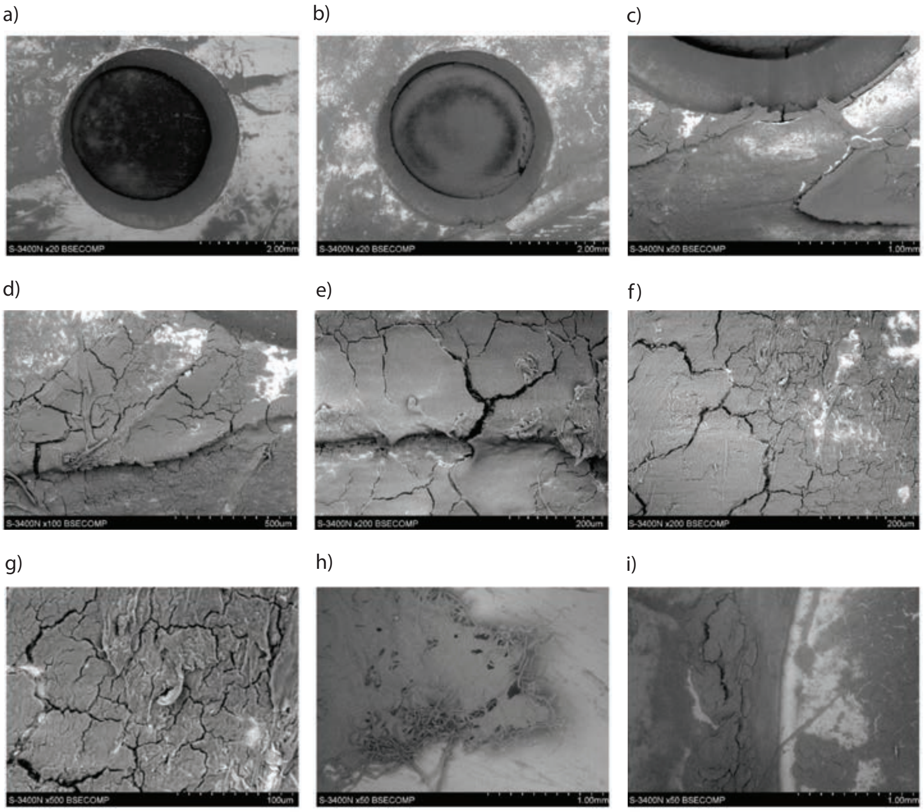
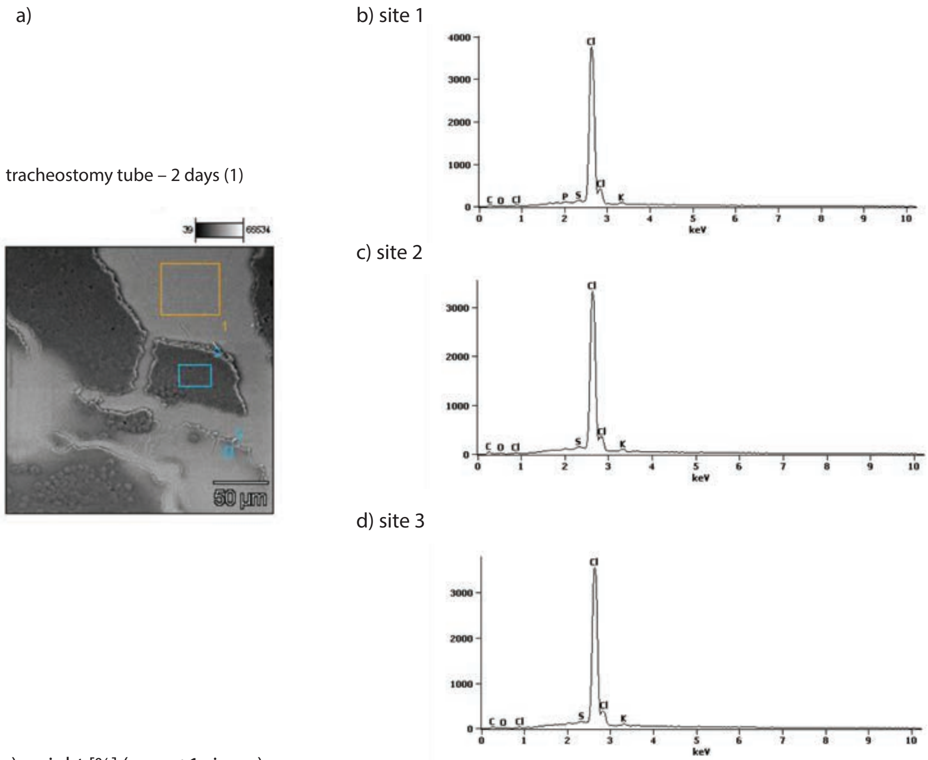



Fig. 4. Morphology of the surface of a tracheostomy tube after 3 months of use: a)–c) surface perpendicular to the axis of the tube, e)–i) side surface of the tube – details

Fig. 4. Morfologia powierzchni rurki tracheostomijnej po 3 miesiącach użytkowania: a)–c) powierzchnia prostopadła do osi rurki, e)–i) powierzchnia boczna rurki – szczegóły




e) weight [%] (error ±1 sigma)

| Site | C-K | O-K | P-K | S-K | Cl-K | K-K |
|---|---|---|---|---|---|---|
| 1 | 63.2 ±4.2 | 11.7 ±1.6 | 0.2 ±0.0 | 3.7 ±0.4 | 17.6 ±0.2 | 3.7 ±0.4 |
| 2 | 58.4 ±4.2 | 16.7 ±2.5 | – | 4.7 ±0.4 | 14.8 ±0.2 | 5.4 ±0.4 |
| 3 | 59.5 ±4.5 | 14.3 ±2.6 | – | 4.2 ±0.4 | 17.3 ±0.2 | 4.6 ±0.5 |

both temporary and long-term tubes. Plastic tubes are usually disposable and require regular replacement.

- Dual-canula tubes, which have rounded ends and an inner canula. The outer tube allows the inner canula to be moved which helps reduce stress on the tissues in the neck. Dual-canula tubes are used to reduce the risk of complications associated with prolonged tracheostomy tube wear.
- Cuffed tubes, which have an elastic cuff that is placed in the trachea to prevent air leakage and the entry of food or fluids into the airway. This cuff can be inflated and controlled to adjust the fit of the tube to the trachea.

In addition, there are different sizes of tracheostomy tubes, which are selected individually for each patient, taking into account the patient's age, body size and anatomical characteristics [3].

## 2. Issue with the lifespan of tracheostomy tubes

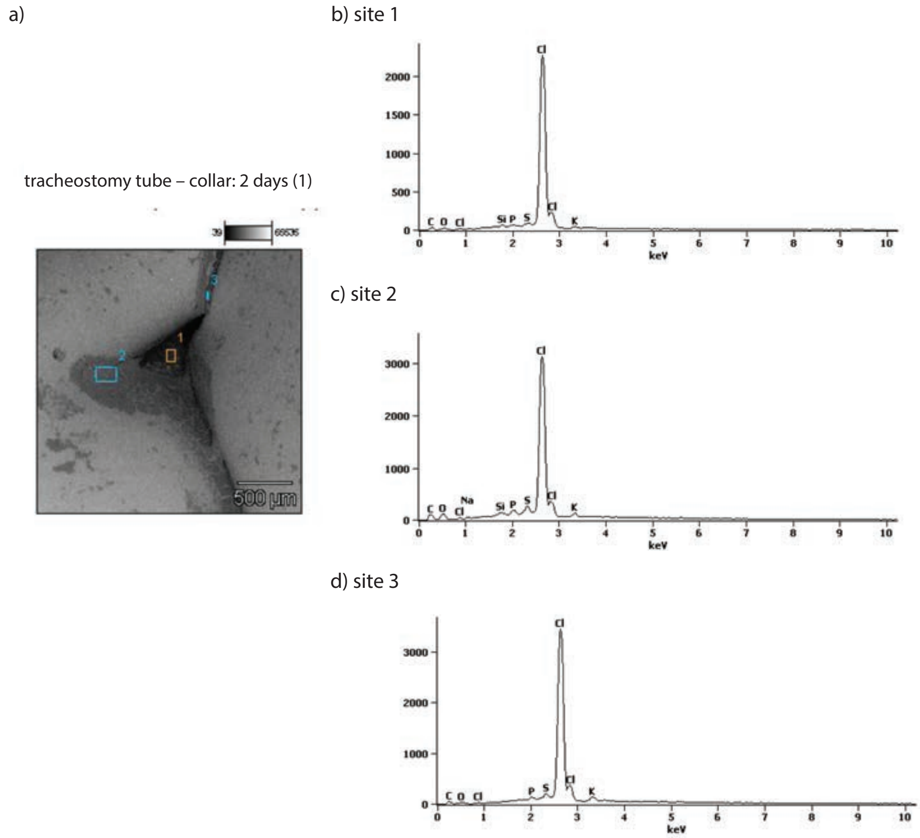
The use of tracheostomy tubes in the tracheal and laryngeal mucosal environment is associated with their limited durability. Factors that contribute to limitations in tracheostomy tube function include:

- the properties of the tube: wear and tear of the material that leads to reduced clinical usefulness and reduced functionality of the tube;
- condition of the tissue surrounding the tracheoesophageal fistula: infection at the implantation site, granulation tissue formation around the tube, enlargement of the fistula.

One of the most important characteristics affecting the durability of a tracheostomy tube is the type and quality of the material from which it is made. Biofilm formation is the most

Fig. 5. Surface morphology of a tracheostomy tube (after 2 day of use; site 1) on the arch with marked areas for chemical composition tests by X-ray microanalysis (site 1–3) (a), X-ray energy dispersion (EDS) spectra (b–d) and chemical analysis at sites indicated in Fig. 5a (e)

Rys. 5. Morfologia powierzchni rurki tracheostomijnej (po 2 dniach użytkowania) na łuku (obszar 1) z zaznaczonymi obszarami do badań składu chemicznego metodą mikroanalizy rentgenowskiej (obszary 1–3) (a), widma promieniowania rentgenowskiego z dyspersją energii (EDS) (b–d) oraz skład chemiczny z obszarów zaznaczonych na rys. 5a (e)

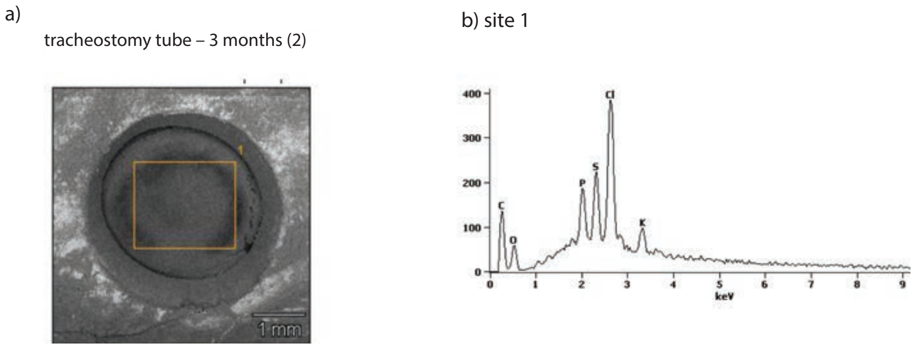



e) weight [%] (error ±1 sigma)

| Site | C-K | O-K | Na-K | Si-K | P-K | S-K | Cl-K | K-K |
|---|---|---|---|---|---|---|---|---|
| 1 | 57.3 ±3.2 | 22.3 ±1.9 | – | 0.2 ±0.0 | 0.2 ±0.0 | 3.0 ±0.3 | 14.3 ±0.1 | 2.6 ±0.3 |
| 2 | 48.8 ±3.7 | 34.7 ±3.1 | 0.6 ±0.2 | 0.2 ±0.1 | 0.4 ±0.1 | 4.5 ±1.1 | 7.1 ±0.2 | 3.7 ±0.9 |
| 3 | 52.5 ±4.2 | 20.2 ±2.3 | – | – | 0.2 ±0.0 | 5.7 ±0.5 | 13.2 ±0.2 | 8.3 ±0.9 |

Fig. 6. Surface morphology of a tracheostomy tube (after 2 day of use) with marked areas for chemical composition tests by X-ray microanalysis (site 1 and 2) (a), X-ray energy dispersion (EDS) spectra (b–d) and chemical analysis at sites indicated in Fig. 6a (e)

Rys. 6. Morfologia powierzchni rurki tracheostomijnej (po 2 dniach użytkowania) w pobliżu tzw. kołnierza (obszar 2), z zaznaczonymi obszarami do badań składu chemicznego metodą mikroanalizy rentgenowskiej (obszary 1–3) (a), widma promieniowania rentgenowskiego z dyspersją energii (EDS) (b–d) oraz skład chemiczny z obszarów zaznaczonych na rys. 6a (e)




c) weight [%] (error ±1 sigma)

| Site | C-K | O-K | P-K | S-K | Cl-K | K-K |
|---|---|---|---|---|---|---|
| 1 | 62.4 ±3.2 | 23.9 ±2.2 | 0.7 ±0.1 | 7.5 ±0.4 | 1.0 ±0.1 | 4.4 ±0.7 |

Fig. 7. Surface morphology of a tracheostomy tube (after 3 months of use) (site 1) on the arch with marked areas for chemical composition tests by X-ray microanalysis (point 1) (a), X-ray energy dispersion (EDS) spectra (b) and chemical analysis at the site indicated in Fig. 7a (c)

Rys. 7. Morfologia powierzchni rurki tracheostomijnej (po 3 miesiącach użytkowania) na łuku (obszar 1) z zaznaczonymi obszarami do badań składu chemicznego metodą mikroanalizy rentgenowskiej (punkt 1) (a), widmo promieniowania rentgenowskiego z dyspersją energii (EDS) (b) oraz skład chemiczny z obszaru zaznaczonego na rys. 7a (c)

significant factor limiting the life of a tube [4]. A biofilm is a colony of bacteria and/or fungi that forms an external matrix. The therapeutic procedure in patients after complete amputation is the implantation of a voice prosthesis [5]. The mucous membranes of the oesophagus and bronchi are not biologically free of microorganisms. The bacterial and fungal flora that inhabit these areas provide an unlimited source of biofilm production. The microorganisms in the biofilm have special defence mechanisms at the cellular level. The most common microorganisms colonising tracheostomy tubes are *Candida* fungi and the bacteria *S. aureus*, *Pseudomonas spp*, *Enterobacter sp*, *Klebsiella spp* and *Proteus spp*. The process of biofilm formation consists of several stages, such as attachment of pathogens to the tube surface, maturation and spread of the biofilm across the tube surface [6].

It should be noted that control of biofilm formation is important in maintaining the durability of the tracheostomy tube. Regular care and cleaning of the tube can help prevent biofilm formation and maintain tube functionality.

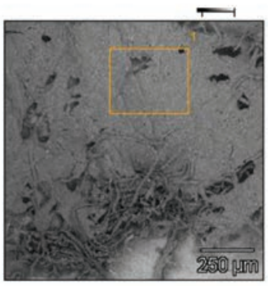
In addition, damage to the surface of the tracheostomy tube can be observed during its use, which can result in micro-injuries to the tracheal mucosa. Micro-injuries are detrimental to the mucosa and lead to granulation tissue formation. A properly designed tube should be made of materials with sufficient hardness, a smooth surface and a shape that minimises contact with the delicate tracheal mucosa.

By incorporating appropriate design features, the risk of damage to the tracheal mucosa can be minimised. This will contribute to a reduction in upper tracheal inflammation.

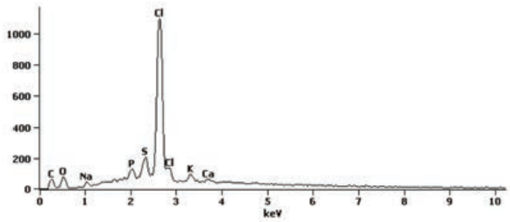
## 3. Study material and methods

The subject of the present study are tracheostomy tubes (Fig. 1). Investigations to assess the surface deterioration of tracheostomy tubes after use by patients for 2 days and for 3 months were carried out using a Hitachi 3400N scanning electron microscope (SEM) equipped with a Thermo NORAN energy dispersive X-ray spectrometer (EDS) and System SEVEN X-ray microanalysis system. Imaging was performed using a backscattered electron (BSE) detector under low vacuum conditions (preparative chamber pressure of 70 Pa). The primary electron energy was 15 keV. Chemical composition analysis was performed by energy dispersive X-ray spectrometry

a)
tracheostomy tube – 3 months (4)




b) site 1




c) weight [%] (error ±1 sigma)

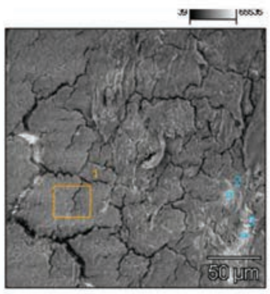
| Site | C-K | O-K | Na-K | P-K | S-K | Cl-K | K-K | Ca-K |
|---|---|---|---|---|---|---|---|---|
| 1 | 50.2 ±3.4 | 33.8 ±2.2 | 1.1 ±0.2 | 0.4 ±0.0 | 7.4 ±0.4 | 3.6 ±0.1 | 3.2 ±0.4 | 0.3 ±0.1 |

Fig. 8. Surface morphology of a tracheostomy tube (after 3 months of use) (site 1) on the arch with marked areas for chemical composition tests by X-ray microanalysis (point 1) (a), X-ray energy dispersion (EDS) spectra (b) and chemical analysis at the site indicated in Fig. 8a (c)

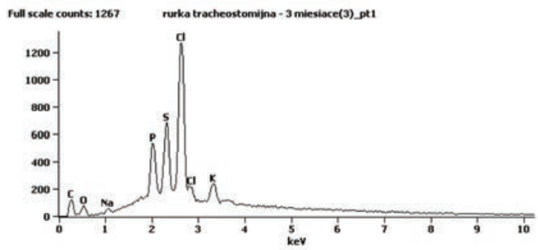
Rys. 8. Morfologia powierzchni rurki tracheostomijnej (po 3 miesiącach użytkowania) na łuku (obszar 1) z zaznaczonymi obszarami do badań składu chemicznego metodą mikroanalizy rentgenowskiej (punkt 1) (a), widmo promieniowania rentgenowskiego z dyspersją energii (EDS) (b) oraz skład chemiczny z obszaru zaznaczonego na rys. 8a (c)

a)

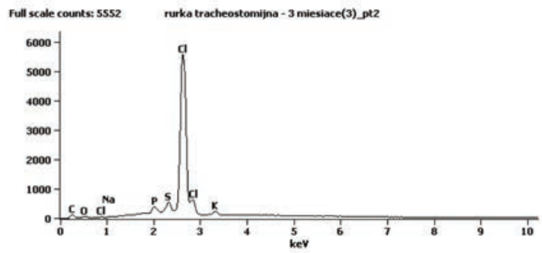
tracheostomy tube – 3 months (3)



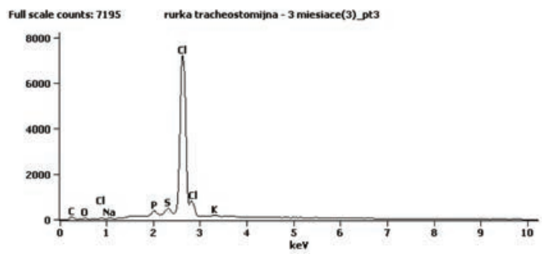

b) site 1




c) site 2




d) site 3




e) weight [%] (error ±1 sigma)

| Tracheostomy tube | C-K | O-K | Na-K | P-K | S-K | Cl-K | K-K |
|---|---|---|---|---|---|---|---|
| 3 months (3)_pt1 | 45.3 ±3.9 | 23.1 ±3.1 | 1.0 ±0.2 | 1.7 ±0.1 | 18.6 ±1.4 | 2.6 ±0.1 | 7.7 ±1.2 |
| 3 months (3)_pt1 | 49.9 ±3.7 | 20.8 ±3.3 | 0.3 ±0.2 | 1.0 ±0.2 | 9.7 ±1.6 | 13.0 ±0.3 | 5.4 ±0.7 |
| 3 months (3)_pt1 | 50.0 ±4.0 | 19.0 ±3.4 | 0.3 ±0.2 | 0.8 ±0.2 | 7.0 ±1.7 | 16.6 ±0.4 | 6.3 ±1.3 |

Fig. 9. Surface morphology of a tracheostomy tube (after 3 months of use; site 1) on the arch with marked areas for chemical composition tests by X-ray microanalysis (points 1–3) (a), X-ray energy dispersion (EDS) spectra (b–d) and chemical analysis at sites indicated in Fig. 9a (e)

Rys. 9. Morfologia powierzchni rurki tracheostomijnej (po 3 miesiącach użytkowania) na łuku (miejsce 1) z zaznaczonymi obszarami do badań składu chemicznego metodą mikroanalizy rentgenowskiej (punkty 1–3) (a), widma promieniowania rentgenowskiego z dyspersją energii (EDS) (b–d) oraz skład chemiczny z obszarów zaznaczonych na rys. 9a (e)

(EDS). Due to the presence of light elements (with atomic number Z < 11), quantitative analysis was performed using standards (Astimex Standard Ltd. METM25-44 and MINM25-53).

## 4. Research results

### <u>4.1. Evaluation of surface morphology of tracheostomy tubes after 2 days and after 3 months of use</u>

Analysis of the tracheostomy tube surface was performed at two selected sites with markedly different levels of physiological fluid interaction (Fig. 2) after the following periods of patient use: the first tube – 2 days, the second – 3 months (Fig. 2). This choice of analysis sites allowed a number of significant changes to be observed, mainly related to interaction with surrounding tissue and biofilm.

The surface morphology of the tubes after 2 days and after 3 months of use differed significantly (Fig. 3, 4). For tubes after 2 days of use, only a few areas on the tube surface were observed to be covered with biofilm, usually in the form of colonies. The biofilm in these areas was very thin and transparent in many places (the tube substrate was visible; Fig. 3b). The biofilm coverage of the tube after 3 months of use was of a completely different nature, with thick deposits in many places (Fig. 4d, 4e).

### <u>4.2. Analysis of the chemical composition of deposits on the surface of tracheostomy tubes after 2 days and after 3 months of use</u>

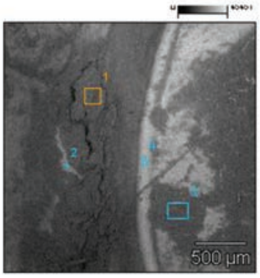
Examination of the chemical composition of the fouling on the surface of the tube after 2 days of use (Fig. 5) showed the presence of mainly chlorine (most likely from the tube material), but also elements included in the deposits on the surface such as P, S, Na, K and C.

Analysis of the surface morphology and chemical composition of a tracheostomy tube in the area of the collar (site 2; Fig. 6) showed no significant differences in the presence of elements compared with the area on the tube arch (site 1; Fig. 5). Of the visible differences, it is worth noting the reduced carbon content and the comparatively increased oxygen content (by about 10%).

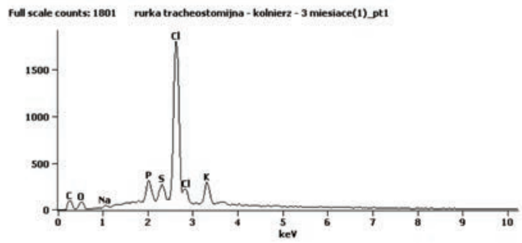
Analysis of the surface morphology and chemical composition of a tracheostomy tube after 3 months of use (Fig. 7–10) showed significant differences compared to analogous areas on the surface after 2 days of tube use (Fig. 5, 6). These differences are mainly related to the presence of the elements Cl, S, P and K, which are clearly more abundant.

a)

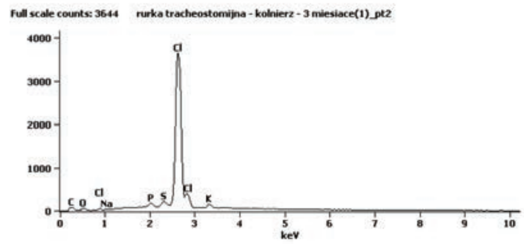
tracheostomy tube: collar – 3 months (1)



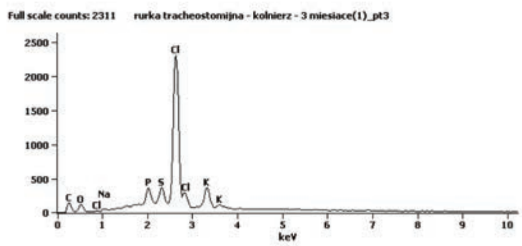

b) site 1



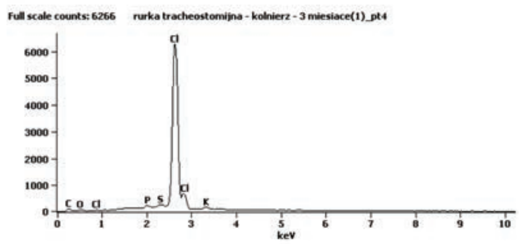

c) site 2




d) site 3




e) site 4




f) weight [%] (error ±1 sigma)

| Tracheostomy tube | C-K | O-K | Na-K | P-K | S-K | Cl-K | K-K |
|---|---|---|---|---|---|---|---|
| **Collar – 3 months (1)_pt1** | 47.1 ±4.0 | 27.7 ±2.9 | 0.7 ±0.2 | 1.0 ±0.1 | 6.7 ±0.5 | 3.8 ±0.1 | 12.9 ±0.1 |
| **Collar – 3 months (1)_pt2** | 57.4 ±4.3 | 22.0 ±2.7 | – | 0.4 ±0.1 | 4.3 ±0.5 | 10.0 ±0.2 | 5.8 ±0.5 |
| **Collar – 3 months (1)_pt3** | 42.5 ±3.3 | 30.9 ±3.2 | 1.0 ±0.2 | 1.0 ±0.1 | 6.6 ±1.1 | 4.4 ±0.1 | 13.6 ±1.2 |
| **Collar – 3 months (1)_pt4** | 53.0 ±4.6 | 22.1 ±3.1 | – | 0.4 ±0.1 | 4.2 ±0.6 | 15.4 ±0.3 | 4.8 ±1.0 |

Fig. 10. Surface morphology of a tracheostomy tube (after 3 months of use) with marked areas for chemical composition tests by X-ray microanalysis (points 1 and 2) (a), X-ray energy dispersion (EDS) spectra (b–e) and chemical analysis at the sited indicated in Fig. 10a (f)

Rys. 10. Morfologia powierzchni rurki tracheostomijnej (po 3 miesiącach użytkowania) w pobliżu tzw. kołnierza, z zaznaczonymi obszarami do badań składu chemicznego metodą mikroanalizy rentgenowskiej (punkty 1–3) (a), widma promieniowania rentgenowskiego z dyspersją energii (EDS) (b–e) oraz skład chemiczny z obszarów zaznaczonych na rys. 10a (f)

## 5. Conclusion

Examination of the surface morphology of tracheostomy tubes used by patients for 3 months, as opposed to those used for 2 days, revealed the presence of numerous biofilm colonies and large areas of the tubes completely encrusted with biofilm colonies. In certain locations, a thick layer of corrosion deposits had formed on the tubes that had been used for 3 months. Prevention of deposit formation is an important aspect determining tube lifespan and functionality. One possible approach would be to inhibit biofilm formation on the tube surface or frequent tube replacement.

The roughness and damage observed on the surface of the tubes may cause microinjuries to the tracheal mucosa over the course of tube use and may lead to granulation around the tracheoesophageal fistula. Therefore, appropriate tube design that minimises the risk of mucosal damage may prolong the life of a tube.

At the same time, it should be emphasised that microanalysis of the chemical composition of the deposits formed on the surface of the tubes did not reveal any elements hazardous to the human body.

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