GUIDANCE FOR TRACE ANALYSIS OF SHORT-, MEDIUM-, AND LONG-CHAIN CHLORINATED PARAFFINS

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Introduction

Chlorinated paraffins (CPs) are high-volume production chemicals widely used as metal working lubricants, plasticizers, and flame retardants[1,2]. They are complex mixtures of polychlorinated linear alkanes (paraffin) varying in chain length from 6 to 38 carbons[3]. Chain length range of raw material paraffin is a common classification criterion for industrial products of CPs. In general, CPs are produced, used, investigated, and regulated based on the categories of short-chain ($C_{10\text{-}13}$, SCCPs), medium-chain ($C_{14\text{-}17}$, MCCPs), and long-chain ($C_{18\text{-}}$, LCCPs) CPs[4]. Weight-based chlorination degree of CPs is another classification criterion, such as CP 52% Cl[5].

In 2017 SCCPs were added in the Stockholm Convention on persistent organic pollutants (POPs), which means that about 16.5% of total CP production[6] is now under global regulation. As substitutes, increasing quantities of the remaining CP categories are expected[7]. However, CPs in general have similar mechanisms of toxicity[8,9] and studies show that both the regulated CPs (SCCPs) and in-use CPs (MCCPs, LCCPs, etc.) are persistent in the envrionment for decades[10] and bioaccumulative in living organisms[11-13] including human beings[14]. Therefore, sensitive and precise analytical approaches for both regulated and in-use CPs are needed for monitoring the effectiveness of regulations as well as the shifting production and use patterns of CPs.

The increasing demand for analysis of CPs in environmental samples and consumer products means that many laboratories will be seeking to establish methods for their quantification. However, the complexity of CP mixtures poses an exceptional challenge for analytical chemists[15,16]. Here we provide practical guidance for establishing analytical methods for CPs with available lab facilities and commercial reference standards based on our recent critical review[16] of over 160 publications.

Results and discussion

Prerequisites for CP analysis: The most important prerequisite for establishing CP analysis is the availability of an analytical instrument. For a given instrument, its chromatographic, detection, and instrument resolution technology (especially for mass spectrometers) determine whether it can resolve (1) CPs from other chemicals such as sample matrix and some organochlorine contaminants, (2) SCCPs, MCCPs, and LCCPs from one another, and (3, 4) individual chain length groups (C_n)/congener groups (C_nCl_m). The available analytical instrument together with the chosen sample clean-up methods and data processing methods determines whether CPs can be quantified as (1) total CPs, (2) total SCCPs, MCCPs, or LCCPs, (3) individual carbon chain lengths, or (4) at best individual congener groups. Figure 1 shows a simplified flow chart of method development.

Instrumentation: Detailed review on capability of analytical instrument is given in our recent paper[16] in the aspects of chromatographic, detection, and instrument resolution technology, respectively. The general performance of an analytical instrument in CP analysis is determined by a combined effect of these three components.

GC-ECNI-LRMS is used as an example of how an analytical instrument available in a lab might determine the specificity of CP analysis that could be developed. Its capability of analyzing CPs is a combined effect of single dimension GC, ECNI ion source, and low-resolution MS. Single dimension GC using suitable instrumental

settings is capable of separating HCB, lindane, and HCH from CPs, but is incapable of separating some PCBs, chlordane, toxaphenes[17], and phthalates[18]. There are also chromatographic overlaps between CP congener groups differing by less than four in terms of total number of carbon and chlorine[17,19]. The ion source ECNI can measure CPs in terms of congener groups, but not including congener groups with <5Cl, which means about 30% – 60% of congener groups in environmental samples are invisible with this ionization method in the case of SCCP analysis[20]. LRMS cannot resolve PCBs, chlordane, toxaphene[17,21], phthalates[18], etc. that were not separated by GC from CPs. Importantly, LRMS also suffers serious interference of SCCPs/MCCPs/LCCPs with each other in the way of nominal masses including C_nCl_m and $C_{n+5}Cl_{m-2}$[22] as well as C_nCl_m and $C_{n+2}Cl_{m-1}$[23]. To resolve SCCPs, MCCPs, and LCCPs from each other requires a HRMS with a mass resolution of >7000[24,25]. As a result, analysis of SCCPs using GC-ECNI-LRMS requires careful clean-up to remove interfering contaminants (see below)[26,27] and is highly uncertain when applied for sample extracts with dominant amounts of MCCPs and/or LCCPs.

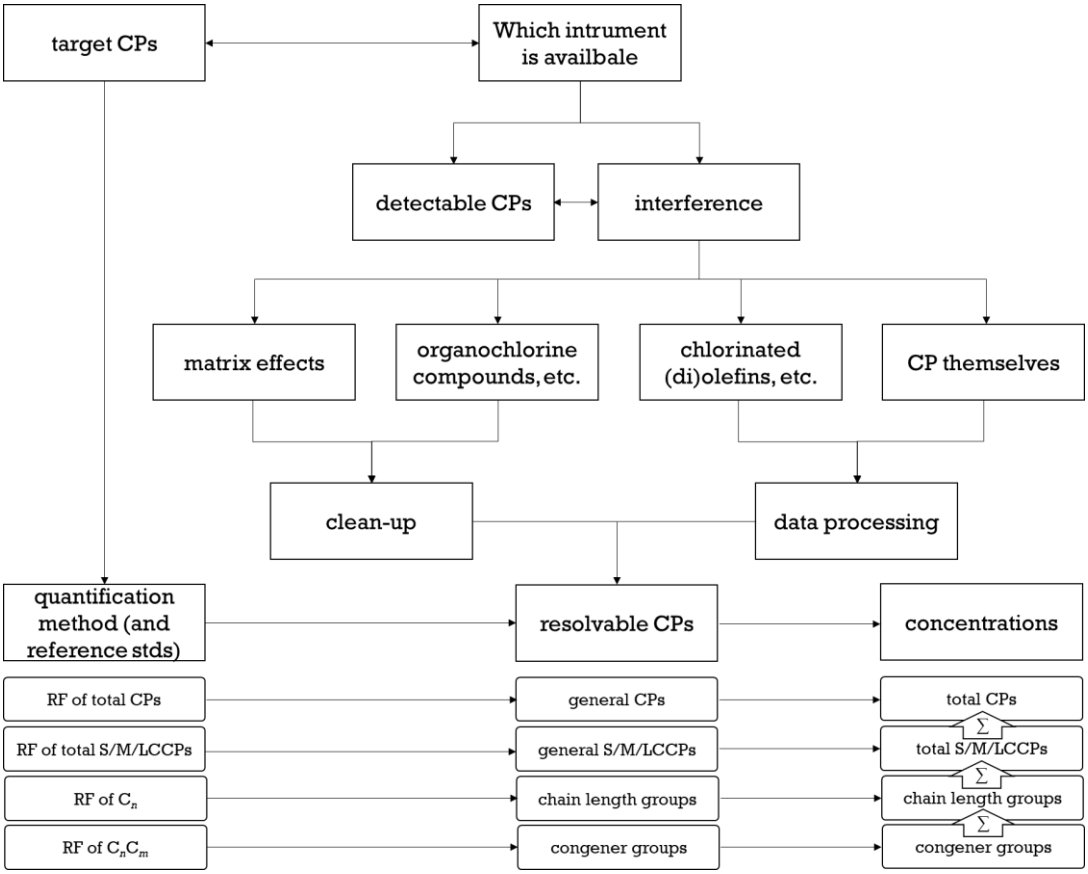

Figure 1. Simplified schematic flow chart of establishing an analytical method of CPs. RF: (instrumental) response factor.

Extraction and clean-up: Extraction methods for other persistent organochlorines could be adapted for recovery of CPs. For example, Tomy et al. used Soxhlet to extract SCCPs from sediment samples[17], the method of which was developed for OCPs[28]. Selective extraction of CPs has so far not been reported. Therefore proper clean-up is necessary in order to remove some of the co-extracted compounds that cause interferences in instrumental analysis of CPs. Chromatographic column techniques using silica or Florisil showed a satisfactory capability of removing some chlorinated interference such as PCBs, DDT and its metabolites from CPs. So far, SCCPs, MCCPs[29], and LCCPs have not been shown to be completely separated from one another in the chromatographic clean-up steps.

The recovery of CPs as a chemical mixture during extraction and clean-up has been mostly evaluated by single chemical surrogate. A ^{13}C labelled CP congener standard[30] has been used as a general recovery standard for SCCPs, MCCPs, and LCCPs in different matrices including indoor dust[31], soil[32], water[13], and biota samples[11]. Organochlorine chemicals other than CPs (such as ^{13}C-α-HCH[26]) have also been used as surrogates, but isolation of these surrogates from CPs have sometimesbeen reported using clean-up columns different from the one used for developing the method[27].

Data acquisition and processing: GC chromatograms of CPs are generally broad bands[21]. Inconsistencies may occur in manual integration. It is helpful to have an automatic algorithm with consistent retention time range and clear definition of baseline[23,33]. To resolve individual congener groups from a HRMS (mass resolution ranging from 7 000 to 50 000[34]), mass spectrum deconvolution[23,35] is a necessary step of data processing prior to quantification. Due to the complexity of mass overlaps, there is lack of reliable data processing methods for resolving SCCPs, MCCPs, or LCCPs with a LRMS.

Quantification: The acquired/processed data are then used for quantifying CPs. Present methods allow CPs to be quantified as mixture group(s), which refer to, from-coarse-to-fine, total CPs, total SCCPs/MCCPs/LCCPs, individual carbon groups, or individual congener groups. Interlaboratory[36,37] and method comparison studies [11,38,39] have indicated that it is possible to accurately measure CPs using different quantification methods, but lower uncertainty can be expected if CPs are quantified to the individual carbon group or congener group level.

Quantifying CPs from the measured signals requires the appropriate instrumental response factors (RFs) with dimensions of instrumental signal/molar concentration of CPs (Figure 1). For example, quantifying CP congener groups requires RFs of corresponding congener groups, otherwise the results are considered to be semi-quantified values. Semi-quantified results can be significantly deviated from theoretical values and are lack of comparability with results obtained from a different instrument method or from same instrument with different settings.

Perspectives

Monitoring SCCPs as POPs requires reliable and precise analytical approaches, while shifting production and use of MCCPs and LCCPs necessitates comprehensive measurement of all CP categories. To fulfill the urgent need of relevant data on these complex substances, rapidness could be one of the top keywords of future analytical methods. Towards comparable CP measurement, quantification should break down the mindset of SCCPs, MCCPs, or LCCPs, and focus on a more detailed level of congener groups. Also, certified reference material and appropriate reference standards are needed.

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