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Life Cycle Assessment of Paper Based Printed Interconnections for ECG Monitoring

Qiansu Wan, Zhuo Zou, and Lirong Zheng

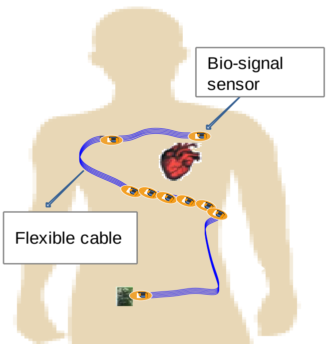
***Abstract*—This paper presents quantitative environment impact evaluation and assessment of inkjet printed flexible cable on soft substrates for Electrocardiography (ECG) monitoring. The studied printed ECG cable is fabricated by inkjet printing of nanoparticles wire on paper substrate which enables wireless transmission of ECG signals between bio-electric electrodes and central medical device. In order to facilitate the inventory analysis, the environmental impacts evaluation of inkjet printing technology has been carried out by comparing with traditional ECG cables. With the life cycle inventory modelling by using GaBi software, the life cycle assessment (LCA) was conducted to qualify the input and output of raw material resources, energy resources used in manufacturing phases and the impacts to environment.**

***Index Terms*—Life Cycle Assessment; Flexible Substrate; Environmental Impacts; Toxic Emissions; Printed Electronics.**

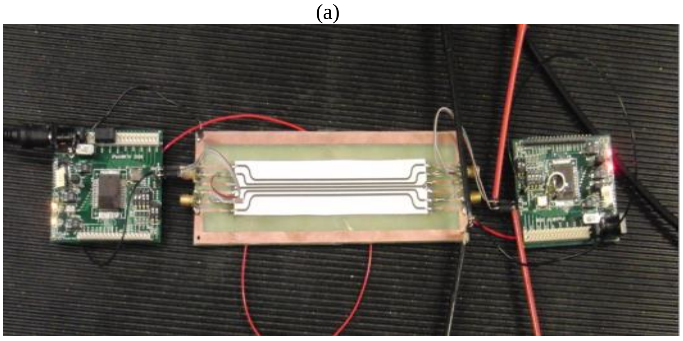
I. Introduction

With the fast growing rate of aging population in developed countries nowadays, Electrocardiogram (ECG) and electromyogram (EMG) are the most commonly measured bio signals in medical field, since heart disease is considered as one of major cause for death all over the world [1]. Due to the limitation of public hospital resources to the people in emergency needs, home healthcare is the way to lighten the workload of doctors and nurses and also allows people to self-monitor their health condition. Thus the wearable healthcare devices become more and more widely use in pervasive and personalized healthcare systems [2]. Different from the traditional ECG monitoring systems which consist of multiple bulky cables and electrodes, a novel wearable ECG monitoring system is developed based on a single inkjet printed interconnection cable and 10 intelligent electrodes [3]. In this new ECG system, the A/D conversions are directly performed on the intelligent electrodes rather than inside a portable device [5], therefore minimum noise interference for ECG data can be achieved. Due to the physical size and rigid nature of the chip package which would cause the wearable ECG device too big and thick to use, a heterogeneous Bio-Sensing Node [4] was proposed, which can integrate low-power silicon-based circuits with printed electronics. As the interconnection between intelligent electrodes and central device, in order to make the printed ECG cable flexible easy to use, and comfortable to patients, a paper based printed flexible cable for wearable ECG devices [6] is developed which enables the connections between user's chest and wearable ECG devices for ECG signal transmission. Inkjet printing technology has been used to manufacture the flexible cable where the conductive metal particles contained inks are directly printed on paper based substrate.

The concept of the printed flexible cable is illustrated in Fig.1. It is fabricated using nano-metal particle contained inks, with the aim of low-cost and disposable after use, which solves problems such as cable tangling, structure failure, as well as hygienic and environmental issues, and as an additive process by using inkjet printing technology, printed flexible cable offers efficient use of materials instead of conventional chemical etching process. On the other hand, different from the new highly integrated inkjet printed cable, key obstacles of traditional cables include the following aspects: firstly, the current normally used ECG cables in clinical field are long cables with a total length of about 100 cm, which suffer from cable tangling problem because they are quite easily intertwined with each other. Hence to detangle the bonded cables not only cost extra time which would interfere with an urgent medical procedural, but also even leads to shortened service time of ECG cables. The second issue is that after



(a)



(b)

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Q. Wan and Z. Zou are with iPack Vinn Excellence Center School of ICT, Royal Institute of Technology (KTH) Eletrum 229, 164 40 Kista-Stockholm, Sweden. (e-mail: {qiansu,zhuo, lirong}@ kth.se)

L. Zheng is with State Key Lab of ASIC & System, Fudan University, Shanghai, 200433, China.

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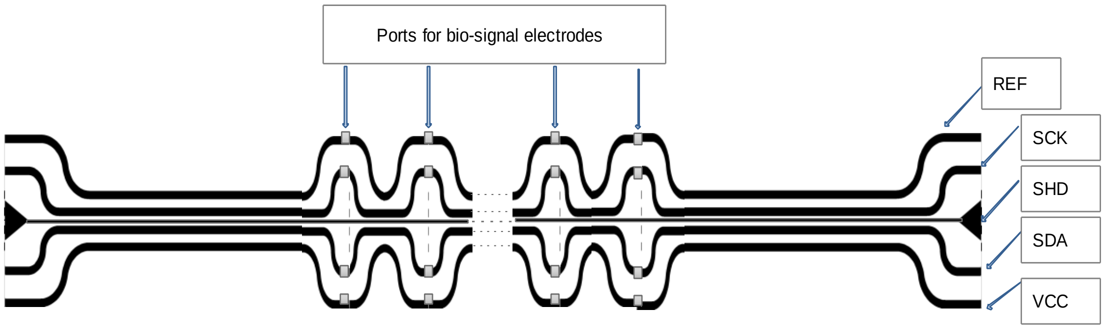

(c)

Fig 1. Printed ECG interconnection's application for wearable ECG monitoring. (a), its measurement setup (b) illustration of the 5-wire ECG cable (c)

Long term usage, the potential structural defects caused by repeatedly bending, stressing and straining a ECG cable may become hindered with signals' transmission or bring in spurious signals. The last issue is that comparing with the new disposable paper-based printed cables, the conventional bio-signal cables which consist of highly integrated plastic parts, copper layers and some other heavy metals, are recognized to be less environmental friendly. Specifically in the end-of-life phase, neither landfilling nor incineration could barely efficiently deal with the discarded cables, which leads to a big amount of money for waste management [16].

In this paper, we introduced paper based inkjet printed interconnection cables for wearable ECG devices that aim to replace the traditional bulky ECG cables. To achieve this purpose, our work focuses on assessment and analysis of the environment impacts of printed electronics by exploring life cycle assessment tool. The major compositional components of printing materials and ECG cables are studied with references of emission compacts to the environment. Due to the complexity of electronic systems and the consistent lack of solid data about a product's whole life cycles [7], the quantitative comparison has been carried out to qualify the input and output of raw material resources and environmental emissions in manufacturing phases.

II. Life Cycle Assessment for Printed Electronics

A. Life Cycle assessment

LCA has been recognized as a user-friendly and efficient tool for assessing the overall environmental impacts of a variety of products, processes or services [8],[9]. LCA is a tool which is capable of collecting and evaluating quantitative data on the inputs and outputs of material, energy and waste flows associated with a product throughout its entire life cycle, so that the environmental impacts can be determined.

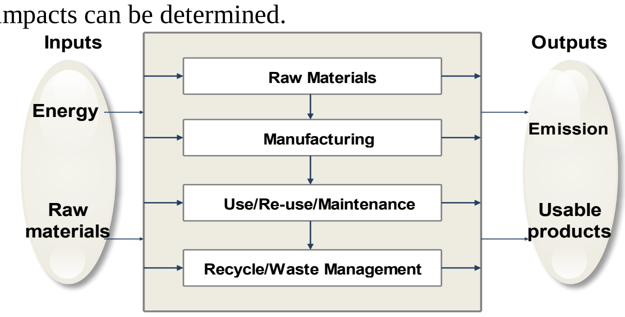

Fig. 2. Life Cycle Stages

The major stages in an LCA mainly include raw material acquisition, materials manufacture, production, use/reuse/maintenance, and the latter stage of waste management. The defined boundaries, assumptions, and conventions to be addressed in each stage are presented. Fig. 2 shows the life cycle inventory boundaries and life cycle stages of a product: the inputs of raw materials and energy, the outputs of waste, emissions through all products' life-cycle stages are compiled to calculate the total load of toxic impacts to environment [15]. By using LCA we can compare the full range of environmental effects assignable to specific products and services by quantifying all inputs and outputs of material flows and assessing how these material flows impact our environment [17]. The obtained information can be used to guide or improve processes, support policy and provide a sound basis for viable solutions [18].

B. Environmental evaluation for printed electronics

For printed electronics, LCA evaluations should be carried out as parallel comparisons between the new technology and the traditional technology due to the reason that it is impossible to create a completed life cycle inventory database for those newly invented products according to its full life cycles. In our case, the conventional bulky ECG cable is used as a reference and alternatives of new technology. Before presenting the environmental impacts evaluation, some of general environmental aspects of printed ECG cables are discussed here:

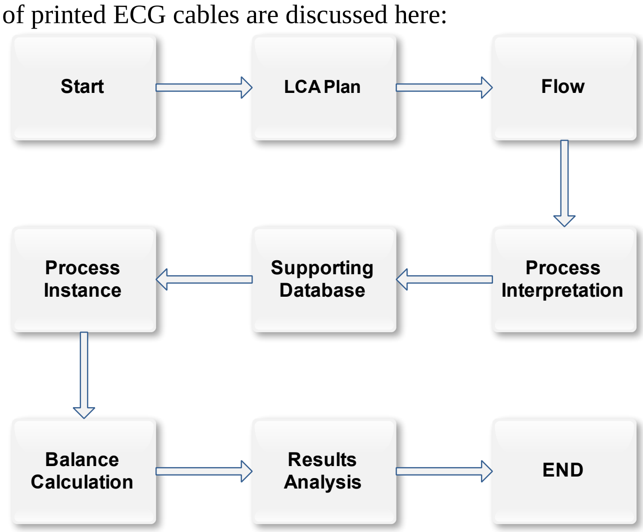

Fig. 3. Procedural Flow Diagram for Life Cycle Analyzing

1) Efficient use of materials

Compared with conventional ECG cables, printed ECG interconnection cables' biggest advantage is the efficient use of materials in development stage. As an additive process,

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the conductive ink is directly printed on the soft substrate without any physical adding and cutting process in different material preparation stages, which leads to significantly smaller amount of raw materials usage.

2) Less use of Toxic substances

During the manufacturing phase, one of the advances of printed ECG cable is avoiding any chemicals involved process. The whole procedure ends when the input conductive ink landing on the paper substrate without any toxic contained chemicals [20]-[22]. Comparing with the new printing technology, conventional ECG cables need to use different kinds of adhesives or solders for packaging and connections which could involve with harmful toxics contained chemicals.

3) Deposable and recyclability

In the end-of-life phase of printed ECG interconnection, not like the reusable conventional ECG cables, it is simply one time used. Due to its nature of soft substrate, incineration would be a very environmental friendly way to minimizing the emissions. And for the conventional ECG cables, with the highly integrity of metal wires, solders and organic packaging, it could not reuse after long term use and has barely any recyclability [23]. At this point, both two cables are not recyclable at their end-of-life phase.

C. LCA methodologies

In order to make the parallel comparison, life cycle inventory analysis has been made for the inkjet printed flexible cable as well as conventional ECG Cables. The procedural flow diagram is based on Gabi's balance calculation as shown in Fig.3. Each step of the LCA methodology is briefly discussed in the succeeding sections.

A plan in the inventory analysis tool is the basis unit for connecting different processes and thereby, modeling the steps of printed electronics life cycle, which is a representation of the system boundaries [10]. Fig. 4 and Fig. 5 show the plan for LCA plan structure of Printed flexible cable and conventional technology respectively. Each flow shows the material or energy flow between every two processes, which is the basis unit in life cycle assessment evaluation tools. The specified database for each individual process will support the process interpretation. All the processes represent the inventory for producing valuable substance such as conductive metal particle contained ink, paper substrate, plastics and electrical components in our case. The supporting database comprises of inputs and outputs for the specified process. The inputs are in the category of renewable resources, non-renewable resources, minerals, waste for recovery, thermal energy and so on. Similarly, the output represents environmental impact such as inorganic/organic emissions to fresh water/air/sea water, heavy metals to air, hydrocarbons to fresh water and so on. The process instance is the local process settings after the plan is completed with the set of processes and corresponding flows [11]-[14].Here in our study, raw material inputs for manufacturing phase of both inkjet printed interconnection cable and traditional ECG cables are listed in Table I and II as below.

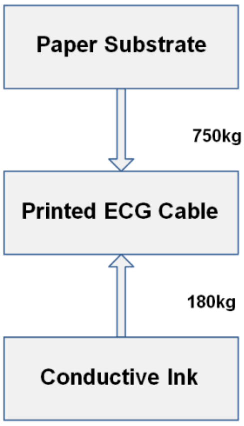

Fig. 4. Plan for LCA structure of Flexible Cable

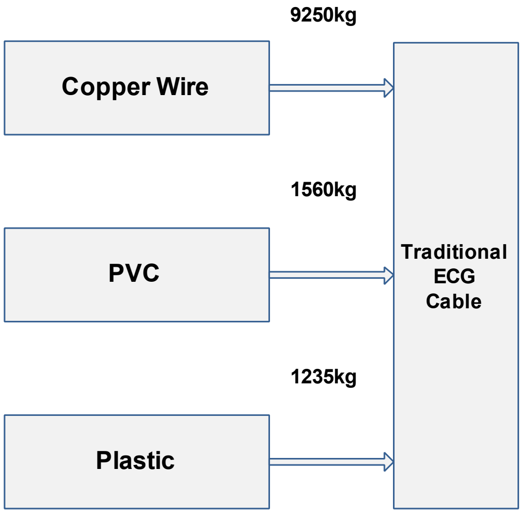

Fig. 5. Plan for LCA structure of traditional ECG cable

TABLE I: PROCESS INTERPRETATION OF PRINTED ECG CABLE

Flows	Amount (kg)	Units
Paper substrate	750	100000
Conductive ink	180	100000

TABLE II: PROCESS INTERPRETATION OF CONVENTIONAL ECG CABLE

Flows	Amount (kg)	Units
PVC	1560	100000
Copper Wire	9250	100000
Plastic Parts	1235	100000

III. ENVIRONMENTAL IMPACTS EVALUATION OF INKJET PRINTING TECHNOLOGY

This section focuses on the results obtained in both technologies i.e. Printed Flexible cable and traditional ECG cable. The environmental impacts evaluation was carried out for different life cycle stages, and the conventional ECG cables were used as an important reference for our new inkjet printing technology. Due to the uncertainty and the lack of life cycle inventory data, our evaluation for both technologies were complemented with the GaBi 4.6 software

A. Results of Inkjet Printing Technology

For the production of 100000 inkjet printed flexible cable, Fig.6 shows the total emissions from inkjet printed ECG interconnection in manufacturing phase. The dominating emission to the environment is to the air, which takes part of 98% of total emissions. Most of the remaining 2% emissions is to fresh water, and sea water receives the rest microscale emissions which is less than 0.1% of total emissions. From input resources, it is noticed that paper substrates consume most part of renewable material resources which mainly consist of water and air. To the other side, consumed nonrenewable resources normally contain metal ore as majority [19].

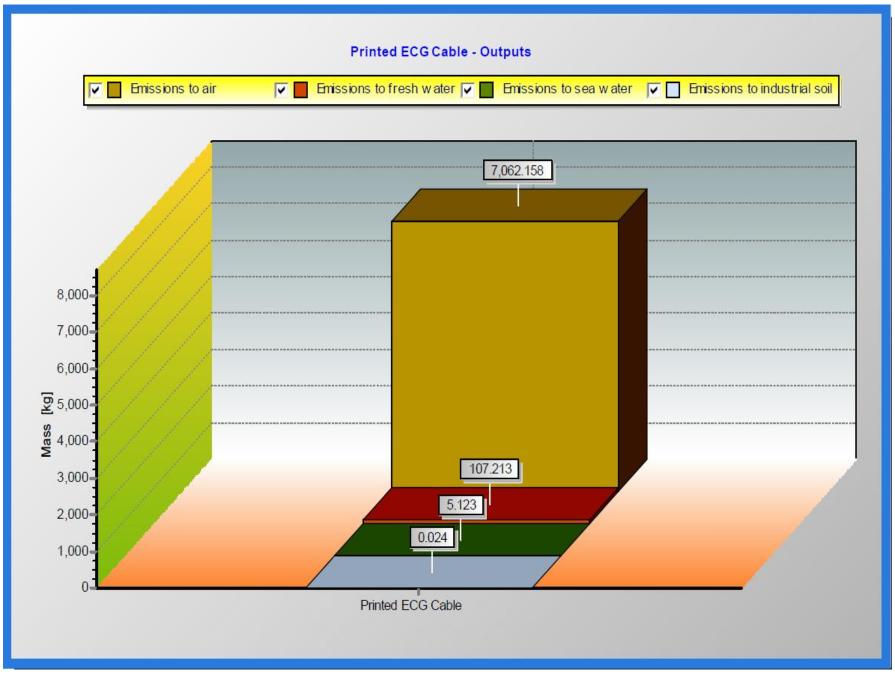

Fig. 6. Total emission of printed flexible cable

As shown in Fig.7, the printed flexible ECG cable produces harmful emissions to air mainly due to inorganic emissions, organic emissions, heavy metals to air, particles to air and radioactive emissions to air. The inorganic emission contains components like ammonia, carbon dioxide, carbon monoxide so on. Among total environmental emissions to air, the percentage of inorganic emissions and other emissions are respectively 51% and 48%. The remaining 1% is for rest of the emissions. The other emissions to air consists of the materials such as heavy metals to air, group PAH to air and halogenated organic emissions to air. The mass of total emissions to air is negligible compared to other emissions.

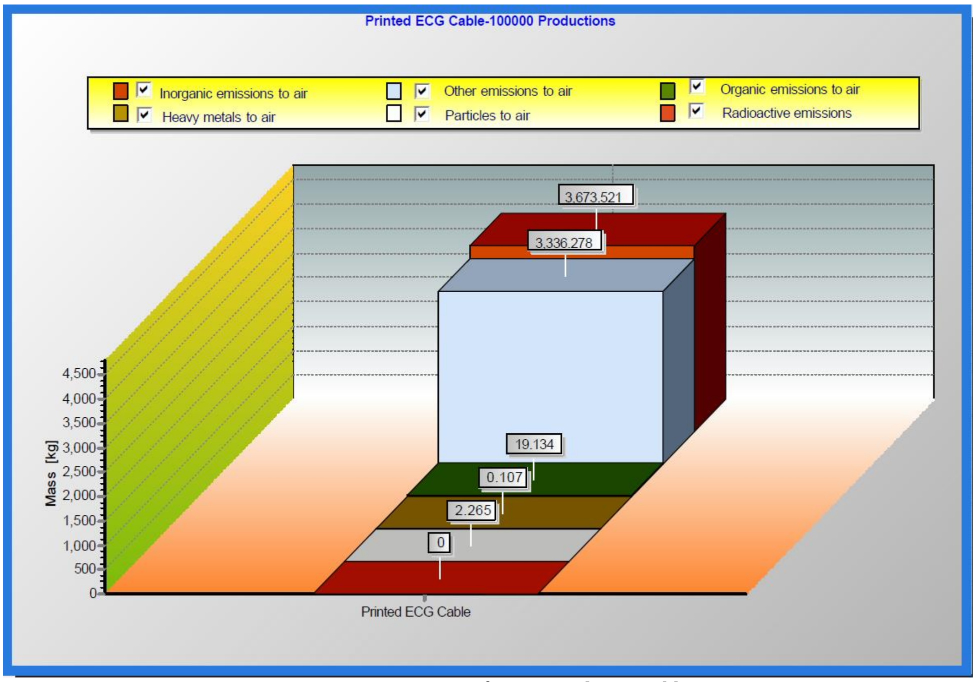

Fig. 7. Emission to air from Printed ECG cable

B. Results of conventional ECG cables

This section of work deals with analysis of environmental emissions for the production of 100000 conventional ECG Cables. For the production of 100000 normal ECG Cables, Fig.8 clearly shows the total environmental emissions in manufacturing phase. The dominating emission to the environment is to the air. The data shows that 75.5% of emissions are into the air and 24% to the fresh water, the amount of pollution to sea water and industrial soil is quite small that can be even ignored.

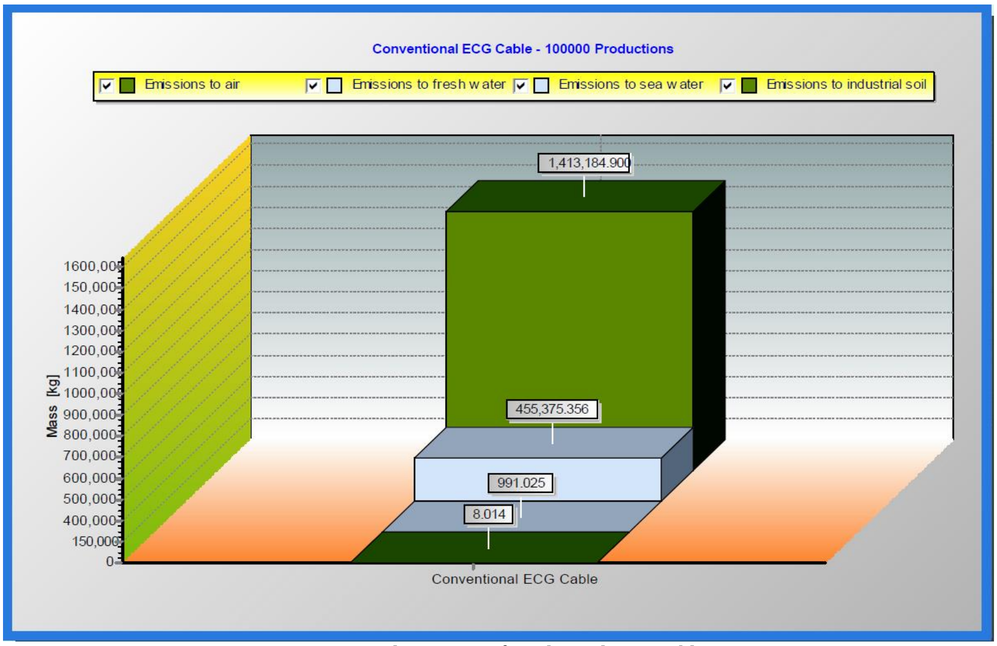

Fig. 8. Total Emission of Traditional ECG cable

Conventional ECG cables produce a big amount of harmful emissions to air mainly caused by in terms of inorganic emissions, organic emissions, heavy metals to air, and particles to air. The inorganic emission mostly contains components like ammonia, carbon dioxide, carbon monoxide and so on. The other emissions to air consists of the materials such as heavy metals to air, group PAH to air and halogenated organic emissions to air. There are other emissions to air such as organic emission, radioactive emission to air and particles to air. The amount of these emissions is negligible compared to inorganic emission.

The secondary emission from conventional ECG cables would pollute fresh water includes the following components. The dominating emission to fresh water is due to inorganic components which contain chloride, calcium and hydroxide as the major constituents.

IV. Discussion

In comparison with traditional ECG cables by the mentioned quantitative data for the total emissions, emissions to air, emissions to fresh water and industrial soil, from Table III we can clearly notice the different environmental performances of these two ECG cables. The evaluation results indicate that a total mass of emission in production of 100000 traditional ECG Cables is 1869550 KG, which is close to 300 times more than the printed Flexible cable with the total emissions of 7174 KG. Furthermore, inkjet printing technology based interconnection cable consumed significantly less raw materials and chemicals in manufacturing phase, and not even need to mention that printed ECG cable is deposable and easy to deal with the environmental impacts in end-of-life phase by incineration or landfilling.

As a simplified LCA evaluation in this work, we only considered the manufacturing phase of printed electronics due to the lack of solid life cycle inventory data. The further work should focus on obtaining reliable data on nanoparticle conductive inks and different life cycle analysis especial for the end-of-life phase, as well as environmental and health risk assessment for new technology like inkjet printing.

TABLE III: Emissions of Printed ECG cable and Conventional ECG cables

	Printed ECG cable(kg)	Conventional ECG cables (kg)
Emissions to air	7062	1413184
Emissions to fresh water	107	455375
Emissions to sea water	5	991
Emissions to industrial soil	0	0
Total emissions	7174	1869550

V. Conclusion

In this paper we have investigated the life cycle assessment and environmental impacts of paper based printed flexible ECG cable with a parallel comparison with traditional ECG cables. Our objective was to conceive life cycle assessment of printed flexible cable in raw materials and manufacturing phase. The results show printed flexible ECG cable causes much less harmful and hazardous impacts to the environment. After the inventory data analysis, we reached to the conclusion that inkjet printed electronics are more environmental friendly.

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The authors declare that there is no conflict of interest regarding the publication of this paper.

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